Reversing the Direction of Paced Ventricular and Atrial Wavefronts Reveals an Oblique Course in Accessory AV Pathways and Improves Localization for Catheter Ablation

Kenichiro Otomo, MD; Mario D. Gonzalez, MD; Karen J. Beckman, MD; Hiroshi Nakagawa, MD, PhD; Anton E. Becker, MD; Nayyar Shah, MD; Kagari Matsudaira, MD; Zulu Wang, MD; Ralph Lazzara, MD; Warren M. Jackman, MD

Background—The purpose of this study was to determine how often accessory atrioventricular (AV) pathways (AP) cross the AV groove obliquely. With an oblique course, the local ventriculoatrial (VA) interval at the site of earliest atrial activation (local-VA) and the local-AV interval at the site of earliest ventricular activation (local-AV) should vary by reversing the direction of the paced ventricular and atrial wavefronts, respectively.

Methods and Results—One hundred fourteen patients with a single AP were studied. Two ventricular and two atrial pacing sites on opposite sides of the AP were selected to reverse the direction of the ventricular and atrial wavefronts along the annulus. Reversing the ventricular wavefront increased local-VA by 15 ms in 91 of 106 (91%) patients. With the shorter local-VA, the ventricular potential overlapped the atrial potential along a 17.2 ± 8.5-mm length of the annulus. No overlap occurred with the opposite wavefront. Reversing the atrial wavefront increased local-AV by 15 ms in 32 of 44 (73%) patients. With the shorter local-AV, the atrial potential overlapped the ventricular potential along an 11.9 ± 8.9-mm length of the annulus. No overlap occurred with the opposite wavefront. Mapping during longer local-VA or local-AV identified an AP potential in 102 of 114 (89%) patients. Catheter ablation eliminated AP conduction in all 111 patients attempted (median, 1 radiofrequency application in 99 patients with an AP potential versus 4.5 applications without an AP potential).

Conclusions—Reversing the direction of the paced ventricular or atrial wavefront reveals an oblique course in most APs and facilitates localization of the AP potential for catheter ablation. (Circulation. 2001;104:550-556.)

Key Words: Wolff-Parkinson-White syndrome ■ catheter ablation ■ mapping ■ electrophysiology

Accessory atrioventricular (AV) pathways (AP) are generally thought to course perpendicular to the AV groove, producing the shortest (and constant) local ventriculoatrial (VA) interval at the AP site during orthodromic AV reentrant tachycardia and during ventricular pacing from any site.1–5 However, studies that use recordings of AP potentials suggest that APs may follow an oblique course.6 We hypothesized that with an oblique course, reversing the direction of the ventricular wavefront along the annulus would alter the local VA interval at the site of earliest atrial activation (local-VA). A wavefront propagating from the direction of the ventricular end (“concurrent” with AP activation, Figure 1A) would produce a short local-VA (CS2 in Figure 1, A1), because activation along the AP would proceed to the site of earliest atrial activation concomitant with the ventricular wavefront. A ventricular wavefront propagating in the opposite (counter-current) direction would produce a longer local-VA (CS2 in Figure 1, B1) because the ventricular wavefront must pass the site of earliest atrial activation before reaching the ventricular end of the AP (CS2 in Figure 1, B1). This has important implications for localizing APs. With a concurrent wavefront, the ventricular potential may overlap and mask the AP potential and site of earliest atrial activation (Figure 1, A2). If the velocity of the ventricular wavefront along the annulus is slower than the AP and atrial wavefronts, the shortest local-VA interval would be shifted away from the AP (CS2 in Figure 1, A2). A counter-current wavefront should expose the atrial activation sequence and AP potential (Figure 1B).

During atrial pacing, a concurrent atrial wavefront would shorten the local AV interval at the site of earliest ventricular activation (local-AV) and may mask the AP potential and site of earliest ventricular activation (Figure 1, C2). A countercurrent wavefront should lengthen the local-AV and expose the AP potential and ventricular activation sequence (Figure 1, D1).
Electrophysiological Study

Patients were studied as previously described. A 7F deflectable quadripolar catheter with a 2-mm-tip electrode was used for ventricular pacing. A catheter with 8 pairs of orthogonal electrodes or 20 electrodes in 10 close pairs was used in the coronary sinus (CS). In patients with a right free wall AP, a 20-electrode catheter (10 close pairs) was positioned around the tricuspid annulus (Figure 2, C and D).

