Electroanatomic Substrate of Idiopathic Left Ventricular Tachycardia
Unidirectional Block and Macroreentry Within the Purkinje Network

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Background—An abnormal potential (retroPP) from the left posterior Purkinje network has been demonstrated during sinus rhythm (SR) in some patients with idiopathic left ventricular tachycardia (ILVT). We hypothesized that this potential can specifically be identified and be a critical substrate for ILVT.

Methods and Results—In 9 patients with ILVT and 6 control patients who underwent mapping of the left ventricle during SR using 3-dimensional electroanatomic mapping, an area with retroPP was found within the posterior Purkinje fiber network only in patients with ILVT. The earliest and latest retroPP was 185.4±57.4 and 465.2±37.3 ms after Purkinje potential; in the other patient with ILVT, an entire left ventricle mapping demonstrated a slow conduction area and passive retrograde activation along the posterior fascicle during ILVT. ILVT was noninducible in 3 patients after SR mapping. Diastolic potentials critical for ILVT during ILVT coincided with the earliest retroPP during SR in 7 patients. Mechanical termination of ILVT occurred in 5 patients. A single radiofrequency pulse was applied at the site with mechanical translation in 5 patients and the site with diastolic potential in 2 patients, and 3 radiofrequency pulses were delivered to the site with the earliest retroPP in the other 3 patients without inducible ILVT after SR mapping. No ILVT was inducible during control stimulation, and none recurred during follow-up of 9.1±5.1 months.

Conclusion—In patients with ILVT, abnormal retroPP within the posterior Purkinje fiber network is a common finding. The earliest retroPP critical for ILVT substrate can be used for guiding successful ablation. (Circulation. 2002;105:462-469.)

Key Words: catheter ablation ■ electrophysiology ■ mapping ■ tachycardia

Idiopathic left ventricular tachycardia (ILVT) with a right bundle branch block morphology and left axis deviation occurs predominantly in young male patients without structural heart disease. It has been demonstrated that the underlying mechanism of ILVT is reentry with an excitable gap and a slow conduction area. Radiofrequency (RF) ablation of ILVT can be performed using pace mapping. 

Methods

Between February 2000 and May 2001, 10 consecutive patients (7 male; age 12 to 36 years) with ILVT were referred to our center. During the clinical arrhythmia, all patients showed a typical right bundle branch block morphology with left axis deviation. All patients were refractory to a mean of 3±1 antiarrhythmic drugs, and 3 patients had previously failed ablation attempts. All patients had structurally normal hearts. Additionally, 6 patients with structurally normal hearts (4 male; age 18 to 42 years) after RF ablation of left accessory pathways were used as a control group.

Electrophysiological Study

After giving informed consent and withdrawal of antiarrhythmic drugs, all patients underwent electrophysiologic evaluation under intravenous sedation. Catheters were introduced to the right ventricular apex (RVA), to the right ventricular outflow tract, and at the His bundle region via the femoral veins. The stimulation protocol consisted of programmed ventricular stimulation from the RVA and right ventricular outflow tract at 2 drive cycle lengths with up to 3 extrastimuli and incremental burst pacing at a cycle length up to 250 ms. If sustained ILVT was not inducible during baseline state, the stimulation was repeated after isoproterenol infusion.

Endocardial EA Mapping of the Left Ventricle

Left ventricular mapping was performed retrogradely with a steerable catheter with a 4-mm electrode tip (Navi Star, Biosense Webster). Bipolar electrograms were recorded on the EA mapping...
system (filtered at 10 to 400 Hz) and a separate Quinton EP system (filtered at 30 to 400 Hz). Validation of this technology and of its use in the left ventricle (LV) has been previously reported. Activation mapping was performed by initial systematic sampling of the entire ventricular endocardial surface and followed by more detailed mapping of the Purkinje fiber network of the left posterior fascicle during SR and ILVT. The local activation time was defined as the interval between the onset of the local electrogram and the timing reference signal. The EA mapping system can additionally calculate the anatomic distance between any 2 designated points. Thus, the length of the left bundle branch was measured from the His region to the bifurcation into the posterior and anterior fascicles, whereas the length of the posterior fascicle was measured from the bifurcation to the site with the latest PP in the posterior fascicle. The area demonstrating abnormal potentials could also be estimated and is presented in square millimeters by assuming a rectangular or trapezoidal shape.

