Topography of Preempting Ventricular Segments in Patients with Wolff-Parkinson-White Syndrome Using Scintigraphic Phase Mapping and Esophageal Pacing

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SUMMARY We analyzed the sequence of ventricular emptying using the phase image in 10 patients with accessory pathways and in 15 normal subjects. In normal subjects, the earliest emptying occurred in ventricular septal, apical and left basal segments. Eight patients had manifest preexcitation; the earliest emptying occurred ectopically in the right ventricle in one of these patients and in the left ventricle in five. The remaining two patients had normal phase maps. Two patients had concealed left-sided pathways. Their phase maps showed earliest emptying in left basal segments. Six of the 10 patients underwent electrophysiologic mapping. There was complete agreement between phase and electrophysiologic maps. Transesophageal atrial pacing increased preexcitation in one patient, normalized the ECG in another and precipitated narrow QRS tachycardia in four patients. Phase maps then showed enlargement, reduction and loss of the ectopic earliest emptying segments, respectively. We conclude that this technique in conjunction with pacing is successful in lateralizing accessory pathways.

NONINVASIVE determination of the site of preexcitation in the Wolff-Parkinson-White syndrome had been attempted in the past with electrocardiography, vectorcardiography, body surface isopotential mapping, carotid pulse analyses, phonocardiography, roentgenkymography, and echocardiography. More recently, phase analysis of the gated radionuclide ventriculogram had been described as a reliable way to study the emptying sequence of the heart. Because there is a close electromechanical coupling of cardiac events, phase analysis was attempted in normal subjects and in patients with accessory pathways to establish the normal pattern of ventricular emptying during sinus rhythm in normal volunteers, to define the abnormal patterns of ventricular emptying during sinus rhythm and transesophageal atrial pacing in patients with the Wolff-Parkinson-White syndrome, and to determine the utility and limitations of the noninvasive approach in mapping the site of preexcitation.

Materials and Methods

Patients

Eight patients had typical electrocardiographic evidence of preexcitation. Seven patients had symptoms of palpitations as described in the Wolff-Parkinson-White syndrome and one patient was asymptomatic. Two other symptomatic patients had concealed accessory pathways. Five were males and five females. Five subjects were healthy volunteers and 10 were patients being evaluated for chest pain in whom subsequent cardiac catheterization had excluded cardiac disease.

Radionuclide Ventriculographic Techniques

The in vivo labeling technique was used with technetium-99m as the radioactive label. The cardiac cycle was divided into 32 or more intervals depending upon the heart rate, aiming for a frame duration of 30 msec or less. The best left anterior oblique view was used for optimal separation of right and left ventricles was used in some patients, a second left or right anterior oblique view was used. A caudal angulation of 20–30° was incorporated to achieve maximal atrial-ventricular separation.

All data were acquired using a mobile gamma camera (Datacamera, General Electric) interfaced to an image-processing computer system (Medical Data Systems A2). Data were collected in histogram byte mode with a hardware zoom (1.48–1.96 ×) to improve spatial resolution. To minimize camera dead time, one of two annular lead shields (i.d. 13.5 or 16.5 cm; o.d. 30.5 cm; thickness 2 mm), depending on the heart size, was placed on the collimator face to exclude extracardiac activity. The gamma camera was peaked at 140 keV with a 20% window. A low-energy, parallel-hole, high-sensitivity collimator was used.

Data were accumulated until any picture element (pixel) in any one frame of the array format of 4096 pixels contained 256 counts. On the average, this resulted in a count density of 280,000–350,000 counts per frame and required 7–10 minutes imaging time per study after a standard adult dose of 25 mCi of technetium-99m and an average camera count rate of 25,000 counts/sec. After data acquisition, the gated study was viewed in cinematic display format to ensure the absence of trail-off in the last frames as a result of fluctuating heart rates. Such frames, when present, were dropped. On the average, because of stringent choice of varying framing rates tailored to the patient’s heart
rate, only one to three end frames were rejected because of poor counting statistics in a 30–40-frame study. All studies were then subjected to temporal and spatial filtering. The space- and time-filtered studies were then processed by a Fourier filter; the final output consisted of three images: the direct constant, the amplitude and the phase.