Reversing the Ventricular Wavefront

Two ventricular pacing sites were selected, based on the site of earliest atrial activation. In patients with a left anterior or left lateral AP, the counterclockwise wavefront (left anterior oblique projection) was obtained by pacing the basal-posteroseptal right ventricle close to the tricuspid annulus (RV-PS, Figure 2A). The clockwise wavefront was obtained by pacing the septal RV outflow tract, close to the pulmonic valve (RV-OT in Figure 2B) or basal left ventricle (LV) from an anterior coronary vein. For a left-posterior or posteroseptal AP, counterclockwise and clockwise wavefronts were obtained by pacing the basal-posteroseptal RV (RV-PS, Figure 2G) and basal LV from a lateral or posterolateral coronary vein (PLCV, Figure 2G). Right lateral or right posterior APs, counterclockwise and clockwise wavefronts were obtained by pacing the basal-anteroventricular RV (RV-AS, Figure 2E) and basal-anteroventricular LV (RV-AL, in Figure 2F).

The local-VA was compared between clockwise and counterclockwise ventricular wavefronts. Ventricular pacing was performed at cycle length 520 ms. Local-VA was measured from the bipolar electrogram (30 to 250 Hz, 200 mm/s) at the site of earliest atrial activation from the first rapid deflection of the ventricular potential to the onset of the atrial potential. A change in local-VA (Δlocal-VA) of ±15 ms was considered significant.

Reversing the Atrial Wavefront

Two atrial pacing sites were selected to reverse the atrial wavefront along the annulus surrounding the site of earliest ventricular activation. Pacing from the RA appendage and posterolateral CS produced opposite atrial wavefronts along most of the tricuspid annulus and mitral annulus. For left lateral APs, pacing the CS distal and proximal to the site of earliest ventricular activation produced clockwise and counterclockwise wavefronts, respectively. Atrial pacing was performed at cycle length 520 ms. Local-AV was measured from the bipolar electrogram at the site of earliest ventricular activation from the first rapid deflection of the atrial potential to the onset of the ventricular potential. A change in local AV (Δlocal-AV) of ±15 ms was considered significant.

Target for Ablation

Ablation was targeted at the mid-region of oblique APs, identified by an isolated AP potential (separate from the local ventricular and atrial potentials). Ventricular pacing was performed from the site producing the longer local-VA. The longer local-VA indicated the ventricular end of the AP was located on the side of the site of earliest atrial activation that was opposite to the ventricular pacing site. Therefore, the retrograde AP potential was sought on the side of earliest atrial activation opposite the side of pacing (CS, Figure 1, B1). Atrial pacing was performed from the site producing the longer local-AV. The antegrade AP potential was sought on the side of earliest ventricular activation opposite the side of pacing (CS, Figure 1, D1). Ablation was performed during atrial or ventricular pacing, whichever provided the most stable position at the site recording the largest, sharpest isolated AP potential on the unipolar electrogram recorded from the ablation electrode. In the absence of recording an AP potential, ablation was targeted just to the side of the site of earliest atrial activation or the site of earliest ventricular activation predicted to be the AP mid-region by the change in local-VA or local-AV, respectively. Radiofrequency current was delivered at 40
to 70 V (15 to 50 W), with impedance monitoring used to control power.  

**Statistical Analysis**  
The significance of the difference in Δlocal-VA and Δlocal-AV between AP locations was assessed by ANOVA, with Scheffe’s method for pairwise comparisons. The significance of the difference in number of radiofrequency applications required for ablation between patients with and those without an AP potential and between patients with and those without a prior failed ablation procedure was assessed by the Mann-Whitney test.

