Acute Atrial Stretch Results in Conduction Slowing and Complex Signals at the Pulmonary Vein to Left Atrial Junction
Insights Into the Mechanism of Pulmonary Vein Arrhythmogenesis

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Background—The pulmonary vein–left atrial (PV–LA) junction is key in pathogenesis of AF, and acute stretch is an important stimulus to AF. We aimed to characterize the response of the junction to acute stretch, hypothesizing that stretch would result in electrophysiological changes predisposing to re-entry.

Methods and Results—Fifteen participants undergoing cardiac surgery underwent evaluation of the right superior PV–LA junction using an epicardial mapping plaque. In 10, this was performed before and after atrial stretch imposed by rapid volume expansion, and in 5, it was performed with an intervening observation period. Activation was characterized by conduction slowing and electrogram fractionation transversely across the PV–LA junction, with lines of block also demonstrated perpendicular to the junction. Conduction was decremental (plaque activation time 135.8±46.8 ms with programmed extra stimuli at 10 ms above effective refractory period versus 66.1±22.9 ms with pacing at 400 ms; \( P<0.001 \)) and percentage fractionation was greater with programmed extra stimuli at 10 ms above 20.7%±14.0% (\( P=0.001 \)). Right atrial pressure increased by 2.5±1.8 mm Hg (\( P=0.002 \)) with volume expansion. Stretch resulted in conduction slowing across the PV–LA junction (increase in activation time 10.9±14.6 ms at acute stretch group versus −0.1±4.5 ms in control group; \( P=0.002 \)). Conduction slowing was more marked with programmed extra stimuli at 10 ms above effective refractory period than with stable pacing (13.4±16.5 ms versus 1.7±5.4 ms; \( P=0.003 \)). Stretch resulted in a significant increase in fractionated electrograms (7.9%±7.0% versus −0.4±3.3; \( P=0.004 \)).

Conclusions—Acute stretch results in conduction slowing across the PV–LA junction, with a greater degree of signal complexity. This substrate may be important in AF initiation and maintenance by promoting re-entry. (Circ Arrhythm Electrophysiol. 2014;7:1189-1197.)

Key Words: atrial fibrillation ■ electrophysiology ■ pulmonary vein ■ stretch

It is recognized that paroxysmal atrial fibrillation (AF) is usually initiated by electric triggers originating in the myocardial sleeves extending from the left atrium (LA) into the pulmonary veins (PVs). Although the mechanism of PV arrhythmogenesis remains unclear, a number of studies have demonstrated that the PV–LA junction plays a critical role in initiation and maintenance of AF. Prior mapping studies in isolated canine preparations and in humans have suggested a substrate for re-entry at the PV–LA junction. In a range of clinical and experimental scenarios, acute stretch can be an important trigger for AF. Several clinical studies have evaluated the effect of acute stretch on the electrophysiology of right atrial (RA) myocardium with divergent results. However, the effect of stretch on the PV and PV–LA junction has not been described.

In the current study, we aimed to characterize the electrophysiological response of the PV and PV–LA junction to acute stretch using high-density mapping in patients undergoing elective cardiac surgery. We hypothesized that stretch would result in electrophysiological changes predisposing to re-entry.

Clinical Perspective on p 1197
Methods
Fifteen participants undergoing elective cardiac surgery were studied. Inclusion criteria were preserved left ventricular (LV) systolic function, a normal hemoglobin level, and preserved renal function (estimated glomerular filtration rate >90 mL/min/1.73 m). No participant had previously documented AF or exposure to antiarrhythmics within 6 months. All gave written and informed consent before participation, with the protocol approved by the Melbourne Health Human Research Ethics Committee.

In an active intervention group (n=10), an electrophysiology study protocol was performed before and immediately after acute stretch of the LA imposed by the rapid infusion of 500 mL crystalloid fluid into a central vein. In a control group (n=5), the study was performed before and after a 5 minute observation period without volume expansion.

Epicardial Mapping
Mapping was performed using a high-density mapping plaque positioned on the anterior surface of the junction between the right superior PV and the LA (Figure 1). The triangular plaque has an effective mapping area of 6.75 cm² with 128 silver-plated copper electrodes creating 117 closed-space bipole (interelectrode distance 2.5 mm). The right superior PV was accessed via Waterston’s groove, and the anterior aspect of its junction with the LA was defined anatomically through direct vision and manual palpation. After median sternotomy and pericardial dissection, the plaque was positioned by the surgeon with the base of the triangle over the LA so as to encompass the PV–LA junction, adjacent LA myocardium, and the proximal PV.