The phase information was displayed as a phase histogram and a phase image (fig. 1). The pixels representing parts of the heart that emptied first had a phase angle of $-90^\circ$, whereas pixels that corresponded to parts of the heart that emptied last had a phase angle of $270^\circ$. Because the emptying sequence of atria and ventricles was diametrically opposite in the normal heart, two histograms were present, representing atria and ventricles, and centered at phase angles $180^\circ$ apart.

The phase image was an outline of the actual heart under study. The color ramp beside the phase histograms coded the respective pixels that corresponded to each part of the heart; blue and yellow represented earliest emptying in the ventricles and atria, respectively, and green and red latest emptying.

Patterns of emptying were analyzed visually by two observers, blind to the electrocardiographic and electrophysiologic information, on both the static and the dynamic phase images. The static phase image was examined for the sites of earliest emptying in the ventricles, which, by definition, had the earliest phase angles and were blue. A preemptying ectopic site (i.e., a segment with early emptying that was outside the normal sites of earliest ventricular emptying) was labeled as left- or right-sided, free wall (parietal) or paraseptal.

The dynamic or cinematic phase display showed propagating color-coded wave fronts spreading from early to late phase pixels. This was accomplished by coloring all pixels with similar phase angles simultaneously at each successive point of the $360^\circ$ angle color ramp. This display effectively represented the sequence of emptying and the degree of disparity between segments within one patient and between patients. It also convincingly demonstrated subtle pattern deviations from normal.19

In one patient (no. 4), a special list-mode collection and reformatting technique was used.20,21 This patient had frequent atrial premature beats that resulted in larger delta waves than in the sinus beats (fig. 2). Because the coupling, postextrasystolic and sinus intervals were constant (680, 1000 and 1000 msec, respectively), studies could be formatted using a software option for independent selection of beats from the RR histogram.21 The sinus beats (cycle length 680 msec) that were interrupted by the atrial premature beats were formatted into one phase map. The premature atrial and the postextrasystolic sinus beats had identical cycle lengths (1000 msec), and therefore could not be separated by cycle length criteria. Accordingly, a composite phase map of both beats was generated. The two phase maps were compared and all differences were ascribed to the effect of the premature atrial beat.

**Esophageal Pacing Technique**

Esophageal pacing was performed in five normal subjects, five patients with Wolff-Parkinson-White syndrome and both patients with concealed bypass tracts. The technique involved the use of a specially designed bipolar "pill" electrode with trailing Teflon-coated leads and a nominal interelectrode distance of 15 mm.22 The electrode was swallowed by the subject and its position monitored by the ECG.

The distance of the electrode from the lips was 28–
36 cm (mean 32.9 cm). PACing was performed through a stimulation isolation unit (Model SIU-4B, Grass Instrument) connected to a physiologic stimulator (Model S4GR Serial J 313R4, Grass Instrument). The mean current level used in the 12 subjects was 19.3 mA (range 12–23 mA) and the square wave pulse averaged 7.8 msec (range 5–15 msec).

Successful atrial capture was defined as a constant one-to-one stimulus–P wave–QRS relationship during varying pacing rates for at least 3 minutes. Once this was achieved, the pacing rate was kept constant at 20–30 beats faster than the sinus rate for the entire radionuclide study. Four of the five control subjects and three of the patients were successfully paced. Four patients went into a supraventricular tachycardia during esophageal pacing. Stable pacing could not be achieved in the remaining control subject.

Electrocardiographic Procedure and Criteria

Standard 12-lead ECGs were recorded in each patient. During the radionuclide and esophageal pacing procedures, the standard lead II was continuously monitored on a three-channel portable electrocardiograph (3300 Electrocardiograph, Parke-Davis).

The following scheme was used to classify patients based upon the morphology of the delta wave and QRS complex of the preexcited beats in the right precordial leads (V_{1,2}) according to criteria described by Rosenbaum et al. and Ueda et al.:

Type A. The R wave is the sole or largest deflection in V_{1,2} and the delta wave is positive (four patients).

