Localization of the Site of Ventricular Preexcitation with Body Surface Maps in Patients with Wolff-Parkinson-White Syndrome

D. Woodrow Benson, Jr., M.D., Ph.D., Richard Sterba, M.D., John J. Gallagher, M.D., Abe Walston II, M.D., and Madison S. Spach, M.D.

SUMMARY Forty-nine patients with Wolff-Parkinson-White syndrome, ages 7 weeks to 51 years, were studied with isopotential body surface maps during normal sinus rhythm, atrial pacing or induced atrial fibrillation. The location of the accessory pathway was determined by multimeter electrophysiologic study or surgical ablation of the accessory pathway. When fusion was minimized and ventricular activation primarily controlled by a single accessory pathway, the distribution of positive and negative potentials on the anterior and posterior torso during QRS (observed at 40 msec) and the ST segment were an excellent index of the location of the site of the accessory pathway. The relationship between a specific sequence of QRS-T wave body surface maps and a specific preexcitation site was similar from patient to patient in the presence of marked differences in age, size, and different cardiac status due to structural congenital cardiac defects. The localization of the site of the accessory pathway using distributions too early in QRS (before 40 msec) was unreliable because the early distributions varied from patient to patient for the same preexcitation site; however, the potential distributions during the ST segment were both stable and consistent from patient to patient for the same preexcitation site. The presence of significant fusion of ventricular activation initiated via a single accessory pathway and the normal conduction system or via multiple accessory pathways complicated the interpretation of body surface distributions. Thus, one can predict accurately at least seven preexcitation sites by the combined use of QRS and ST-segment body surface maps.

THE ELECTROCARDIOGRAPHIC FEATURES of the Wolff-Parkinson-White (WPW) syndrome are the result of fusion of ventricular activation initiated via the normal conduction system and one or more accessory atrioventricular (AV) pathways. Accessory pathways can exist anywhere along the AV ring except where the left atrium is attached to the aortic ring, i.e., between the left and right fibrous trigones. There has been considerable interest in localizing the sites of the accessory pathways because successful surgical interruption of the pathways may cure arrhythmias in selected patients. The preoperative diagnostic approach for identifying the site of the accessory pathway has focused on the measurement of local activation times at multiple sites in the left and right atria with catheters when the pathway conducts retrogradely; the location of the earliest time of retrograde atrial activation is identified as the area where the pathway is located. Similar atrial activation sequence measurements are made at surgery when there is retrograde conduction and from ventricular epicardial measurements when there is antegrade conduction in the accessory pathways.

Analysis of QRS during the delta wave with body surface maps in patients with WPW syndrome has been reported. Yamada et al. reported three patterns of surface potential distributions, but did not confirm pathway locations by catheter or operative measurements. De Ambrogi et al. did the most complete study of the delta wave with surface maps. They identified six types of body surface maps according to the location of the maxima and minima during the first 5–12 msec of the delta wave.

In this report we present our analysis of isopotential body surface maps in patients with WPW syndrome in whom the site of the pathway was documented to be at one of eight sites: anterior and posteroseptal sites, and sites at lateral, posterior and anterior locations on the right and left ventricles. We wanted to know whether analysis of both QRS and ST-T-wave body surface maps in patients of different age, size and cardiac status allowed discrimination of adjacent preexcitation sites when the site of preexcitation primarily controlled the sequence of ventricular activation (i.e., minimal or no fusion).