Electrophysiology Study Protocol
Pacing was performed sequentially from the LA and PV aspects of the mapping plaque, from the most distal midline bipolar with stable capture. LA and PV effective refractory periods (ERPs) were determined at a cycle length of 400 ms at twice the diastolic threshold. An incremental pacing technique was used, with an initial interval of 150 and 10 ms increments. ERP was defined as the longest coupling interval that failed to propagate across the mapping plaque. ERPs were measured twice, with a third measurement if these 2 values differed by >10 ms. Bipolar electrograms were recorded onto the UneMap mapping system (Uniservices, Auckland, New Zealand) for offline analysis (Figure 1).

Isochronal maps were constructed during sinus rhythm, pacing at a cycle length of 400 ms, and programmed extra stimuli (PES) at 10 ms above ERP. Maps were generated with 3 ms intervals in local activation time (AT) to assess conduction and activation patterns. Total AT was defined as the time for activation to travel from the earliest to the latest site of activation on the plaque and was assessed for each map. Complex electrograms were defined as electrograms of >50 ms duration with ≥3 deflections from baseline or as double potentials separated by an isoelectric interval of >30 ms (Figure 1). The number of fractionated electrograms as a percentage of all recorded electrograms was determined for each map.

Figure 1. Mapping plaque positioning and example electrograms. A, Position of the epicardial mapping plaque on the anterior surface of the right superior pulmonary vein–left atrial (RSPV–LA) junction, accessed between the right atrial (RA) and the right-sided PVs. The base of the plaque lies over the LA and the apex on the RSPV, with the midportion over the anatomic junction. B, Electrograms recorded during stable pacing at 400 ms (left) and with premature stimulation (right). After the stimulus (black arrow), the activation time (AT; red arrow) increases markedly with short cycle length activation. C, Complex electrograms with 2 components separated by an isoelectric interval recorded during stable pacing at 400 ms (left) and premature stimulation (right). The time to the initial phase of activation increases, and the duration of the isoelectric interval increases markedly. D, Electrograms before (left) and after (right) acute stretch. The AT increases markedly with stretch. E, Electrograms before (left) and after (right) acute stretch. Both the AT and the duration of activation increase.
Hemodynamic Evaluation

Arterial oxygenation was measured by pulse oximetry and end-tidal carbon dioxide levels were measured through the ventilator circuit. Arterial pressure was measured invasively, and a multi-lumen catheter was advanced into the pulmonary artery via the right interval jugular vein to allow continuous monitoring of pulmonary artery and RA pressures. Pulmonary capillary wedge pressures were not routinely measured because of institutional concern regarding pulmonary artery balloon inflation. A transesophageal echocardiogram was performed throughout the procedure, allowing Doppler assessment of mitral valve inflow and tissue Doppler assessment of mitral annular movement.

Statistical Analysis

Statistical analysis was performed using commercially available software (GenStat 16th Edition, VSN International Ltd, Hempstead, UK). Data are presented as mean±SD unless otherwise stated. Categorical variables were compared between groups with \( \chi^2 \) or Fisher exact test. Means of normally distributed variables were compared using paired Student’s \( t \)-tests for comparisons before and after intervention. A 2-sample \( t \) test was used to compare means between other groups.

Table 1. Participant Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Atrial Stretch (n=10)</th>
<th>Control (n=5)</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>65±5</td>
<td>60±14</td>
<td>0.30</td>
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<tr>
<td>Sex, M/F</td>
<td>8/2</td>
<td>2/3</td>
<td>0.25</td>
</tr>
<tr>
<td>Hypertension, %</td>
<td>80</td>
<td>50</td>
<td>0.56</td>
</tr>
<tr>
<td>Diabetes mellitus, %</td>
<td>30</td>
<td>20</td>
<td>0.95</td>
</tr>
<tr>
<td>BMI, kg/m(^2)</td>
<td>32±6</td>
<td>28±5</td>
<td>0.25</td>
</tr>
<tr>
<td>LA diameter, cm</td>
<td>3.8±0.7</td>
<td>4.0±0.6</td>
<td>0.74</td>
</tr>
<tr>
<td>LV ejection fraction, %</td>
<td>60±2</td>
<td>58±5</td>
<td>0.13</td>
</tr>
<tr>
<td>RA pressure, mm Hg</td>
<td>7.2±1.6</td>
<td>6.9±0.8</td>
<td>0.71</td>
</tr>
<tr>
<td>( E/E' )</td>
<td>7.2±1.6</td>
<td>6.6±1.2</td>
<td>0.54</td>
</tr>
<tr>
<td>ACE inhibitor, %</td>
<td>60</td>
<td>40</td>
<td>0.61</td>
</tr>
<tr>
<td>B-blocker, %</td>
<td>30</td>
<td>60</td>
<td>0.33</td>
</tr>
</tbody>
</table>