Type B. An rS pattern in V_{1,2} leads with variable polarity of the delta wave (one patient).

Type C. A QS or W pattern is present in V_{1} and the delta wave is negative (three patients).

Electrophysiologic Techniques and Measurements

Electrophysiologic studies were performed using standard techniques in six of the 10 patients. Briefly, closely spaced (10 mm) bipolar electrode catheters were positioned in the high and low right atrium and across the tricuspid valve to the right ventricle to record the His bundle electrogram and to stimulate the right ventricle. The coronary sinus was entered in four patients for left atrial recording and stimulation. In two patients, the left atrium was entered directly by the transseptal approach. Electrograms were recorded on a multichannel physiologic recorder (Electronics for Medicine VR12) after filtering through a band width of 30–500 Hz. The following electrophysiologic criteria were used: Ventricular preexcitation was diagnosed on the basis of a short or immeasurable HV interval (< 20 msec) with progressive approximation or incorporation of the His spike into the QRS complex with increasing delta wave during progressively rapid atrial pacing, absence of the Wenckebach phenomenon on surface ECGs at atrial pacing rates above 180 beats/min and evidence of ectopic retrograde atrial capture sequence during ventricular pacing, echo beats or tachycardia. The location of accessory pathway was determined by simultaneous or sequential electrode-catheter mapping at multiple atrial sites at the start and end of and during induced reentrant supraventricular tachycardia and during ventricular pacing.

Definitions

Preemptying. An earlier emptying of radioactivity from a segment of the affected heart relative to the pattern of emptying in the same segment in normal hearts. Preemptying is the earliest emptying in the phase image and, by definition, must be ectopic (i.e., not in the usual segments of earliest emptying in the normal heart).

Phase maps and histograms. The Fourier-transformed data from a radionuclide ventriculogram relating the sequence of ventricular emptying from early to late phases. This is represented topographically on the actual image of the ventricles as color-coded maps or as histograms.

Results

Interobserver Agreement

There was a complete interobserver agreement in locating preemptying segment in all cases using static and dynamic visual analyses.

Ventricular Emptying in Normal Subjects

A consistent pattern was seen in the phase image in all 15 normal subjects during sinus rhythm at heart rates of 65–100 beats/min (fig. 1). Earliest emptying occurred in the interventricular septal, apical and left basal regions of the heart. The rest of the heart then emptied synchronously as the wave fronts of emptying from these three segments moved outward at indentical rates to merge with one another within 15–20° of the RR interval.

High-quality phase images were obtained in four of the five normal control subjects who were subjected to transesophageal atrial pacing. The pattern of ventricular emptying was the same as that during sinus rhythm. In addition, two subjects were paced at two heart rates (90 and 120 beats/min), but there was no appreciable alteration in the sequence of ventricular emptying.

Ventricular Emptying in Patients with Wolff-Parkinson-White Syndrome

Normal Sinus Rhythm

During normal sinus rhythm (heart rates of 58–91 beats/min), the phase maps of patients 7 and 8 were identical to those of the normal controls despite the presence of short PR intervals and delta waves on the ECG. In the remaining six patients with overt preexcitation, the earliest emptying occurred outside the normal areas described above. These preemptying segments were found in the left ventricular free wall in patients 2, 3, 4, 5 and 6 and in the right ventricular free wall in patient 1 (fig. 3).

In patient 4, who had frequent atrial premature beats, list mode techniques enabled two maps to be formed. In the phase map during sinus beats (when the delta waves were small), an abnormal preemptying segment was present in the left basal area (fig. 2A).
FIGURE 3. Phase images from patient with a left-sided (A) and a right-sided (B) bypass tract during sinus rhythm. Earliest emptying occurred in the left basal (1) and septal (2) regions in patient A and in the right lateral (1) and septal (2) regions in patient B. The corresponding four-lead ECGs are shown below.

The phase map of the composite atrial premature beats (when the delta waves were large) and the postextrasystolic sinus beats showed a similarly located but larger preemptying segment (fig. 2B).

