Differences in QRS Configuration During Unipolar Pacing From Adjacent Sites: Implications for the Spatial Resolution Of Pace-Mapping

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To examine the spatial resolution of unipolar pace-mapping, 12 lead electrocardiograms (ECGs) recorded during pacing from each of the poles of a quadripolar catheter (5 mm interelectrode distance) were examined. Unipolar pacing was performed from each of the poles at late diastolic threshold, twice threshold and 10 mA at a cycle length of 500 ms. In 15 patients, pacing was performed at the right ventricular apex and in 14 at various left ventricular sites. Pacing from the distal catheter pole at threshold (index ECG) was used to simulate the site of origin of ventricular tachycardia, and all other ECGs were compared with the index ECG.

Electrocardiograms were evaluated by two independent observers for 1) minor configuration differences (match, new small component, change in the amplitude of individual components or change in QRS shape); 2) major differences in configuration (new large component, marked change in the amplitude of an existing component or two minor changes); and 3) peak to peak changes in amplitude.

Minor differences in configuration were seen in a mean of 1.4 ± 1.9, 4.6 ± 2.4 and 4.4 ± 2.9 leads during pacing at 5, 10 and 15 mm from the index site. Major differences in configuration were seen in a mean of 0.3 ± 0.5, 2.1 ± 2.1 and 3.7 ± 2.3 leads during pacing at 5, 10 and 15 mm from the index site. Differences in amplitude were seen in a mean of 3.1 ± 2.2, 5.6 ± 2.5 and 6.8 ± 3.0 leads per ECG during pacing at 5, 10 and 15 mm from the index ECG pacing site, respectively. During pacing at 5 mm from the index site, 24 of 29 patients had ECGs with at least one lead showing a configuration difference; 28 of 29 patients had ECGs with at least one lead showing an amplitude or configuration difference. Pacing current strength had no effect on configuration differences found during unipolar pacing and had minor effects on amplitude differences.

In conclusion, if only major differences in configuration are sought, ECGs during pacing from sites as far apart as 15 mm may be similar. However, if ECGs are examined for minor differences in configuration and amplitude, pacing sites only 5 mm apart can usually be distinguished. Current strength has little effect on ECGs recorded during unipolar pacing. These findings suggest that the spatial resolution of unipolar pace-mapping is generally within 5 mm.

Methods

Study design (Table 1). Twelve-lead electrocardiograms (ECGs) were recorded during pacing using different electrode configurations or different stimulus intensities from one site in each of 29 patients. Pacing was performed in the right ventricle in 15 patients and in the left ventricle in 14. Pacing at the right ventricular apex was used to ensure a constant pacing site for comparison among patients. Unipolar pacing was performed from each of the poles of a quadripolar catheter (5 mm interelectrode distance) positioned so that all four poles were in contact with the endocardium. Stimulus intensities of threshold, twice
threshold and 10 mA were used during pacing from each of the catheter poles, for a total of 12 ECGs (Table I). Pacing from the distal electrode at threshold was used to simulate the area of origin of a ventricular tachycardia. To examine the spatial resolution of pace-mapping and effect of stimulus intensity on it, the ECG recorded with unipolar pacing from the distal pole at threshold (index ECG) was compared with each of the 11 others. Although ventricular tachycardia occurs most frequently in patients with structural heart disease, tachycardias may occur in patients with a structurally normal heart or arise in the right ventricle, or both. Thus, ventricular tachycardia localization may be important in such patients as well.

Study Patients. Inclusion criteria for patients were: 1) electrophysiologic study in the absence of antiarrhythmic medications; 2) sinus rhythm at a rate <110 beats/min; and 3) the ability to obtain unipolar stimulation thresholds from all four poles of the catheter. The left ventricular pacing site was septal in four patients, inferolateral in five and anterior in five. A Bloom DTU 210 stimulator with constant current isolation unit was used for pacing and a Siemens-Elema Mingograf 7 recorder was used for recording 12 lead ECGs, 6 leads at a time, at a paper speed of 25 mm/s.

The late diastolic stimulation threshold was determined in incremental fashion in steps of 0.1 mA. Pacing was performed at current strengths equal to threshold, twice threshold and 10 mA. The pulse width was 2 ms. A catheter in the inferior vena cava was used as the indifferent electrode (7). Electrocardiograms were recorded during pacing at a cycle length of 500 ms. Six seconds of recording time was obtained for each group of leads. The ECGs were amplified and displayed at a gain of 1 mm/mV and filtered at 0.05-1,000 Hz. After the 12 ECGs were recorded, pacing was once again performed from the distal catheter pole to ensure that catheter position remained unchanged.