ACE indicates angiotensin-converting enzyme; BMI, body mass index; LA, left atrium; LV, left ventricule; and RA, right atrial.

Table 2. Change in Physiological Variables With Acute Stretch

<table>
<thead>
<tr>
<th></th>
<th>Atrial Stretch (n=10)</th>
<th>Control (n=5)</th>
<th>( \Delta )</th>
<th>( P ) Value</th>
<th>( \Delta )</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR, beats per minute</td>
<td>5.0±10.0</td>
<td>4.0±6.0</td>
<td>0.17</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>2.7±11.8</td>
<td>1.7±17.0</td>
<td>0.61</td>
<td>0.89</td>
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</tr>
<tr>
<td>mPAP, mm Hg</td>
<td>0.2±3.9</td>
<td>1.6±2.0</td>
<td>0.87</td>
<td>0.20</td>
<td></td>
<td></td>
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<tr>
<td>ET-CO(_2), mm Hg</td>
<td>0.1±0.7</td>
<td>0.8±0.8</td>
<td>0.68</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpO(_2), mm Hg</td>
<td>0.1±0.3</td>
<td>0.34</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E/E' )</td>
<td>1.8±2.4</td>
<td>0.4±0.2</td>
<td>0.06</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RA pressure, mm Hg</td>
<td>2.5±1.8</td>
<td>0.3±0.8</td>
<td>0.002</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ET-CO\(_2\) indicates end-tidal carbon dioxide; HR, heart rate; MAP, mean arterial pressure; mPAP, mean pulmonary artery pressure; RA, right atrial; and SpO\(_2\), arterial oxygenation.
Nonparametric exact tests were used for variables not normally distributed. Statistical significance was assessed at the 0.05 level.

Outcome variables were total AT and the percentage of fractionated electrograms derived from each isochronal map, with both baseline data and the change after intervention analyzed. These outcome variables were compared between intervention groups, directions of plaque activation (LA and PV), and modes of activation (sinus rhythm, stable pacing at 400 ms, and PES at 10 ms above ERP) with linear mixed models. The participant identifier was included as a random term, and intervention group, activation direction, and activation mode were included as fixed terms. Dependent variables were transformed to meet the assumptions of normality in the distribution of the residuals and homoscedasticity in the variance of residuals across all levels of the independent variables. Interactions between intervention group, direction, and mode were subsequently added to the model, with the approximate least significant difference method at a 0.05 level used to estimate the significance of differences within the interacting levels. The model was also applied with intervention groups replaced by participant groups based on the measured change in RA pressure (RAP $\geq$ 2 and RAP < 2 mm Hg).

**Results**

In the acute atrial stretch group, 6 participants were undergoing coronary artery bypass graft surgery, 3 were undergoing aortic valve replacement, and 1 was undergoing mitral valve replacement. In the control group, 3 were undergoing coronary artery bypass graft surgery, 1 aortic valve replacement, and 1 mitral valve replacement. Groups were well balanced for important baseline characteristics (Table 1).

**Baseline Data**

**Activation Patterns Across the PV–LA Junction**

Plaque activation was typically characterized by activation moving across the PV–LA junction, with a zone of slow conduction marked by isochronal crowding and electrogram fractionation most apparent parallel to the PV–LA junction itself (Figure 2). In several cases, activation patterns were more complex, with circuitous patterns that could include propagation outside the mapped area. Zones of slow conduction with dense crowding of isochrones were also found perpendicular to the LA-PV junction, with activation turning around the end of the line and returning toward the original site of activation (Figure 3, Videos 1 and 2 in the Data Supplement). Despite this substrate, sustained re-entry was not observed. The anatomic region of conduction slowing and block remained constant in each participant, regardless of activation direction and mode.