Esophageal Pacing

Esophageal pacing with successful atrial capture was achieved in three of the five patients in whom it was attempted. The other two went into supraventricular tachycardia.

In patient 1, the surface ECG showed a normalized QRS pattern (loss of delta wave) during esophageal pacing. The phase map, which had shown a large preemptying right free wall segment during sinus rhythm, now showed a marked diminution in the size of the segment. There was also an appreciable enlargement in the early emptying pixels in the septal area (fig. 4B) compared with the phase map during sinus rhythm (fig. 3B).

In patient 2, esophageal pacing resulted in increased preexcitation (larger delta wave) on the surface ECG compared with sinus rhythm. The corresponding phase map showed obliteration of the early emptying pixels in the septal region and enlargement of the area of preemptying in the left basal region of the left ventricle compared with the phase map during sinus rhythm (figs. 3A and 4A).

In patient 8, despite an increase in the delta wave

FIGURE 4. Phase images from the same patients as in figure 3 during transesophageal atrial pacing. In patient A, the delta waves enlarged and segment 1 also enlarged with loss of early emptying in the septal region. In patient B, the delta waves became smaller and segment 1 also diminished in size, while the septal segment (2) enlarged relative to figure 4.
during esophageal pacing, there was no change in the phase maps during sinus rhythm and esophageal pacing. This patient’s phase map during sinus rhythm also did not show preemptying despite electrocardiographic evidence of preexcitation.

Induced Reentrant Supraventricular Tachycardia

During esophageal pacing, a narrow QRS complex tachycardia was induced in two of the five Wolff-Parkinson-White patients (nos. 4 and 6). There were no adverse hemodynamic effects and the radionuclide studies were safely and successfully acquired in both cases. The tachycardia was easily terminated by a burst of esophageal pacing in one patient and by theValsalva maneuver in the other. In both patients, the phase maps during sinus rhythm and during the tachycardia were different.

The phase map during sinus rhythm in both patients showed an ectopic left ventricular parietal segment of preemptying. During supraventricular tachycardia, the patterns were indistinguishable from the phase map of a normal control (fig. 2C).

Ventricular Emptying in Patients with a Concealed Accessory Bypass Tract at Rest and During Supraventricular Tachycardia

Patients 9 and 10 had no evidence of ventricular preexcitation on repeated surface ECG. Patient 9 had a small delta wave during coronary sinus pacing during electrophysiologic study. Patient 10 showed antegrade block in the accessory pathway, which, however, conducted in the retrograde direction during ventricular pacing and reentrant supraventricular tachycardia.

In both patients, ectopic preemptying segments were seen in the left ventricular paraseptal and basal areas, respectively, in the phase maps during sinus rhythm. The corresponding 12-lead ECG and the monitored lead during the radionuclide study failed to show any delta waves (fig. 5). With esophageal pacing, both patients developed a supraventricular tachycardia, during which the phase maps were indistinguishable from those of normal controls.

Electrophysiologic Mapping

Electrophysiologic mapping was accomplished in six of the 10 patients (table 1). A right parietal bypass tract was found in one patient who also had an ectopic right-sided region of earliest emptying on the phase map. Parietal left-sided bypass tracts were discovered in five patients. There was concordance in the phase maps in all these patients. Both patients with concealed bypass tracts had left-sided pathways that were also visible on the phase maps. Two patients who had normal phase maps despite the presence of delta waves on the ECG did not consent to undergo electrophysiologic studies. One of these was asymptomatic and the other had brief, infrequent episodes of palpitations.

Discussion

Accurate electrophysiologic mapping of the location of accessory bypass tracts in patients with the Wolff-Parkinson-White syndrome is essential to guide surgical interruption, as these pathways are neither visibly nor palpably distinguishable from normal cardiac tissue. Electrophysiologic mapping techniques are highly time-consuming and involve specialized equipment and personnel. Noninvasive techniques have been explored, but they are hampered by a lack of direct visualization of the heart except for roentgenkonography and M-mode echocardiography. Both these approaches lack sensitivity because accurate positioning of the preexcited segment relative to the imaging device is required. Phase analysis of the gated radionuclide ventriculogram appears to be a useful alternative.