RF Ablation
RF energy was delivered from the distal electrode of the mapping catheter for 120 seconds with a preselected temperature of 60°C. RF energy was started at 20 W and increased up to 40 W to reach the target temperature. After every RF pulse, reinduction of the ILVT was attempted by programmed stimulation.

Control Stimulation and Follow-up
The procedure was considered successful when ILVT was not inducible at the end of ablation and during a second control stimulation, which was performed 1 day later. Follow-up information was obtained either from the referring physicians or in our outpatient clinic.

Statistical Analysis
Values are given as mean±SD as appropriate. Mann-Whitney U and Wilcoxon tests were used for comparisons. *P<0.05 is considered significant.

Results
Before LV mapping, the cycle length of sustained tachycardia was 406±83 ms (range, 270 to 540 ms). ILVT was easily and reproducibly induced by programmed stimulation in all 10 patients.

Figure 1. A, Identification of the left specific conduction system during SR in structurally normal heart. Note that the areas with orange and brown tags present a short, sharp, high-frequency and low-amplitude potential preceding the ventricular activation in the anatomic area of the left specific conduction system. The areas with orange tags represent the His bundle region recorded from the noncoronary aortic sinus. The left bundle branch (LB) position was marked at the bifurcation point. B, Animated propagation map of the LV from frames 1 through 4 in the right anterior oblique view during SR, as in panel A. Areas in blue represent undepolarized regions; red areas are the advancing depolarization wave front. Note that the left ventricle was initially activated at the His bundle (frame 1), then at the left bundle branch (frame 2), and then progressively at the Purkinje network (frame 3) before the entire left ventricle was finally activated (frame 4).
Endocardial EA Mapping of the LV During SR

EA mapping during SR was successfully performed in 9 patients with ILVT (group 1) and 6 control patients (group 2). A mean of 167±42 points (range, 101 to 271) was acquired to reconstruct the LV with a diastolic volume of 103±35 mL (range, 52 to 163 mL). During SR, a short, sharp, high-frequency and low-amplitude potential preceding the ventricular potential was identified in the area of the left bundle and Purkinje conduction system (Figure 1A) in all 15 patients. Analysis of the LV activation showed its propagation through the His-Purkinje fiber network (Figure 1B). The left bundle branch and left posterior fascicle were 17.7±3.7 mm (range, 11.8 to 22.2 mm) and 33.0±5.6 mm (range, 27.0 to 45.8 mm) in length, respectively. The conduction time from the His to the latest PP in the left posterior fascicle was 32.3±3.9 ms (range, 26 to 40 ms). No difference in these parameters was found between the 2 groups.

In group 1, an area with 1 to 3 abnormal potentials was found during SR. Those abnormal potentials were short, sharp, and of high frequency and low amplitude after PP and ventricular activation independent of the T or P wave (Figure 2) and were located in the midinferior septum within the posterior fascicular network. The earliest and latest potentials were recorded 185.4±57.4 and 465.2±37.5 ms after the PP (Table). During SR, these abnormal potentials may represent a retrograde Purkinje activation (retroPP) with slow conduction over a Purkinje-Purkinje or Purkinje-ventricular-Purkinje connection attributable to unidirectional block.