**Plaque Activation Time**

There was no significant difference in baseline AT between the acute stretch and control groups, either with data generated by guest on April 15, 2017 http://circep.ahajournals.org/ Downloaded from

| Table 3. Effect of Acute Atrial Stretch on LA and PV Refractoriness |
|---------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Atrial Stretch (n=10) | Control (n=5) | Atrial Stretch (n=10) | Control (n=5) | Atrial Stretch (n=10) | Control (n=5) | Atrial Stretch (n=10) | Control (n=5) |
| LA ERP, ms | 274±36 | 269±32 | 0.58 | 262±51 | 256±61 | 0.40 | 231±27* | 233±32 | 0.48 | 225±52* | 223±57 | 0.79 |
| PV ERP, ms | 231±27* | 233±32 | 0.48 | 225±52* | 223±57 | 0.79 | ERP indicates effective refractory period; LA, left atrial; and PV, pulmonary vein. |

*Overall baseline PV ERP significantly shorter than LA ERP (229±34 vs 264±40; P=0.006).
during sinus rhythm included (acute stretch group 90.7±42.4 ms versus control group 94.5±60.0 ms; P=0.79) or with data limited to that generated during pacing at 400 ms and with PES at 10 ms above ERP (98.5±43.7 ms versus 101.7±63.7 ms; P=0.90). There was no significant difference in AT with LA pacing compared with PV pacing (LA pacing 93.9±39.6 ms versus PV activation 107.3±62.5 ms; P=0.38). AT was significantly longer during PES at 10 ms above ERP than with stable pacing at 400 ms (135.8±46.8 ms versus 66.1±22.9 ms; P<0.001; Figure 4A).

Percent Fractionated Electrograms
The location of fractionated electrograms mirrored the location of isochronal crowding. There was no significant difference in baseline percent fractionated electrograms between the acute stretch and control groups with sinus rhythm data included (acute stretch group 26.8%±18.0% versus 34.4%±17.4%; P=0.20) or excluded (acute stretch group 25.1%±15.8% versus 30.6%±15.9%; P=0.23). There was a significantly greater proportion of fractionated electrograms with PV than with LA pacing (PV pacing 32.4%±15.4% versus LA pacing 22.8%±15.2%; P=0.01). There was significantly more fractionation with PES at 10 ms above ERP than with pacing at 400 ms (33.5%±15.3% versus 20.7%±14.0%; P=0.001; Figure 4B).

Effect of Acute Left Atrial Stretch

Physiological Change
There were no significant differences in baseline physiology between the acute stretch and control groups. Fluid loading was associated with a significant increase in RA pressure of 2.5±1.8 mm Hg (P=0.002), a 35% increase from baseline. This change was sustained for the duration of the mapping protocol. There was some increase in the E/E’ ratio of 1.8±2.4 (P=0.06), as an indirect measure of LA pressure. There were no changes during the observation phase in the control group (Table 2).

Atrial Refractoriness
There were no significant differences in baseline ERPs between the acute stretch and control groups. The PV ERP was significantly shorter than the LA ERP (P=0.006). There were no systematic changes in PV or LA ERPs with acute stretch (Table 3).

Change in Plaque Activation Time
In comparison to the control group, acute atrial stretch resulted in significant conduction slowing across the PV–LA junction, with longer ATs (Table 4; Figures 5 and 6). This increase was reflected in increased isochronal crowding, typically most marked at the PV–LA junction itself. Stretch was consistently associated with an increase in the complexity of the baseline pattern of conduction across the PV–LA junction.

Conduction slowing in response to stretch was significantly more marked with PES at 10 ms above ERP compared with that seen with pacing at 400 ms (Table 4; Figures 6 and 7). The magnitude of stretch-induced conduction slowing was similar with LA and PV pacing.

Total AT data were also analyzed according to the magnitude of change in RA pressure (ΔRA pressure <2 mm Hg versus ΔRA pressure ≥2 mm Hg). An increase of ≥2 mm Hg was associated with significantly a greater increase in AT than was a change of <2 mm Hg (11.5±15.9 versus 2.8±7.7 ms; P=0.01).

Change in Percent Fractionated Electrograms
Compared with the control group, the acute stretch group manifests a significant increase in the proportion of fractionated electrograms (Table 4; Figure 6). There was no significant difference in the extent of change in percent fractionation with acute stretch when comparing PES at 10 ms above ERP with stable pacing at 400 ms or when comparing LA activation to PV activation.