Local electrograms at each of the four catheter poles were recorded at a paper speed of 100 mm/s and an amplitude of 10 to 80 mm/mV. Local electrograms were filtered at 50 to 500 Hz. Electrogram amplitude was determined to the nearest 0.1 mV and electrogram duration to the nearest 5 ms. Electrogram duration was determined from a fixed gain recording (10 mm/mV) (8).

Electrocardiogram Analysis

Electrocardiograms were analyzed independently by two observers and were examined for amplitude and configuration differences according to the following criteria.

Amplitude. Spontaneous variability in QRS amplitude can occur secondary to respiration or other factors. To account for this variability, spontaneous changes in QRS amplitude within a given lead at a given pacing position was calculated as follows: In a subset of five ECGs, QRS amplitude was measured for each beat during the 6 s recording period. A mean coefficient of variation of 4.5 ± 2.5 mV was found, and this appeared to be largely due to respiration. Differences of up to 6 mV in amplitude due to spontaneous variability were seen in a 6 s recording. To
eliminate this source of variability, the QRS amplitude of the largest QRS complex during the 6 s period was determined. Comparisons of several 6 s recordings demonstrated a maximal variability of 2 mV in the QRS amplitude of the largest QRS complexes. Therefore, comparisons of QRS amplitude were based on the largest QRS complex in a particular lead and only differences that exceeded 2 mV were considered real and not due to spontaneous variability.

**Configuration.** Specific criteria were defined to minimize the subjectivity in the comparison of QRS configuration. All configuration comparisons were made in reference to the index ECG: pacing from the distal electrode in a unipolar cathodal fashion. For each of the 11 other ECGs, each lead was graded independently by two observers as: 1) no difference, 2) minor configuration differences, or 3) major configuration differences. Only one configuration difference was assigned to each lead. Thus, if a major configuration difference was noted, minor differences were ignored.

**Minor configuration differences consisted of:** 1) appearance or disappearance of a notch (Fig. 1A); 2) appearance or disappearance of a Q, R or S wave that was <25% of the peak to peak QRS amplitude (Fig. 1B); 3) a change >25% but <50% in the ratio of the amplitude of the individual component to the total QRS amplitude (Fig. 1C), and 4) a change in the shape of a major component, either a marked change in slope of the upstroke or a change in the configuration of the peak (Fig. 1D).

**Major configuration differences consisted of the following:** 1) appearance or disappearance of a component that was >50% of the QRS amplitude (Fig. 2A); 2) difference in the amplitude of a component of the QRS complex of >50% of the total QRS amplitude (Fig. 2B); and 3) two or more minor configuration differences (Fig. 2C).

When examining differences in QRS configuration, 6 s recording periods from each of the ECGs were viewed side by side. If the QRS configuration varied from beat to beat in a particular lead of the two ECGs being compared, the two leads were considered not to differ if any one QRS complex had a similar configuration of the two ECGs (Fig. 3).

Two specific situations were not classified as configuration differences: change in QRS amplitude with no difference in configuration and a notch in the first 40 ms of the QRS during pacing at 10 mA (Fig. 4). The latter phenomenon was observed frequently, and although it may represent a true change in local activation with pacing at high current strength, it was not believed to have diagnostic value for tachycardia localization and thus was ignored. In addition, the initial portions of the QRS complex were obscured during high current strength pacing. This made interpretation of differences impossible (Fig. 4).

**Data analysis.** Data are expressed as mean values ± SD. As previously described, ECGs 2 to 12 were compared with ECG 1, the index ECG. Differences between ECGs were expressed in two ways: the mean number of leads per ECG that showed a difference and the number of patients who had one or more leads that showed a difference.

In general, the square roots of the data were analyzed rather than the raw data to control for the skewness in the raw data distributions. Differences in QRS configuration and amplitude between two pacing sites were evaluated with Student's t test, whereas differences among the three heart disease groups were analyzed with analysis of variance. Differences in QRS configuration and amplitude using different electrode configurations and different current strengths were compared by repeated measures analysis of variance or by paired t tests when appropriate. Multiple comparisons were performed using Fisher's least significant difference procedure. A p value <0.05 was considered significant.