**Results**  
**Reversing the Ventricular Wavefront**  
Retrograde AP conduction was studied in 106 patients (64 with left free wall, 18 with right free wall, 19 with posteroseptal, and 5 with anteroseptal APs). Figure 3 illustrates the results in a patient with a left lateral AP. Pacing from the basal-posteroseptal RV (RV-PS) produced a counterclockwise ventricular wavefront. The ventricular potentials overlapped the atrial potentials, obscuring the site of earliest atrial activation (Figure 3A). Reversing the wavefront by pacing the RV outflow tract (RV-OT) increased the local VA interval near the atrial end of the AP, allowing clear identification of the site of earliest atrial activation (CS3, Figure 3B). The 55-ms increase in local-VA with the clockwise ventricular wavefront indicates (1) the AP has an oblique course; and (2) the ventricular end is located posterior to the atrial end. Distinct retrograde AP potentials (arrows) can be traced posteriorly from the site of earliest atrial activation in electrogram CS3 to electrogram CS6, suggesting the distance between the atrial and ventricular insertions is >15 mm. Atrial activation is relatively late along the mid-region of the AP (CS5 and CS6). Lower velocity along the annulus of the ventricular wavefront than the atrial wavefront resulted in shorter local VA intervals anterior to the atrial end of the AP during posterior pacing (CSd in Figure 3A) and posterior to the ventricular end during anterior pacing (CSp in Figure 3B).

Reversing the direction of the ventricular wavefront changed the local-VA by 5 to 90 ms in all 106 patients (26±21 to 49±24 ms), and the magnitude of change was similar in all AP locations (Figure 4A). The change in local-VA (Δlocal-VA) was ≥15 ms in 91 of 106 (86%) patients (Figure 4B). There was no difference in Δlocal-VA between patients with and those without a prior ablation failure (Figure 4B).

With a concurrent wavefront (shorter local-VA), the ventricular potentials overlapped the atrial potentials along a 17.2±8.5-mm length of the CS or tricuspid annulus surrounding the site of earliest atrial activation in 79 of 106 (75%)
patients (Figure 3A). Reversing the wavefront separated the ventricular and atrial potentials in all 79 patients, allowing clear identification of the site of earliest atrial activation and retrograde AP potential.

Reversing the Atrial Wavefront
Antegrade AP conduction was studied in 44 patients (14 with left free wall, 15 with right free wall, 12 with postero septal, and 3 with antero septal APs). Figure 5 illustrates the results in a patient with an antero septal-midseptal AP. Pacing the right atrial appendage produced a clockwise wavefront along the septal tricuspid annulus, with the atrial potential overlapping the AP potential (MSd, Figure 5A). Reversing the wavefront by pacing the posterolateral CS increased the local-AV from 25 to 45 ms, allowing clear identification of the site of earliest ventricular activation and the AP potential (Figure 5B). The increase in local-AV indicates an oblique course with the atrial end located anterior to the ventricular end.

Interobserver Variation
Four blinded investigators measured the Δlocal-VA in 20 consecutive patients and Δlocal-AV in 10 consecutive patients. The difference between the largest and smallest measurement of the 4 observers for each of the 30 Δlocal-VA or Δlocal-AV intervals was 6.8 ± 3.8 ms.

Concordance of the Oblique Course During Antegrade and Retrograde Conduction
Figure 2, E and F, and Figure 6 illustrate the concordance in the direction of the oblique course identified during ventricular pacing and during atrial pacing in a patient with an antero septal–right anterior paraseptal AP. Pacing the basal anterolateral RV (Figure 2F) produced a ventricular wavefront propagating slowly along the tricuspid annulus in the clockwise direction. Rapid AP conduction produced a retrograde atrial potential before the local ventricular potential at the site of earliest atrial activation (HBp, electrogram, local-
VA = −5 ms, Figure 6A). Reversing the ventricular wavefront (counterclockwise) by pacing the basal-anteroseptal RV (Figure 2E) increased the local-VA from −5 to 40 ms, allowing clear identification of the retrograde AP potential (Figure 6B). The longer local-VA indicates the ventricular end of the AP is located rightward of the atrial end.

The local-AV at the site of earliest ventricular activation (Map catheter in Figure 2, E and F, and TA ant electrogram in Figure 6) was shorter during proximal CS pacing producing a counterclockwise atrial wavefront (20 ms, Figure 6C) than during RA appendage pacing producing a clockwise wavefront (35 ms, Figure 6D). The longer local-AV during right atrial appendage pacing indicates that the atrial end of the AP was located leftward (septal) of the ventricular end, concordant with the direction of the oblique course that was identified during ventricular pacing. The direction of the oblique course was examined during both atrial and ventricular pacing in 35 patients and was concordant in all.

