Evidence for Longitudinal and Transverse Fiber Conduction in Human Pulmonary Veins
Relevance for Catheter Ablation

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Background—Segmental ostial ablation of the pulmonary veins (PVs) allows for successful control of paroxysmal atrial fibrillation in many patients. We hypothesized that mapping of the left atrial-PV junction with a 64-electrode basket catheter would allow characterization of conduction patterns that would identify sites where ablation is required to electrically isolate the PV.

Methods and Results—A 64-electrode basket catheter was used to map the PVs of 50 patients undergoing PV isolation procedures for the treatment of atrial fibrillation. Activation along each spline was classified as reflecting either longitudinal, transverse, or no activation. A longitudinal activation pattern recorded along a spline during sinus rhythm in right-sided PV and during CS pacing in left-sided PV before the delivery of any RF energy application had a sensitivity and specificity for a required ostial ablation site of 83% and 82%, respectively. When longitudinal activation along the spline was present during preablation recordings in both sinus rhythm and CS pacing, the sensitivity and specificity were 92% and 90%, respectively. A longitudinal activation pattern after the first RF application that produced a change in PV activation sequence had a sensitivity and specificity for sites where further ablation was required of 91% and 94%, respectively.

Conclusions—Mapping of PV activation with a 64-electrode basket catheter allows characterization of conduction patterns that predict requirement for ablation. The presence of a longitudinal activation pattern is a strong predictor of ostial sites where ablative energy is required to electrically isolate the PV. (Circulation. 2003;108:590-597.)

Key Words: arrhythmias • ablation • pulmonary veins

Atrial fibrillation (AF) can be treated by radiofrequency (RF) catheter ablation designed to electrically isolate initiating foci within the PVs from the left atrium.1–3 Two general strategies have been used to achieve PV isolation. First, mapping of the activation pattern within the PVs at their junction with the left atrium has been used to guide ablation of fibers traversing the PV ostium. Second, the left atrium (LA) surrounding the PVs can be ablated following an anatomic approach.4–6 The first approach has been shown by several investigators2–3 to allow for complete electrical isolation of the targeted PV by limiting the ablation lesions to discrete segments at the ostium of the vein. Discrimination of pulmonary venous from LA potentials may be challenging when mapping a single plane with a circular catheter and may require pacing at multiple sites. Furthermore, the anatomy of the junction of PVs with the LA is often a complex, funnel-shaped structure that has irregular planes, making it difficult to identify a clear ostium.7,8 In addition to these gross morphological features, the histology of the PVs is also complex with muscle fibers oriented in longitudinal, circumferential, and oblique directions.9

A multiple electrode basket catheter that can conform to the anatomy of the PVs might allow a detailed analysis of electrical conduction within the PVs. We hypothesized that mapping of the LA–PV junction with a 64-electrode basket catheter would allow identification of activation patterns that would be useful to guide catheter ablation to achieve PV isolation.

Methods

Patient Population
Consecutive patients referred to the University of Alabama at Birmingham for catheter ablation for the treatment of paroxysmal AF were included in this study. All patients had failed at least one Class I or III antiarrhythmic medication before ablation. All patients were treated with warfarin for a minimum of 3 weeks before ablation. All patients provided written, informed consent for the procedure.

Electrophysiological Study
Transseptal catheterization was performed utilizing an 8F transseptal sheath (Daig SL2) with a Brockenbrough needle. Heparin was administered to achieve an activated clotting time (ACT) >250 seconds. After selective angiograms of the PVs were performed, a
Ablation Procedure
RF energy was delivered from the ablation catheter at the site recording earliest PV activation at the ostium during sinus rhythm for right pulmonary veins or during distal CS pacing for left pulmonary veins. Energy was delivered with a target temperature of 55 °C for 30 to 60 seconds with maximum power limited to 30 Watts. After each RF application, electrograms were recorded from the basket catheter and further RF applications were delivered at the site of earliest residual PV activation. This was repeated until there was dissociation of PV potentials from the left atrium or elimination of all PV potentials. If in the baseline state very frequent paroxysms of AF were noted to arise from one or 2 PVs, these arrhythmogenic veins were isolated. Provocative maneuvers (rapid atrial pacing, isuprel up to 6 microgram per minute, and/or cardioversion of induced atrial fibrillation) were performed, and if no frequent premature atrial contractions or atrial fibrillation was induced, no other veins were targeted for therapy. Otherwise, attempts were made to eliminate or isolate all potentials in PVs with an ostial diameter ≥14 mm.