Methods

Patients

We obtained total body surface maps from 49 patients with the WPW syndrome (table 1). The patients were 7 weeks to 51 years old. Eleven patients had associated cardiac anomalies. Single accessory AV pathways were present in 46 patients, and three patients had two or three accessory pathways. Multicatheter electrophysiologic studies were performed in 48 patients. Accessory pathways were ablated surgically in 28 patients. All patients had accessory pathways that conducted antegradely, but not all of the accessory pathways conducted...
retrogradely. However, pathway locations were confirmed in all patients by one or more of the following: measurement of local activation times at multiple atrial sites with catheters during orthodromic reciprocating tachycardia or ventricular pacing; determination of ventricular and atrial epicardial activation times at surgery; or surgical exploration. Thirty-six patients were studied during sinus rhythm and 13 were studied as part of the preoperative catheter electrophysiologic study. To produce maximal preexcitation, the maps were obtained during atrial pacing in 12 patients and induced atrial fibrillation in one patient.

To ensure that ventricular activation was controlled by the preexcitation site, we required that QRS duration be at least 15 msec longer than the age-adjusted ninety-eighth percentile of normal for patients 16 years or younger; for older patients, we required that QRS duration be 120 msec or longer. Thirty-seven of the patients met these criteria; they are the “marked preexcitation” group. In general, the PR intervals for this group were shorter than 100 msec, but three patients with Ebstein's anomaly had PR intervals of 112, 123 and 191 msec. Single accessory pathways were found in 35 of the marked preexcitation group; multiple accessory pathways were found in two patients (table 1). This study deals primarily with the 35 patients with single accessory pathways and marked preexcitation. We divided these 35 patients into eight groups, depending on the location of the accessory pathways as determined by electrophysiologic study or surgical exploration. Sites were classified as anterior and posterior septal sites or sites on the lateral, posterior, or anterior left or right ventricle (fig. 1). The remaining 14 patients, two with marked preexcitation and multiple accessory pathways and 12 without marked preexcitation, were considered to have significant fusion of ventricular activation and are discussed separately.

Method of Producing Maps
To minimize the effects of variation in the degree of fusion during preexcitation, the maps were produced from 24 simultaneously recorded ECGs from the anterior and posterior torso. This lead set allows accurate estimation of potentials at 150 locations on the anterior and posterior torso with respect to Wilson's central terminal. The methods for recording the wave forms and constructing the maps have been described in detail. Briefly, wave forms were recorded at digital sample rates of 500-1000 samples/sec using a stationary or mobile recording system. All wave forms were stored on digital tape.

After all data were recorded, the digitized wave forms were redisplayed and photographed for detailed editing to construct the 150-point maps. The wave forms were carefully edited to ensure that high-quality wave forms had been obtained. The baselines were picked in the TU-P interval, and baseline adjustment was performed by linear interpolation. Wave forms with irregular baseline movement were discarded. A computer program automatically computed the potentials at 150 locations for each instant, displayed them as potential distributions and photographed each map on 16 mm film for subsequent instant-by-instant and motion analysis.

Evaluation of Maps
The maps for each patient were carefully screened, and all were found suitable for analysis. We initially evaluated the maps by determining the PR interval and the QRS duration. Because preexcitation was present, the maxima and minima due to atrial excitation or repolarization versus early ventricular excitation may be difficult to distinguish. We distinguished between these possibilities based on experimental studies in chimpanzees and on the previous interpretation of PR-segment maps.

![Figure 1](http://circ.ahajournals.org/)

**Figure 1.** Eight sites of ventricular preexcitation. This schematic cross-section of the heart shows the location of eight sites of single accessory pathways for 35 patients with marked preexcitation. The numbers at each site indicate the number of patients with marked preexcitation and one accessory pathway.