Normal Ventricular Emptying

It became obvious early in the present study that the previously described normal pattern of ventricular emptying was an oversimplification. The time course and spread of the electrical excitatory process of the normal heart had been meticulously and exhaustively studied by Durer et al. Three left ventricular sites and one right ventricular endocardial site were shown to be nearly synchronously excited first at the start of the ventricular activity potential. These were on the left surface of the midseptum, the anterior basal wall of the left ventricle near the aortic root, the lower third at the junction of septum and posterior wall and near the insertion of the anterior papillary muscle of the right ventricle. These regions became confluent 20 msec after the onset of excitation and enveloped most of the heart except for a posterobasal, a middle lateral and an apical anterior area. The last segments to be activated were either posterobasal or posterolateral segments in the left ventricle and the pulmonary conal and posterobasal areas in the right ventricle. The normal topography of ventricular emptying in our study corresponded closely to this electrical pattern; the earliest emptying occurred in the septal, left ventricular basal, and right ventricular apical segments of the heart. The emptying wave fronts spread at similar rates from these three.
areas and became confluent within 20% of the RR interval. The outflow segments of both ventricles emptied last. Characterization of this normal pattern was important to allow differentiation from the abnormal. During an intervention such as esophageal pacing, a preemptying segment could enlarge or diminish in size in harmony with the size of the delta wave, providing direct proof of electromechanical coupling. Conversely, a normally situated early emptying segment did not change in size with esophageal pacing.

**Ventricular Preemptying in the Wolff-Parkinson-White Syndrome**

Using phase imaging, we found abnormal preemptying ventricular segments in six of the eight patients with preexcitation. Independent electrophysiologic studies were performed on four of these patients and the electrical maps concurred with the phase maps in each case. An intervention such as esophageal pacing produced increased preexcitation in two patients, loss of preexcitation in one patient and narrow QRS tachycardias in two patients. Phase maps were appreciably altered in four of these five patients to allow for independent validation of the sites of preemptying. In one patient, a natural perturbation — frequent atrial premature beats — allowed significant alteration in the electrical excitation and a change in the phase map to allow for validation.

A simple, noninvasive procedure such as esophageal pacing should be added to the technique in patients with preexcitation to confirm the location of preemptying.

These various patterns before and during esophageal pacing and during reentrant tachycardia lead us to conclude that the phase maps are reliable and accurate maps of the sequence of ventricular emptying in patients with preexcitation. The close electromechanical link permits the use of such maps to localize the preexcited sites of the ventricle corresponding to the location of the accessory pathway.

In two patients with obvious short PR intervals and delta waves on the surface ECG, no abnormality was seen on the phase maps. Esophageal pacing was performed on one of these two patients who had a visible increase in the delta wave, but there was no alteration in the phase image. We inferred that these two patients could have septal bypass tracts or combinations of an atrioventricular, nodofascicular or nodovenous tracts so that the preexcited ventricular segments were essentially septal and therefore indistinguishable from normal. Another explanation could be that the preemptying segments were too small to be resolved. This was unlikely, at least in one patient whose delta wave was visible in all leads of the 12-lead ECG and constituted 25% of the QRS complex. Unfortunately, electrophysiologic studies were not done in either patient.

Using the phase imaging approach, parietal bypass tracts could be lateralized and even localized, but septal and paraseptal tracts might not be characterized and their existence could only be inferred by exclusion of the presence of parietal connections.

**Preemptying in Concealed Accessory Bypass Tracts**

In both patients in whom electrophysiologic tests had demonstrated a bypass tract during supraventricular tachycardia, the phase maps at rest showed preemptying in the left ventricle.

Repeated ECGs did not show evidence of preexcitation. There are at least two reasons why such pathways are concealed on the surface ECG. First, the bypass tract may be truly concealed during sinus rhythm and atrial pacing because of unidirectional antegrade conduction block. In these patients, the phase maps will look normal during both sinus rhythm and the tachycardia so that the tracts are truly invisible and can only be detected electrophysiologically. Second, concealment of preexcitation may be due to the limitations of the 12-lead ECG in reflecting total cardiac activity. The delta wave vector can be so unusually located or so small as to be undetected on any of the 12 leads.