Again there was a significantly greater increase in fractionation in association with an RA pressure rise of ≥2 mm Hg compared with <2 mm Hg (7.8±6.7 versus 2.4±6.6; P=0.04).

Discussion
This study demonstrates that acute atrial stretch results in conduction slowing across the PV–LA junction, with an increase in the proportion of complex signals and more complex patterns of activation. There are no systematic changes in tissue refractoriness.
Additional key findings include the following:

1. Activation across the PV–LA junction is characterized by zones of slow conduction, marked by complex electrograms. These are typically located transversely across the PV–LA junction but variant patterns exist, including the presence of dense bands of conduction block perpendicular to the junction.

2. Conduction at the PV–LA junction is decremental, with increasing delay in response to shorter-cycle length activation. This effect is amplified by the imposition of acute stretch, with a greater change in response to stretch seen with short cycle length activation.

3. There is some evidence of directional dependence, with activation from the PV associated with more fractionated electrograms than activation from the LA, but the anatomic location and basic pattern of conduction slowing was not dependent on activation direction.

We have demonstrated that the electrophysiological characteristics of the PV–LA junction provide a substrate conducive to re-entry, with regions of conduction slowing and circuitous patterns of activation. Our observation that atrial stretch, particularly when interacting with short cycle length activation, significantly enhances this substrate provides a potential explanation for the role of acute stretch in development of AF in varying clinical scenarios. This might be in the form of PV–LA reciprocating re-entry as previously described. Alternatively, conduction slowing and heterogeneity at the PV–LA junction may result in break-up of wavefronts originating from a deeper PV focus.

**PV–LA Junction as a Substrate for Re-Entry**

Our findings are consistent with observations from previous anatomic studies that the PV–LA junction provides an anatomic basis for re-entry, with disorganized muscle architecture, patchy fibrosis, and conduction anisotropy. It also concurs with observations from animal studies of zones of slowed conduction and signal fractionation at the PV–LA junction during short cycle length activation that correlate with abrupt changes in muscle fiber orientation and from human studies of a PV–LA reciprocating circuit inducible by short-coupled PV extra stimuli with breakthrough points at the PV–LA junction.

A previous study by our group of the electrophysiology of the PV–LA junction described various patterns of conduction across the PV–LA junction that shared the common feature of regions of conduction slowing transverse across the PV–LA junction. The current study extends these observations not only by examining the effects of acute stretch but also by demonstrating dense bands of isochronal crowding that run perpendicular to the PV–LA junction. Sustained re-entry was not observed in this study, with the use of only a single extra stimulus at 10 ms above the ERP because of the risk of inducing AF with a more aggressive protocol in patients undergoing cardiac surgery.

**Acute Atrial Stretch and Conduction Block**

Several animal studies have investigated the effects of acute stretch on atrial electrophysiology, demonstrating increased atrial ERPs, increased dispersion of refractoriness, slower intra-atrial conduction, and enhanced vulnerability to AF. Studies of human atrial electrophysiology performed in the electrophysiology laboratory have focused on RA refractoriness in patients without structural heart disease. These studies demonstrated variable results, including no change in ERP, a reduction in ERP, and an increase in ERP. Several human studies have also observed acute stretch to be associated with slowing in RA conduction, enhancing vulnerability to AF. In these clinical studies, stretch has been induced either by simultaneous atrio-ventricular pacing or by volume expansion, and none has specifically studied the PV–LA junction. The magnitude of the RA pressure increase...
was frequently similar\(^6\text{--}^{12}\) to the 2.5 mmHg (34%) increase reported in this study.

Kuijpers et al\(^{21}\) have reported the results of acute stretch when applied to a computer model of the human atria. In this model, stretch increased vulnerability to AF initiation, with stimulation near the PV–LA junction used to trigger arrhythmia episodes. An increase in the dispersion of refractoriness was found to be mechanistically important, but conduction slowing and local conduction block were likewise influential. Another recent study examined the effect of acute stretch in patients with established AF and advanced atrial remodeling undergoing cardiac surgery.\(^{22}\) With patients on cardio-pulmonary bypass and intra-atrial pressure governed by manipulation of the extra-corporeal circuit, acute atrial dilatation resulted in slowed intra-atrial conduction. The authors suggest that slowed atrial conduction and areas of conduction block, manifest by increased AF cycle lengths in the LA- and RA-free wall, might be important for maintenance of AF through promoting re-entrant circuits in the atria. The present study suggests an alternative mechanism, whereby re-entry at the PV–LA junction might sustain human AF. Of course, these mechanisms might be complementary, with PV–LA re-entry relatively more important early in the disease process and sustained intra-atrial re-entry relatively more important in the setting of more advanced atrial disease.