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**Table 1. Clinical Data**

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A.</strong> 49 patients: ages 7 weeks to 51 years</td>
<td></td>
</tr>
<tr>
<td>1. Single accessory pathway</td>
<td>46</td>
</tr>
<tr>
<td>2. Multiple accessory pathways</td>
<td>3</td>
</tr>
<tr>
<td><strong>B.</strong> Confirmation of pathway location</td>
<td></td>
</tr>
<tr>
<td>1. Multicatheter electrophysiologic study</td>
<td>48</td>
</tr>
<tr>
<td>2. Surgery for pathway ablation</td>
<td>28</td>
</tr>
<tr>
<td><strong>C.</strong> Associated anomalies</td>
<td></td>
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<tr>
<td>1. Ebstein's anomaly</td>
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</tr>
<tr>
<td>2. Corrected transposition complex</td>
<td>2</td>
</tr>
<tr>
<td>3. Ostium primum atrial septal defect</td>
<td>1</td>
</tr>
<tr>
<td>4. Subvalvular aortic stenosis</td>
<td>1</td>
</tr>
<tr>
<td>5. Valvular aortic stenosis and insufficiency</td>
<td>1</td>
</tr>
<tr>
<td>6. Ventricular septal defect</td>
<td>1</td>
</tr>
<tr>
<td><strong>D.</strong> 37 patients with marked preexcitation</td>
<td></td>
</tr>
<tr>
<td>1. Single accessory pathway</td>
<td>35</td>
</tr>
<tr>
<td>2. Multiple accessory pathways</td>
<td>2</td>
</tr>
<tr>
<td>a. Normal sinus rhythm</td>
<td>24</td>
</tr>
<tr>
<td>b. Atrial pacing</td>
<td>12</td>
</tr>
<tr>
<td>c. Induced atrial fibrillation</td>
<td>1</td>
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</table>
Difficult to distinguish between maxima and minima caused by terminal ventricular excitation rather than repolarization. We distinguished between these two based on previous experimental studies and on the previous interpretation of terminal QRS maps. The QRS and ST-T-wave maps for each patient were compared with other patients with an accessory pathway that had been documented as detailed above. The maps were compared by visual inspection; the major emphasis of the comparisons was on the general distribution of positive and negative potentials on the torso, as well as the location of the maxima and minima. One of us then compared the maps without knowledge of the results of the catheter studies or surgery; comparisons were made between patients with the same site of preexcitation as well as between patients with different sites of preexcitation.

**Results**

**Problems in Analysis of the Delta Wave:**

**Changes in Early QRS**

Figures 2 and 3 illustrate map sequences during QRS and the ST-T wave for two patients: a 16-year-old patient with a right anterior pathway and a 12-year-old patient with a left anterior pathway. These representative QRS-T wave sequences illustrate the

**Figure 2.** Map sequences during QRS and ST-T wave from a right anterior site in a 16-year-old. Each map represents a single instant, as noted below each map. The torso has been represented by a rolled-out cylinder cut along the right axillary line. Maxima and minima are denoted by the large plus and minus signs; their magnitude in millivolts is noted above each map. The isopotential lines are drawn on a logarithmic scale; dashed lines indicate negative potentials and solid lines indicate positive potentials. The zero potential lines is the prominent dashed line. Note the major change in the distribution of positive and negative potentials at 40 msec.
initial QRS changes in the potential distributions. Major changes in the potential distributions during the first 10–40 msec were seen in one-third of the patients with marked preexcitation (fig. 2), but in two-thirds of the patients, relatively stable potential distributions were established during initial QRS (fig. 3). In contrast to the QRS maps, the distributions of positive and negative potentials during the ST segment were stable for all of the patients with marked preexcitation, and stable repolarization maxima and minima were established early during the ST segment.

The format of the maps is the same in all figures. The torso has been represented by a rolled-out cylinder cut along the right axillary line. The resulting rectangle has 16 columns and 10 rows; the far left column has been duplicated as the far right column. The clavicles and shoulders and the waist and navel are represented schematically. The isopotential lines are drawn according to logarithmic differences in voltage values. The solid lines represent positive potentials and the dashed lines represent negative potentials. The zero reference potential is indicated by the prominent dashed line. The numbers at each point of the map represent the voltage value at that point (microvolts × 10). The plus and minus signs indicate the polarity. The instant at which the map was ob-

**Figure 3.** Map sequences during QRS and ST-T wave from a left anterior site in a 12-year-old. These maps were obtained during left atrial pacing from the coronary sinus. Note pacing artifact on scalar trace below each map. The distribution of positive and negative potentials throughout early QRS are similar.
tained is noted on the scalar tracing below each map.