During SR, only a single retroPP was recorded over an area of 219±89 mm² (range, 140 to 304 mm²), with the shortest...
and longest PP-to-retroPP interval of 236.3±38.7 ms (range, 190 to 283 ms) and 466.3±21.4 ms (range, 435 to 483 ms) in 4 patients (Figure 2A, Table). In the remaining 5 patients, 1 to 3 retroPP were found over an area of 506.8±34.9 mm² (range, 231 to 910 mm²), with the shortest and longest PP-to-retroPP interval of 144.8±28.8 ms (range, 104 to 173 ms) and 464.4±49.7 ms (range, 416 to 543 ms) (Figure 2B, Table). In those 9 patients, the earliest retroPP was individually located within the posterior fascicular network. In patient No. 4, an area (147 mm²) with abnormal retroPP was also found within the anterior fascicle Purkinje network, with earliest and latest PP-to-retroPP interval of 375 and 445 ms. No difference was found between patients with and without previously failed RF ablation (Table).

In group 2, no retroPP could be found during SR in any patient. During ventricular stimulation, the earliest but not latest retroPP was demonstrated with decremental conduction (Figure 3).

In 3 of 9 patients with ILVT, the tachycardia could not be induced after SR mapping despite an aggressive programmed ventricular stimulation. In the remaining 6 patients, during ILVT a short, sharp DP of high frequency and low amplitude was only found near the sites with the earliest retroPP, which was previously recorded during SR. However, in those 6 patients, ILVT was also not inducible when the mapping catheter was located at the area of earliest retroPP.

In 4 of the 6 patients with inducible ILVT, mechanical termination (MT) reproducibly occurred without any ventricular premature beat when mapping the area with the earliest retroPP. In 3 patients, cycle length variation was observed before MT. In patient No. 7, changes of PP-to-DP

<table>
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<tr>
<th>Patient</th>
<th>CL, ms</th>
<th>Area With retroPP, mm²</th>
<th>Earliest retroPP Location</th>
<th>PP-retroPP Interval, range in ms</th>
<th>ILVT-CL, ms</th>
<th>DP-V, ILVT, ms</th>
<th>PP-V, ILVT, ms</th>
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<th>PP-retroPP, SR, ms</th>
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CL indicates cycle length; NA, not inducible after SR mapping.
*Previously failed ablation.
†Area with single retrograde potential.

Figure 3. Tracings are ECG leads I, II, and V1 and intracardiac electrograms recorded from map catheter (Map) located at the area with earliest retroPP, His region, and RVA. Note that the interval from stimulus artifact to the retroPP (asterisk) was 250 ms during sinus beat and progressively prolonged at the pace cycle length of 510 ms.
interval or DP-to-PP interval resulted in cycle length variation (Figures 4A and 4B), which may suggest multiple entrances and exits in the reentrant circuit, until the ILVT was terminated with loss of the PP with the DP split into 2 components. At the site of MT, a retroPP was recorded with identical morphology to DP during SR (Figure 4C). In 2 other patients, changes in tachycardia cycle length were only associated with changes in DP-to-ventricular interval; in patient No. 4, ventricular activation preceded DP with constant ventricular-to-DP interval in 1 episode (Figure 5), which strongly suggested that ventricular myocardium was critical for maintaining the reentry circuit. Analysis of MT showed that the termination always occurred with a loss of PP in all patients. The site with MT was marked on EA mapping for guiding RF ablation.

**Endocardial EA Mapping of the LV During ILVT**

During ILVT, an entire LV mapping was obtained in patient No. 1, showing a focal origin with a very slow conduction area. A short, sharp, high-frequency potential preceding ventricular activation was recorded over a relatively large area, representing the activation of the left bundle and Purkinje system. The potential was recorded progressively later from the posterior fascicle to the left bundle branch and finally to the anterior fascicle. Only a small area with 1 or multiple DPs was located in the medial-inferior septum (Figure 6). The activation time between the sites with earliest DP and the earliest PP was 179 ms, with a distance of 11.2 mm. The propagation map showed that the posterior fascicle was activated passively and retrogradely during tachycardia (Figures 7A through 7F). When mapping the area with DP and earliest PP, MT occurred and resulted in noninducibility for >2 hours. Before RF ablation, a retroPP was recorded with PP-to-retroPP of 250 ms at the site with MT during SR, whereas the latest retroPP was recorded with a PP-to-retroPP interval of 580 ms when mapping the area during SR.