Direction of the Oblique Course
Figure 7 illustrates the direction of the oblique course in the 114 APs, divided into 8 anatomic regions. In most left free wall and right free wall APs, the ventricular end was located posterior to the atrial end. In most posteroseptal APs, the ventricular end was located rightward (septal) of the atrial end. In most anteroseptal and right anterior–paraseptal APs, the ventricular end was located rightward (lateral) of the atrial end.

AP Potential
A retrograde or antegrade AP potential was recorded in 102 of 114 (89%) patients by ventricular pacing from the site producing the longer local-VA and searching on the side of earliest atrial activation opposite the ventricular pacing site or by atrial pacing from the site producing the longer local-AV and searching on the side of earliest ventricular activation opposite the atrial pacing site.
Ablation
Ablation was not attempted in 3 patients because of risk of AV block (anteroseptal AP, 1 patient) or coronary artery injury (epicardial posteroseptal AP, 2 patients). AP conduction was successfully eliminated in the remaining 111 patients by 1 to 18 (median, 1) radiofrequency applications. The number of radiofrequency applications was significantly smaller in patients with an isolated AP potential (median, 1 versus 4.5, P<0.05, Figure 8A). There was no significant difference in the number of radiofrequency applications between patients with and those without a prior unsuccessful ablation procedure (Figure 8B).

There were no complications related to the use of the 2 atrial pacing sites, 2 ventricular pacing sites, or ablation.

Discussion
Reversing the paced ventricular or atrial wavefront increased the local-VA or local-AV by ≥15 ms in 99 of 114 (87%) patients, which suggests that most APs have an oblique course. The increase in local-VA or local-AV greatly facilitated identification of the AP potential. An antegrade or retrograde AP potential was recorded in 102 of 114 (89%) patients. The frequent recording of an isolated AP potential (separate from the local atrial and ventricular potentials) also supports the hypothesis of an oblique course because fusion of the atrial, AP, and ventricular potentials might be expected with nonoblique accessory pathways. Ablation at the AP recording site eliminated AP conduction with a median of 1 radiofrequency application (even if the patient had 1 or more prior unsuccessful ablation procedures), supporting the accessory pathway origin for the AP potential.

Anatomic Correlation
The presence of an oblique course has not been emphasized in previous histological studies. However, most APs described had their atrial and ventricular insertions in separate histological sections, consistent with an oblique course. To verify this point, one of the investigators restudied the microscopic sections described previously. The distance between the atrial and ventricular ends could be examined in 4 cases. In cases 2 and 3 (both left posterior APs), the distance between the atrial and ventricular insertions (measured between the sections in which the last trace of AP had vanished) was 3.15 mm and 2.8 mm, respectively. The ventricular insertion was oriented toward the crux (septal) in both hearts, as was found in the present study. In case 6, a left lateral AP, the atrial insertion was located outside the block of tissue, which ended 2.9 mm from the ventricular insertion. In case 4, with Ebstein’s malformation of the tricuspid valve, the AP was located inferior to the CS ostium. The ventricular insertion was located 3.1 mm anterior to the atrial insertion.

Clinical Implications
Although the site of the shortest local-VA interval during orthodromic AV reentrant tachycardia or ventricular pacing is often considered the optimal target for AP ablation,1-5 the reliability of this criterion has been debated.2,3,10 The present study suggests that this criterion is misleading in oblique APs. In oblique APs, the shortest local-VA interval would be shifted away from the AP in the direction of the ventricular wavefront if the velocity of the ventricular wavefront along the annulus is less than the velocity of the atrial wavefront (CSp in Figure 1, A2, and Figure 3A and CSd in Figure 1, B2, and Figure 3B). Similarly, the site of the shortest local-AV interval (often considered an optimal criterion to select an ablation site during antegrade AP conduction2,4,10) can be shifted away from the AP in the direction of the atrial wavefront if the atrial wavefront is slower than the ventricular wavefront (CSd in Figure 1, C2, and CSp in Figure 1, D2, and Figure 5A).