Right Anterior Pathway (fig. 2)

Right anterior pathway maps were obtained during normal sinus rhythm with marked preexcitation. Early QRS (10 msec) was characterized by a maximum over the upper sternum with positive potentials over the right upper chest; the rest of the torso was covered by low-level negative potentials with an inferior minimum. At 20 msec, the maximum intensified, and the positive potentials extended inferiorly. The distribution at 30 msec was similar; the maximum intensified, but the minimum moved over the back. A major change in the distribution occurred at 40 msec as a prominent minimum with negative potentials appeared over the right upper chest. The positive potentials extended inferiorly over most of the lower torso, and the maximum shifted to the left. At 70 msec, the distribution of positive and negative potentials was similar to that at 40 msec. The maximum shifted inferiorly and to the left, but the location of the minimum was relatively unchanged. Late in QRS (161 msec), the distribution was quite complex. The excitation maximum and positive potentials moved onto the back and the minimum and negative potentials shifted inferiorly. A repolarization maximum appeared over the right upper chest. At 202 msec, the repolarization maximum intensified and positive potentials covered the upper two-thirds of the right chest. The repolarization minimum was over the left anterior chest, and negative potentials covered most of the left chest and lower torso. At 262 msec, the distribution was similar except for intensification of the maximum and minimum. Late in the T wave (394 msec), the relative distribution of positive and negative potentials was similar to that at earlier instants in the T wave.

Left Anterior Pathway (fig. 3)

The left anterior pathway maps were obtained while the low posterior left atrium was paced (120 beat/min) via a catheter in the distal coronary sinus. Early QRS (10 msec) was characterized by positive potentials over the anterior chest, with a maximum over the left upper chest; a minimum was over the upper back. The major change in the distribution at 20 msec was that low-level positive potentials covered the entire lower torso. Except for intensification of the maximum and minimum, the distributions did not apparently change at 30, 40 or 70 msec. The distribution was quite complex during late QRS (118 msec), with the appearance of two maxima and two minima. The repolarization maximum and positive potentials appeared over the upper back, the area previously occupied by the excitation minimum. During the ST segment (154 msec), the distribution was again simple, with negative potentials over the anterior chest and lower torso and positive potentials over the upper back. Early in the T wave (226 msec), the distribution was stable except for intensification of the maximum and minimum. Late in the T wave (302 msec), the maximum and positive potentials shifted over the left axilla, but most of the anterior chest and lower torso was covered by negative potentials.

Comparison of Different Sites

Figures 4 and 5 are maps at a single instant for eight patients, each representative of a group of patients with a pathway at one of the eight sites. The QRS maps were obtained 40 msec after the onset of QRS and the ST-segment maps were obtained about 40 msec after the end of QRS. to emphasize the clear differences in the general distributions of positive and negative potentials, the isopotential lines (except for the zero potential line) and the numbers at the 150 sites have been omitted from the figures. The format of the torso is the same as that in figures 2 and 3.

QRS Maps at 40 msec (fig. 4)

At 40 msec on the QRS maps, the location of the maximum is always on the upper left anterior chest near the sternum. The minimum moves first from high on the right anterior chest to the lower torso and then high on the left chest and back as the site of the pathway moves from the front to the right, onto the back and then to the left side of the heart. The QRS patterns at 40 msec for both the anterior right ventricle and anterior septal sites were virtually identical, a finding that occurred in all eight patients with anterior right ventricle or anterior septal pathways. Also, note the similarity of the distribution of positive and negative potentials that occurred for the posterior right ventricle and posterior septal sites; however, note the marked difference in the location of the minimum at these two sites.