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**Figure 4.** Continuous recording from panels A through C shows surface ECG leads I, II, and V1 and intracardiac electrograms recorded from map catheter (maps 1 and 2 and maps 3 and 4) and the RVA during cycle length variation before and during MT of the tachycardia in patient No. 7. A, Cycle length variation was mainly attributable to change in the interval from PP (arrow) to DP (asterisk). B, Cycle length variation was attributable to the change in the DP-to-PP interval. C, Tachycardia finally terminates with loss of PP when DP was split into 2 small components, whereas 1 potential after PP and ventricular activation was recorded with the same morphology as the DP in the following sinus beat.
RF Ablation and Follow-up
The clinical tachycardias were successfully abolished in all patients. The PP-to-V, DP-to-V, and PP-to-DP intervals (all during ILVT) and PP-to-retroPP interval (during SR) at successful ablation sites are shown in the Table. Identical morphologies of DP and retroPP were observed at the successful ablation site in the 7 patients (6 patients with complete SR mapping and 1 with complete ILVT mapping).

A single RF pulse was applied at the site with MT in 5 patients and at the site with DP in 2 patients. In the other 3 patients without inducible ILVT after SR mapping, 3 RF applications were delivered to the area with the earliest

Figure 5. Tracings are ECG leads I, II, and V1 and intracardiac electrograms recorded from map catheter (Map) and the RVA in patient No. 4. During cycle length variation before mechanic termination of the tachycardia, ventricular activation preceded the DP (asterisk) with a constant ventricular-to-DP interval. The DP-to-ventricular interval change resulted in cycle length variation, and the variable interval between the PP (arrow) and the onset of QRS produced the slight change of QRS morphology in alternating beats.

Figure 6. Complete endocardial left ventricular map during idiopathic left ventricular tachycardia in patient No. 1. Activation map is depicted in the colors of the rainbow (right bar), with red zone being the earliest activation and purple the latest relative to the minimal value of the QRS complex in lead II. The sites of 1 or 3 DPs (asterisk) were marked with blue tags, and the sites with brown tags indicate a short, sharp, high-frequency and low-amplitude potential (arrow) preceding ventricular activation. The His bundle region is depicted by the 2 orange dots. Note that this mapping showed a focal origin with a very slow conduction area, because MT (marked by dark brown tag) resulted in noninducibility of ILVT for >2 hours.
retroPP. RF applications resulted in loss of the earliest retroPP and no change in the interval of PP-to-latest retroPP.

The procedure time was 262±45 minutes with fluoroscopic time of 5.4±1.4 minutes. No complications occurred. ILVT was not inducible without and with isoproterenol infusion at the end of the ablation and during the second stimulation in all patients. All patients were free of symptoms without antiarrhythmic drugs during a mean follow-up of 9.1±5.1 months (range, 4 to 17 months).

Discussion

The present study describes a new EA mapping approach of the LV in patients with and without ILVT. This study investigated (1) the mapping of the left specific conduction system; (2) the identification of abnormal retroPP in the posterior Purkinje fiber network during SR in patients with ILVT; (3) the ILVT reentrant circuit involving ventricular myocardium; and (4) the use of the earliest retroPP to guide a successful RF ablation of ILVT.

EA Mapping of the Left Specific Conduction System

To our knowledge, this is the first study about mapping the left specific conduction system in vivo using EA mapping in structurally normal hearts. In this study, the length of the left bundle branch was 17.7±3.7 mm (range, 11.8 to 22.2 mm). This correlates with the previous studies showing that the left bundle branch is ~1 to 3 cm in length and bifurcates into the posterior and anterior fascicle in the adult.13,14 Accordingly, the specific conduction system is histologically surrounded by connective tissue that separates it from the ventricular myocardium.13–15 The conduction system can be identified with EA mapping guided by a short, sharp, high-frequency potential.