Data Analysis
Activation along each spline of the basket catheter in the PV was recorded during sinus rhythm or CS pacing and was classified as either longitudinal, transverse, or no activation. The pattern of PV activation along each spline was classified as longitudinal if activation progressively spread from the proximal electrodes at the ostium of the PV to the distal bipolar electrograms (Figure 2A). When the bipolar electrograms along the spline were activated simultaneously or when there was distal to proximal spread of activation along a spline, the activation pattern was described as transverse, implying that the spline was activated by a wavefront that was not parallel to the long axis of the vein. Figure 2B shows an example of a spline with a transverse pattern of activation. On this spline from the basket in the left superior pulmonary vein, electrograms are recorded simultaneously in electrodes 7-8, 6-7, 5-6, 4-5, and 3-4. Splines where the activation proceeded from distal to proximal were also classified as transverse because the initial activation reached the distal portion of the spline and only later proceeded toward the ostium (Figure 2C).

RF current was applied at the site of earliest PV activation, regardless of the activation pattern. Because catheter ablation was performed in an iterative manner with mapping after each RF application, mapping data were analyzed to calculate sensitivity, specificity, and predictive value of the sequential and simultaneous activation patterns before the application of any RF current to a PV ostium as well as after the first RF application that produced a change in PV activation sequence. The proportion of the circumference of the PV that was ablated was determined from the number and position of splines that received adjacent RF applications.

Results
Study Population
The study population was composed of 50 consecutive patients with paroxysmal AF who were referred for PV isolation. There were 34 males and 16 females with a mean age of 53±13 years. Paroxysmal AF had been present for 9±6 years and had been resistant to treatment with 2.3±1.2 class I or class III antiarrhythmic drugs. The left atrium was ≥39 mm in 16% of patients, and the left ventricular ejection fraction was less than 0.45 in 18% of patients.

Catheter Ablation
Catheter ablation was successful in isolating 162 targeted PVs (mean 3.2 per patient) with a mean of 7.3±4.0 RF
Figure 2. Illustration of longitudinal and transverse patterns of spline activation. A, Spline with longitudinal activation. Earliest PV activity is recorded at electrode pair E 5-6. Transverse pattern of activation, manifested as simultaneous recordings along a spline, is shown in B. Simultaneous recording of PV potentials along a spline suggests that the electrodes along the spline are activated by a wide electrical wavefront propagating perpendicular to several electrodes along a spline. When a narrow wavefront travels initially along the long axis of the vein and later spreads perpendicular to the long axis of the vein it may reach a spline from its distal end first, then travel along a fiber leading to a sequence of activation from distal to proximal. Electrograms in C show transverse activation that is simultaneous on the most distal end (H4-H5 through H1-H2) but with activation from distal to proximal (from H4-H5 through H7-H8).

Figure 3. PV potentials before and after segmental ostial ablation. Only electrograms from splines A through D are shown. In this vein, splines E through H did not show electrical activity. A, Before ablation, earliest activation of the PV is recorded at electrode pairs C7-C8, with longitudinal activation of this spline. B, After application of RF current near electrode pair C7-C8, electrograms are delayed. Furthermore, a change in the activation patterns is noted: in spline D, the proximal electrograms are now absent (D7-D8 through D5-D6), and the remaining electrograms have transverse (simultaneous) activation (D4-D5 through D2-D3). Spline B now has the earliest electrograms (B7-B8) and longitudinal activation is present. After application of radiofrequency current at electrode pair B7-B8, all PV activity was eliminated (C).
applications per PV (Table 1). Electrical isolation was documented by the successful elimination of PV potentials during sinus rhythm or CS pacing (Figure 3), or by the recording of electrical activity within the PV dissociated from atrial activation (Figure 4). The percentage of the circumference of the PV that received RF applications in order to achieve isolation was 65 ± 12% for the LIPV, 62 ± 18% for the LSPV, 53 ± 18% for the RSPV, and 46 ± 10% for the RIPV (P < 0.0001 ANOVA, P < 0.001 for difference between right and left PVs by Fisher’s PLSD for circumference). The mean fluoroscopy time and overall procedure durations were 58 ± 31 and 168 ± 64 minutes, respectively. Complications included pericardial tamponade requiring pericardiocentesis in one patient, and groin hematomas in 3 patients.