ST-segment Maps

Figure 5 illustrates the ST-segment maps for the same eight patients as shown in figure 4. The positive and negative potentials for the ST-segment maps are virtual mirror images when compared to QRS. The distributions for the anterior right ventricle and anterior septal sites are similar, a consistent finding for the patients with anterior right ventricular or septal sites.

The patterns of QRS and ST-segment maps (excluding the anterior right ventricular and septal sites) were specific for each site, except in two patients in whom the QRS and ST-segment maps suggested different but adjacent sites. One patient, a 2-month-old infant with a documented posterior left ventricular site, had an ST-segment map that suggested an adjacent site, lateral left ventricular; however, the QRS map suggested a posterior left ventricular site. Another patient, a 10-year-old with complex congenital heart disease and an anterior left ventricular site, had a QRS map that suggested a lateral left ventricular site; the ST-segment map correctly indicated an anterior left ventricular site.

Similarity of Maps in Different Patients

with the Same Preexcitation Site

Figure 6 is a comparison of QRS and ST-T-wave maps from three patients who were documented at
surgery to have a lateral right ventricular site. These three patients were chosen for comparison because they illustrate that even in the presence of a wide range of size, age and cardiac state, the patterns are similar for both QRS and ST-segment maps. Although there are minor differences between the maps, the maps are more similar to one another than to the patterns at adjacent sites (figs. 4 and 5).

Figure 7 is a comparison of three patients with a documented posterior right ventricular site of preexcitation. The patients were chosen for comparison because of their marked differences in age, size and cardiac state. Despite these differences, the QRS and ST-segment maps for these three patients are similar.

Effect of Significant Fusion
The effect of significant fusion of ventricular activation from either the normal conduction system or mul-

**QRS BODY SURFACE MAPS**

![QRS Body Surface Maps](image)

**Figure 4.** QRS maps for eight sites. The map at each site is from a representative patient with a single accessory pathway at one of the eight sites. The maps were obtained about 40 msec after the onset of QRS. The map format is the same as that in figures 2 and 3, except that the numbers at each point and the isopotential lines (except the zero potential line) have been omitted. The prominent line is the zero potential line. The areas of positive potentials have been shaded. The plus and minus signs indicate the location of maxima and minima.
Multiple accessory pathways was examined by evaluating the maps of the remaining 14 patients (i.e., excluding the 35 patients with marked preexcitation and a single accessory pathway). The significance of minimizing the degree of ventricular activation initiated via the normal conduction system is well illustrated by evaluating the maps of the 12 patients who did not have marked preexcitation. We evaluated the QRS and ST-T-wave maps of the 11 of these patients with a single accessory pathway. Only one patient had QRS and ST-segment maps with potential distributions characteristic of other patients with a pathway in the same location. Of the other 10 patients, only four had QRS maps and another four had ST-segment maps that correctly located the site.

Two patients had multiple pathways with marked preexcitation. One patient, an adolescent with Ebstein's anomaly, had both a posterior septal and a lateral right ventricular pathway based on the measurement of atrial activation times during reciprocation.

**ST SEGMENT BODY SURFACE MAPS**

![Diagram of body surface maps](image)

**Figure 5.** ST-segment maps for eight sites. The map at each site is from the patient shown in figure 4. The maps were obtained about 40 msec after the termination of QRS.
LATERAL RIGHT VENTRICLE

Figure 6. Comparison of lateral right ventricular sites. QRS and ST-segment maps from three patients with a lateral right ventricular site of preexcitation are compared. Even in the presence of a wide range of size, age and cardiac state, the QRS and ST-segment maps are similar. AS = aortic stenosis.

Discussion

When ventricular activation is primarily controlled by a single accessory AV pathway (an ectopic site), the pattern of surface potential distributions during the QRS and ST-T wave are reproducibly similar from patient to patient for a given site. This finding may be important in predicting the location of a single preexcitation site using body surface ECGs. Our comparison of potential distributions resulting from different sites of ventricular preexcitation in patients of different sizes agrees remarkably well with the experimental results of Spach et al. for similar sites of ectopic ventricular stimulation in a single chimpanzee, and further extends similar observations in previous case reports.