**Limitations**

We directly measured RA pressure caused by institutional concern regarding risks of routine measurement of pulmonary capillary wedge pressure. Also, with no participant in this study having a previously documented history of AF, it might be questioned whether it is appropriate to extend our observations to a population with AF. Potential participants with a history of AF were specifically excluded because the risk
imposed by inducing AF through short-cycle stimulation was considered excessive. Nevertheless, given that the study population, with a high burden of cardiovascular comorbidities and undergoing surgery for coronary or valvular heart disease, is certainly typical of the population at risk of developing AF, the authors think it is reasonable to consider these data to provide an insight into the mechanism of arrhythmogenesis in human AF.

**Conclusions**

Acute atrial stretch results in conduction slowing across the PV–LA junction characterized by a greater degree of signal complexity. These changes may play an important role in AF initiation and maintenance by promoting a substrate favorable to re-entry at the PV–LA junction.

**Sources of Funding**

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**Disclosures**

None.

**References**


**Figure 7.** The interaction between acute stretch and mode of activation. Relatively little change in AT after stretch with either sinus rhythm (SR) or pacing at 400 ms, but an increase of 19 ms during short-cycle length activation, marked by greater crowding of isochrones. No change in the basic pattern of activation.

**CLINICAL PERSPECTIVE**

Chronic atrial stretch in a range of cardiovascular pathologies, including hypertension, mitral valve disease, and heart failure have long been associated with left atrial and pulmonary vein remodeling and an increased prevalence of atrial fibrillation (AF). A range of clinical scenarios in which the atria are exposed to an acute increase in pressure, such as acute heart failure and sleep disordered breathing, are also associated with development of AF. Previous studies of rapid changes in atrial pressure have focussed on right atrial electrophysiology, and particularly on tissue refractoriness, or on wavefront propagation in AF itself. This is the first study to systematically examine the effect of acute stretch on the electrophysiology of the pulmonary vein–left atrial junction, a region known to be important to the various mechanisms suggested as underpinning paroxysmal AF. In response to acute stretch, we demonstrate significant conduction slowing and circuitous activation pathways marked by complex electrogram fractionation. We highlight the potential for re-entry at the pulmonary vein–left atrial junction as a mechanism by which AF might be sustained in the setting of acute stretch. Overall, this is a reminder of the importance of optimizing control of any comorbidities, which can precipitate AF or accelerate remodeling of the atria and pulmonary veins.
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Supplemental Material

Video File Legend

Propagation maps are created using the timing of local activation at each bipole on the mapping plaque during stable pacing and with activation at 10msec above ERP, with the pacing stimulus at time zero. Each animation demonstrates 3 mapping plaque activations at a constant cycle length of 400msec, followed by a premature activation at 10msec above ERP. Using commercially available software (DataTank, Visual Data Tools Inc, Chapel Hill, NC, USA) each recording is sampled at a rate of 1000Hz, with individual activations at each fixed bipolar site on the epicardial plaque animated independently. When activation occurs at a given site this location is animated ‘on’ for an activation time window of 20msec, and the product of all individual bipole activations reveals propagating wavefronts. Atrial slow conduction has been defined as a local conduction velocity of 10-20cm/sec and conduction block as <10cm/sec, so given the 2.5mm inter-bipole spacing a difference in local activation times of 25 and 35 msec between adjacent bipoles in the horizontal and oblique trajectories respectively would represent conduction block. It is unlikely that 2 adjacent bipoles would be activated by the leading edge of the same wavefront if the difference in local activation times are greater than these values, which represent the physiological limits of normal wavefront propagation.

Video 1: Wavefront propagation proceeds from the left atrium (LA) into the pulmonary vein (PV) and pivots around a linear band of complex electrograms (marked on the plaque by pink diamonds) to return to the LA.

Video 2: Wavefront propagation proceeds from the LA into the PV and then divides, with ongoing propagation both into the PV and simultaneously back into the LA. A region of complex signals is found at the location of wavefront splitting. Conduction following the 4th activation, with shorter cycle length activation at 10msec above ERP, is visibly slower than conduction following the initial 3 activations at a stable cycle length of 400msec.