**Activation Patterns Within the PVs**

Table 1 summarizes the preablation activation patterns during CS pacing for left-sided PVs and sinus rhythm for right-sided PVs. A longitudinal pattern of electrical activation within the PV was recorded before ablation along 4.3 ± 1.8 splines per PV with no difference noted among the 4 PVs (P = NS). PV isolation required the application of RF current adjacent to 83.4% of splines recording a longitudinal activation pattern. In contrast, a transverse pattern of activation was recorded before ablation along a mean of (2.7 ± 1.8) splines per PV. When a transverse pattern was initially recorded, catheter ablation was required near the spline in only 26% of cases. There was no PV activity in a mean of 1.1 ± 1.0 splines per PV. Thus, the sensitivity of a longitudinal pattern was 83% with a positive predictive value of 84%. The lack of a longitudinal activation pattern provided a specificity of 82% with a negative predictive value of 81%.

Figure 5 shows the effect of pacing in the electrical recordings from left PVs. Table 1 summarizes the effect of pacing site on activation pattern for all veins for which preablation sinus and distal CS pacing were recorded. A change in the direction of LA activation from right to left (during sinus rhythm) to left to right (during distal CS pacing) often produced a clear separation between far-field LA potentials and local PV potentials, as well as an easier identification of the site with the earliest PV activation. Recognition of a longitudinal pattern in left-sided PVs was higher during distal CS pacing (53% of splines) than during sinus rhythm (46%). When the activation pattern along a

### Table 1. Activation Patterns Before Ablation

<table>
<thead>
<tr>
<th></th>
<th>LIPV (n=42)</th>
<th>LSPV (n=46)</th>
<th>RSPV (n=44)</th>
<th>RIPV (n=26)</th>
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<tr>
<td>Ostial diameter, mm</td>
<td>21.2±2.2</td>
<td>21.5±1.9</td>
<td>20.9±2.5</td>
<td>17.8±1.9</td>
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<td>RF applications/vein</td>
<td>8.4±3.7</td>
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<tr>
<td>Percent circumference ablated</td>
<td>65±12</td>
<td>62±18</td>
<td>53±18</td>
<td>46±10</td>
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<tr>
<td>Initial activation pattern*</td>
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<tr>
<td>Longitudinal</td>
<td>4.1±1.7</td>
<td>4.4±1.9</td>
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<tr>
<td>Transverse</td>
<td>3.0±1.6</td>
<td>2.8±1.7</td>
<td>2.6±1.5</td>
<td>2.3±2.2</td>
</tr>
<tr>
<td>No activation</td>
<td>0.9±1.2</td>
<td>0.8±1.3</td>
<td>1.1±1.1</td>
<td>1.5±1.4</td>
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<tr>
<td>Longitudinal activation</td>
<td></td>
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<tr>
<td>Sensitivity (ablation required)</td>
<td>0.80</td>
<td>0.84</td>
<td>0.87</td>
<td>0.82</td>
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<td>PPV (ablation required)</td>
<td>0.81</td>
<td>0.81</td>
<td>0.88</td>
<td>0.91</td>
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<tr>
<td>Transverse activation</td>
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<tr>
<td>Specificity (ablation not required)</td>
<td>0.85</td>
<td>0.78</td>
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<td>NPV (ablation not required)</td>
<td>0.75</td>
<td>0.78</td>
<td>0.84</td>
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</table>