Although AP conduction can be eliminated by ablation anywhere between the atrial and ventricular ends, radiofrequency applications targeted to the atrial end (site of earliest atrial activation during retrograde AP conduction) or ventricular end (site of earliest ventricular activation during antegrade AP conduction) may fail.2,4 This observation suggests that the recording range of the 4-mm electrode (unipolar or bipolar configuration) commonly used for radiofrequency ablation is greater than the radiofrequency lesion radius. During retrograde AP conduction, earliest atrial activation may be recorded 3 to 5 mm (or possibly more) from the actual AP insertion. Ablation is likely to be successful if the electrode is located 3 to 5 mm from the atrial insertion in the direction of the ventricular insertion and unsuccessful if located in the opposite direction. During antegrade AP conduction, ablation at a site recording earliest ventricular activation is likely to be successful even if the electrode is located 3 to 5 mm from the ventricular end but in the direction of the atrial insertion and unsuccessful if located in the opposite direction. This explains the 40% ablation success for the criterion of local ventricular activation preceding the onset of the delta wave by ≥0 ms during antegrade AP conduction,2,4,11 even though ventricular activation usually can be recorded as much as 30 ms before the delta wave in right-sided APs and 15 to 20 ms in left-sided APs. It is likely that the local ventricular potential precedes the delta wave over (≥0 ms) a distance of 5 to 10 mm from the actual ventricular insertion. If the electrode is located 5 to 10 mm from the ventricular insertion in the direction of the atrial insertion, ablation is likely to be successful. Conversely, ablation is likely to fail if the electrode is located in the opposite direction.

Two other techniques have been used to improve localization of the sites of earliest retrograde atrial or antegrade ventricular activation. One uses an unfiltered unipolar electrogram,10 which exhibits an initial steep negative component (no far-field activation) at the site of onset of activation. In the other, the atrial insertion is localized with the use of an unfiltered bipolar electrogram with the electrodes oriented parallel to the annulus.12 During retrograde AP conduction, the atrial insertion is identified as the site where the polarity of the atrial potential reverses.

Targeting an isolated AP potential has been associated with the highest ablation success.2,4,7,11 The usefulness of this criterion has been thought to be limited by difficulty in locating or validating an AP potential.4,5 The present study suggests that the difficulty in identifying the AP potential is often related to the oblique course. A ventricular or atrial
wavefront propagating concurrent with the accessory pathway may overlap and mask the AP potential (Figure 1, A2 and C2, and Figures 3A and 5A). By pacing from the side producing the longer local-VA or local-AV, an AP potential was recorded in 102 of 114 patients (89%). AP conduction was eliminated by a median of 1 radiofrequency application in the 99 patients in whom ablation targeted an isolated AP potential, compared with a median of 4.5 radiofrequency applications in the 12 patients without an AP potential (Figure 8A). By recognizing the oblique course and finding an AP potential, a single radiofrequency application eliminated AP conduction in 32 of 60 (53%) patients with at least 1 prior unsuccessful radiofrequency ablation procedure (Figure 8B). This suggests that the prior ablation may have failed because of difficulty localizing the AP as a result of the oblique course.

Study Limitations
The principal limitation of this study is the inability to determine the precise value of $\Delta_{\text{local-VA}}$ or $\Delta_{\text{local-AV}}$, which identifies an oblique course. This limitation is based on several factors. The first relates to the accuracy of identifying the exact site of earliest retrograde atrial or earliest antegrade ventricular activation. Another factor is a measurement error related to identifying the local ventricular activation time of the paced ventricular potential at the site of earliest atrial activation and the local atrial activation time of the paced atrial potential at the site of earliest ventricular activation. Interobserver differences are also a possibility. However, the maximum difference between 4 observers in the measurement of $\Delta_{\text{local-VA}}$ or $\Delta_{\text{local-AV}}$ in 30 patients was only $6.8 \pm 3.8$ ms. Finally, reversing the activation wavefront may have resulted in different conduction velocities within the AP. On the basis of these factors, we chose a $\Delta_{\text{local-VA}}$ or $\Delta_{\text{local-AV}}$ of $\pm 15$ ms as identifying an oblique course.

References
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