Abnormal Purkinje Activation in Patients With ILVT During SR

In all patients with ILVT, an area with single or multiple retroPPs within the posterior Purkinje fiber network was found by using EA mapping during SR before RF ablation. A similar potential was recorded in previous studies using conventional mapping.8–10 Tsuchiya et al8,10 recorded this potential during SR when terminating ILVT by intravenous verapamil or RF application. Nagomi et al9 also reported that this potential was found in 1 of 15 patients before RF ablation and in all 15 patients after RF ablation and suggested that this potential possibly represented an activation of bystander Purkinje or a fascicular fiber. The presence of abnormal retroPP during SR in patients with ILVT but not in control patients strongly suggests that the area with the retroPP is the EA substrate for ILVT and may be indicative of a specific disease involving the posterior Purkinje network.

An interesting finding in the present study was that DP during ILVT coincided with the earliest retroPP, with identical morphologies of both potentials in 7 patients but not with the latest retroPP during SR. The PP-to-V interval at the successful ablation site with DP in 7 patients was relatively short (mean, 13±8 ms; individual values listed in the Table) compared with the study by Nakagawa et al3 (mean, 27±9 ms). The elimination of the earliest retroPP by RF pulses during SR also resulted in successful ablation. This strongly suggests that the earliest retroPP and DP are critical for ILVT reentry circuit.

Reentry Circuit in Patients With ILVT

Previous studies suggest that the reentry circuit is confined to the posterior Purkinje system with an excitable gap and slow conduction area.2–10 Our mapping provides evidence for a slow conduction area with passive retrograde activation along the posterior fascicle during ILVT, although a complete mapping of the reentry circuit was not achieved because of MT. Also, in patient No. 4, the mapping provided additional evidence that the ventricular myocardium was involved in the reentry circuit on the basis of the fact that the ventricular activation preceded the DP with a constant ventricular-to-DP interval during cycle length variations of the tachycardia before MT.

In accordance with previous studies on successful ablation of the earliest PP and entrainment mapping,3,4,6,8–10 we
hypothesized that ILVT reentry may be a small macroreentrant circuit consisting of 1 antegrade Purkinje fiber with PP, 1 retrograde Purkinje fiber with retroPP, and ventricular myocardium as the bridge. This conforms to the previous experimental studies that the reentry circuit is located in the Purkinje network, because the Purkinje-ventricular myocardial junction seems to be particularly susceptible to the development of unidirectional conduction block.\textsuperscript{16,17} In some patients, the reentry circuit may have multiple entrances and exits because of complex Purkinje network.

In our series, MT with loss of PP occurred in 5 patients, and mechanical injury of the critical substrate occurred in 3 other patients after SR mapping. This finding additionally supports previous studies that the critical area of ILVT is located in the subendocardium and suitable for catheter ablation.\textsuperscript{7,8}

RF Ablation

Although RF ablation of ILVT can be performed successfully,\textsuperscript{3,5,7–10} ILVT recurrence is reported, especially in patients with noninducible ILVT attributable to catheter manipulation. Using EA mapping, the site with MT could be precisely marked to provide a more accurate anatomic location for RF ablation. Most importantly, the sites of earliest retroPP could also be identified during SR, even in 3 patients with noninducible ILVT after SR mapping. The elimination of the earliest retroPP by RF pulses resulted in no ILVT recurrence during control stimulation and a mean of 9 months follow-up. This approach provides a new strategy to abolish the critical area for ILVT during SR.

Study Limitations

This study has several limitations. No resetting and entrainment were performed during ILVT because of frequent MT of the tachycardia while manipulating the mapping catheter in the area with DP. In addition, incidental injury to the earliest PP could not be excluded at the successful site with DP and short PP-to-V interval because of a small anatomic area.

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References

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