**Activation pattern during CS pacing***

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<tr>
<th></th>
<th>LIPV (n=26)</th>
<th>LSPV (n=31)</th>
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<tbody>
<tr>
<td>Longitudinal</td>
<td>4.1±1.7</td>
<td>4.4±1.9</td>
</tr>
<tr>
<td>Transverse</td>
<td>3.0±1.6</td>
<td>2.8±1.7</td>
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<tr>
<td>No activation</td>
<td>0.9±1.3</td>
<td>0.9±1.2</td>
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<tr>
<td>Longitudinal activation during both CS pacing and sinus</td>
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<tr>
<td>Sensitivity (ablation required)</td>
<td>0.90</td>
<td>0.94</td>
</tr>
<tr>
<td>PPV (ablation required)</td>
<td>0.92</td>
<td>0.91</td>
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<tr>
<td>Transverse activation during both CS pacing and sinus</td>
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<tr>
<td>Specificity (ablation not required)</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>NPV (ablation not required)</td>
<td>0.88</td>
<td>0.94</td>
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</table>

*Splines/vein.
spline was transverse in sinus rhythm, pacing from the distal CS converted the pattern to longitudinal in 14% of splines in the LIPV and 18% of splines in the LSPV. Furthermore, when a spline demonstrated longitudinal activation during both sinus rhythm and during distal CS pacing, RF current was required at 92% of such sites in order to achieve PV isolation.

Application of RF current to an ostial PV site demonstrating longitudinal activation commonly resulted in a marked delay in activation along the spline with a shift to a transverse activation pattern (Figure 3). This was often associated with a shift from a transverse to longitudinal activation at other splines, thereby allowing recognition of LA-PV connections with longer activation times that required ablation in order to achieve PV isolation.

Discussion

The pattern of activation along the splines of a basket catheter can be used to practical advantage to guide catheter ablation procedures that are designed to achieve PV isolation. When electrical activation within the PV proceeds from proximal to distal along a spline (a longitudinal pattern), there is a high probability that ablative energy must be applied at this site in order to achieve electrical isolation. In contrast, it is much less likely that ablative energy will be required at sites were evidence of transverse conduction is present.

The orientation of myocardial fibers within human PVs is complex, with longitudinal, transverse, and spiral arrangements reported. Mapping with a 64-electrode basket catheter in this study demonstrates that the pattern of electrical activation within human PVs is also complex. Figure 2 illustrates how the activation pattern on different splines may reflect different patterns of electrical conduction within a PV. A longitudinal activation pattern along the spline most likely reflects a wavefront advancing from the left atrium into the PV along the long axis of the vein. In this study, this pattern of activation (longitudinal) was highly predictive of ostial sites where a connection between the left atrium and the
pulmonary vein was present and where it was necessary to ablate to electrically isolate the vein.

Splines that were not activated in a longitudinal manner are likely activated by electrical wavefronts approaching the spline in a direction that is not parallel to the long axis of the vein. Figure 2 also illustrates how a transverse pattern of activation implies that the wavefront has entered the vein at a different site before approaching the spline in a perpendicular orientation with simultaneous activation along the spline or with earliest activation at a distal electrode that then propagates toward the ostium of the vein. Electrical recordings within pulmonary veins may be due to far-field signals, particularly when recording within the left pulmonary veins. Similar to studies with circular mapping catheter,