For similar sequences of ventricular activation, there is a similarity of epicardial events throughout excitation and repolarization, regardless of the site of ectopic ventricular stimulation. Spach et al. showed from epicardial measurements in chimpanzees for ectopic sequences that during early excitation, there was an intense minimum at the ectopic site with an adjacent maximum and low-level positive potentials, while the initial repolarization maximum was at the ectopic site and the minimum was at the location where excitation had ended on the opposite side of the heart. Thus, the ST-T wave was as useful as QRS at localizing the ectopic site. That the ST-T wave should be as useful as QRS at localizing different sites was shown experimentally to be a consequence of the epicardial potential distributions resulting from ectopic ventricular stimulation. These epicardial repolarization potential distributions have been explained quantitatively on the basis of the "SI theory," the spatial intracellular potential distribution.

In chimpanzees, ectopic sequences from adjacent ventricular sites 2–3 cm apart at the level of the AV ring can be discriminated by body surface potential distributions by using the general distribution of low-
level potentials on the torso. This is a small distance between adjacent sites in an older child, adult or chimpanzee, but it is a large distance in a small infant and may approximate the distance between the left and right ventricles. However, when the ventricles are markedly preexcited, excellent localization of adjacent sites can be obtained without regard to patient size. Spach et al. showed that two major features govern the projection of epicardial events to the body surface: the magnitude of the epicardial potential gradients and the distance over which they exist on the epicardial surface (cardiac sources), and the distance to the recording area on the body surface (volume conductor). Thus, because our results are influenced so little by patient size and thus heart size, the distance between adjacent sites that can be discriminated is relative to the size of the patient, i.e., heart and body surface sizes are normalized. Eight divisions of the AV ring permit adequate discrimination of adjacent sites regardless of patient size. The one exception — the similarity of the distributions when the site is anterior right ventricular or anteroseptal — is probably because this region of the heart is overlain by the right ventricular outflow tract.

De Ambroggi et al. suggested using the maximum and minimum during the delta wave to characterize the potential distributions. Our results show that the location of the maximum is relatively stationary while, generally, the minimum moves about the torso, depending on the site of preexcitation. The locations of the QRS maximum and minimum were frequently useful for distinguishing right-sided sites from left-sided sites, but they were less helpful for distinguishing adjacent sites. In comparing the potentials resulting from the same preexcitation site in different patients, we found that there may be significant changes in the location of the minimum, while there was little or no change in the distribution of the low-level potentials (fig. 6). Conversely, in comparing patients with adjacent preexcitation sites, there frequently was little or no change in the location of the maxima and minima, while major changes were apparent in the distribution of the low-level positive and negative potentials on the torso (fig. 4).
Localization of the site of ventricular preexcitation could be accomplished by analysis of the delta wave during the first 20 msec of QRS.\textsuperscript{7, 10} Although this was true for approximately two-thirds of the patients in our study, the remaining one-third had significant variability of potential distributions during the first 10-40 msec of QRS for the same documented preexcitation site. For example, in the patient whose QRS maps are shown in figure 2, we attempted to localize the site of the pathway by analyzing the maps during the first 20 msec. These initial QRS maps suggested a site at the posterior or lateral left ventricle. However, at 40 msec, the patterns were typical for an anterior right ventricular site, and this was confirmed at surgery. The origin of these changes in surface potential distributions during the first 10-40 msec is unknown, but they result from local factors, such as relative endocardial or epicardial location of pathway, that cause different initial wave fronts in the area of the ventricular preexcitation. However, one benefit of using the ST-T-wave distributions is that early repolarization is not subject to the same kind of variability, because the repolarization currents are generated from potential gradients that are distributed over a larger area than the excitation currents.\textsuperscript{18}

References

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