**Limitations of the Technique**

Some conduction and contraction abnormalities may be mistaken for preemptying segments. For ex-

### Table 1. Clinical Features and Results of Electrocardiographic, Electrophysiologic and Phase Map Localization of the Bypass Tract

<table>
<thead>
<tr>
<th>Pt</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Symptomatic</th>
<th>ECG type*</th>
<th>EP map</th>
<th>Phase map</th>
<th>Atrial pacing</th>
<th>Pacing outcome</th>
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<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>28</td>
<td>Yes</td>
<td>C</td>
<td>Right</td>
<td>Right</td>
<td>Yes</td>
<td>Δ ↓</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>62</td>
<td>Yes</td>
<td>B</td>
<td>Left</td>
<td>Left</td>
<td>Yes</td>
<td>Δ ↑</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>36</td>
<td>Yes</td>
<td>A</td>
<td>—</td>
<td>Left</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>12</td>
<td>Yes</td>
<td>A</td>
<td>Left</td>
<td>Left</td>
<td>Yes</td>
<td>SVT</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>13</td>
<td>Yes</td>
<td>A</td>
<td>—</td>
<td>Left</td>
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<td>—</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>31</td>
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<td>Left</td>
<td>Left</td>
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<td>SVT</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>23</td>
<td>Yes</td>
<td>C</td>
<td>—</td>
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<td>—</td>
</tr>
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<td>8</td>
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<td>M</td>
<td>18</td>
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</tr>
<tr>
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<td>15</td>
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<td></td>
<td>Left</td>
<td>Left</td>
<td>Yes</td>
<td>SVT</td>
</tr>
</tbody>
</table>

*See Methods for definition of ECG types.

Abbreviations: EP = electrophysiologic; — = not done; Δ = delta wave on ECG; ↑ = increased; ↓ = decreased; SVT = supraventricular tachycardia.
ample, in bundle branch blocks, the earliest emptying phases are in the contralateral ventricle and may be mistaken for ectopic preexcitation. However, the phase histograms in bundle branch blocks are often wider than those in preexcitation, and the diagnosis is obvious on a 12-lead ECG.

Regional wall motion defects may lead to phase maps with normal segments resembling ectopic preemitting sites. However, the hypokinetic segments will match with the later emptying regions and will also have reduced amplitudes. In preexcitation, despite the phasic inhomogeneities, the amplitude images show a homogeneous concentric pattern.

Although not seen in our patients, preexcitation and regional wall motion defects from coronary artery disease can coexist. In such a situation, it is conceivable that an ischemic, yet preexcited, segment may show late rather than premature emptying. This electromechanically dissociated pattern may limit the use of this technique. Other limitations relate to the potential difficulty in locating parasetal pathways and multiple pathways.

Phase maps are probably closer to endocardial than to epicardial electrical activation maps. Because the endocardial localization of the accessory pathway may not correspond to the epicardial site, this may be a limitation. Phase mapping cannot replace electrophysiologic studies, for it cannot provide electrical information (such as refractory periods of the accessory pathways) and it requires further quantitative analysis that will remove the subjectivity of visual perception of patterns.

Clinical Implications

Phase mapping with esophageal pacing may prove useful as a screening test before electrophysiologic studies in patients designated for surgery. When parietal pathways are evident, endocardial mapping may not be necessary and the patient could undergo epicardial mapping at surgery. Phase mapping may complement electrophysiologic studies by alerting the electrophysiologist to probable septal pathways and lateralizing others where the surface ECG is unhelpful. When involvement of a concealed bypass tract is suspected in a supraventricular tachycardia, a phase map may reveal preemtping despite a normal ECG. However, a normal phase map does not exclude this possibility.

Although the role of phase mapping in the assessment of the success of surgical interruption or drug-induced block of the accessory pathways in the Wolff-Parkinson-White syndrome has yet to be determined, phase mapping and esophageal pacing techniques clearly have great potential in these situations.

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