**Figure 5.** A, Electrical recordings within the left superior PV during sinus rhythm showing poor differentiation between LA (far-field) potential from the local PV activity. B, Recordings during pacing from the distal CS. Clear differentiation between far-field LA signals (small arrows) and PV potentials (large arrows) is obtained, particularly in splines C, D, G, and H. Earliest PV potential is recorded in spline G where sequential activation is also present.
pacing from the distal CS, the source of electrical signals recorded within the basket catheter was still not clear. In this situation, pacing from the base of the left atrial appendage or the posterior wall of the left atrium was useful to discriminate far-field LA from near-field PV potentials. In the present study, when there was any uncertainty about the source of the recorded signals, we confirmed that the potentials attributed to local pulmonary vein activity originated within the vein (as opposed to a far-field LA source) by pacing from multiple sites and documenting that the signals were not advanced closer to the pacing stimulus. Between 14% (in left inferior PVs) and 18% (in left superior PVs) of the splines in left pulmonary veins classified as transverse when mapped in sinus rhythm were classified as longitudinal when mapped in left atrial appendage pacing. Similar changes were occasionally seen when pacing from different left atrial sites. Contrary to far-field LA signals, local PV activity was not shifted significantly closer to the pacing stimulus. Between 14% (in left inferior PVs) and 18% (in left superior PVs) of the splines in left pulmonary veins classified as transverse when mapped in sinus rhythm were classified as having longitudinal activation when mapped in left atrial appendage pacing. Similar changes were occasionally seen when pacing from different left atrial sites. Contrary to far-field LA signals, local PV activity was not shifted significantly closer to the pacing stimulus. After ablation, all potentials attributed to local PV activity were either eliminated (Figure 3C), or where dissociated from LA activity (Figure 4). Electrical recordings with the basket catheter that are due to far-field LA depolarization were recognized by the following: (1) they occurred before the PV potentials during sinus rhythm or atrial pacing; (2) they occurred almost simultaneously along several electrodes in multiple splines; and (3) they were advanced closer to the pacing stimulus by pacing from a site close to the source of the signals. Because the basket catheter allows assessment of the direction of electrical propagation, discrimination of far-field LA from PV potentials is facilitated.

**Comparison With Circular PV Mapping Catheters**

Several authors have demonstrated the utility of circular PV mapping catheters to guide PV isolation. This strategy targets the site of earliest PV activation for ablation. A shift in polarity of the PV potentials at radial sites around the PV has been proposed as a further method to recognize LA-PV connections. Although the use of circular catheters has proven efficacy, there are several limitations. First, the circular catheter records in only one geometric plane. If the LA-PV junction is irregular, it may be impossible to position a circular catheter at the same position relative to the ostium of the PV around its entire circumference. Thus, a circular catheter may record at the LA-PV junction along one side of the catheter while being deeper within the PV along the opposite side. Second, it may not always be possible to position a circular catheter perpendicular to the long axis of the PV. Third, it may be difficult with fluoroscopy alone to be certain just how far a circular catheter is positioned within the PV. This may have important implications for avoidance of PV stenosis. Although intracardiac ultrasound may be useful to ensure proper positioning of the circular catheter at the PV ostium, this technique adds to the expense of the procedure.

A multielectrode basket catheter that conforms to the contours of the LA-PV junction overcomes most of the limitations of circular catheters. However, basket catheter has several limitations of its own. First, this catheter requires a special sheath with a limited number of preshaped curves. This may present challenges for positioning this catheter within the right inferior PV. Second, the splines may contact one another when the basket catheter is positioned within a relatively small PV, thereby inducing electrical artifact. Third, the splines may not always be equally spaced relative to the circumference of the PV. As a result, areas in which several splines are clustered may be densely mapped while other regions are less densely recorded. Finally, the geometry of the basket catheter is more complex than a circular catheter, a factor that may predispose to greater thrombogenicity. Although the splines of this catheter are coated with heparin and no embolic complications were observed in this study, all patients received a reversible glycoprotein IIb/IIIa platelet antagonist in addition to heparin. Further studies may be required to be certain that the basket catheter does not predispose to thromboemboli and to define the role of reversible glycoprotein IIb/IIIa platelet inhibitors during AF ablation procedures.

**Conclusions**

Human PVs have complex patterns of electrical activation suggesting longitudinal and transverse myocardial conduc-
tion fibers. A longitudinal pattern of activation in which conduction propagates from the LA-PV junction along the spline of a basket catheter suggests a site that requires the application of ablative energy to achieve PV isolation. In contrast, splines with a transverse activation pattern, manifested by either simultaneous recordings or distal to proximal activation are much less likely to require ablation.

References