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*Figure 1.* Minor configuration differences. Each figure shows one lead from the index electrocardiogram (ECG) (top) and the same lead from another ECG from the same patient (bottom). A to D show minor configuration differences. A, type 1 (notch); B, type 1 (new small deflection); C, type 3 (deflection amplitude change); D, type 4 (shape change).
Results

Thresholds and electrograms (Table 2). Mean unipolar pacing thresholds for catheter poles 1 to 3 were not significantly different from each other. The pacing threshold from pole 4 (15 mm from the tip) was higher than from the other poles. Local electrogram amplitudes and durations were not significantly different among the four catheter poles.

Analysis of configuration. A total of 3,828 leads (eleven 12 lead ECGs in each of 29 patients) were analyzed. The two observers agreed in 92% of cases. There were 184 disagreements (5%) between minor and no differences, 103 disagreements (3%) between minor and major differences and 11 disagreements (0.3%) between no differences and major differences. Differences were resolved by consensus.

Configuration differences (Tables 3 and 4). There was a progressive increase in the mean number of leads per ECG that showed a difference from the index ECG as the distance from the index ECG pacing site increased. Data are shown for minor configuration differences, major configuration differences and any configuration difference in Table 3. Overall, minor configuration differences were more common than major differences. When pacing at pole 2 (5 mm from the pacing site of the index ECG), a mean of 2.4 ± 1.9 leads showed a minor difference but a mean of only 0.3 ± 0.5 lead showed a major difference. However, when pacing at pole 4 (15 mm from the index ECG pacing site), a mean of 4.4 ± 2.9 leads showed minor configuration differences and 3.7 ± 2.3 leads showed major configuration differences (p = NS). Current strength had little effect on the number of leads showing configuration differences compared with the index ECG. Configuration differences occurred with a similar prevalence in the limb and chest leads.
of 29 patients had an ECG with at least one lead that showed a configuration difference from that of the index ECG. During pacing at pole 2, 24 (83%) of 29 patients had an ECG with at least one lead that showed a configuration difference. During pacing at pole 3 or 4, all patients had at least one lead that showed a configuration difference from that of the index ECG.

Among the 981 ECG leads showing minor configuration differences, 477 (48%) were type 1 (match), 335 (34%) were type 2 (new small component), 169 (17%) were type 3 (change in amplitude of an existing component) and 9 (1%) were type 4 (change in shape). Of 380 leads showing a major difference, 271 (51%) were type 1 (new large component), 114 (22%) were type 2 (ratio change) and 145 (27%) were type 3 (two or more minor differences).

Amplitude differences (Tables 5 and 6). Amplitude differences were more common as the distance from the pacing site increased. The mean number of leads showing an amplitude difference of >2 mV between electrocardiograms 2 to 12 and the index ECG increased from a mean of 3.1 ± 2.2 leads at pole 2 to a mean of 6.8 ± 3.0 leads at pole 4 (p < 0.001). When comparing the index ECG with those recorded 5 to 15 mm away from it, there was little effect of pacing current strength on the number of leads with amplitude differences. However, ECGs recorded when pacing at twice threshold or 10 mA from the distal electrode occasionally showed amplitude differences from the index ECG (Tables 5 and 6). Although the mean number of leads per ECG was small (0.9 to 1.6), 11 of the 29 patients had at least one lead with an amplitude difference when comparing pacing at twice threshold to threshold at the index pacing site and 21 patients had at least one lead with an amplitude difference when pacing at 10 mA (Table 6). Amplitude differences occurred more frequently in the chest leads than in the limb leads (p < 0.01). This difference reached significance for ECGs 5 and 7 to 10.

Total differences (Tables 5 and 6). A mean of 4.9 ± 2.3, 8.9 ± 2.1 and 10.0 ± 2.3 leads per ECG showed any difference (either amplitude or configuration) when pacing 5, 10 and 15 mm away from the index pacing sites. All but one patient had at least one lead showing some difference when pacing sites were as close as 5 mm apart and all patients had at least one lead showing a difference when pacing sites were 10 and 15 mm apart (Table 6).

Stimulus intensity had no significant effect on the mean number of leads per patient or the number of patients showing differences between ECGs during unipolar pacing. However, pacing at higher current strengths frequently obscured the initial portion of the QRS complex (Fig. 4). As noted in the Methods section, these differences were not included in the analysis.

Effects of pacing site and heart disease. Left ventricular pacing was associated with a greater number of minor but fewer major configuration differences than was right ventricular pacing. This difference reached significance for ECGs 10 to 12 (p < 0.05 for both major and minor differences). Amplitude differences were slightly more common during right ventricular pacing. This difference reached significance only for ECG 11.

Underlying heart disease had no effect on configuration differences but did have an effect on amplitude differences. Patients with coronary artery disease had fewer amplitude differences than did patients with either no heart disease or those with cardiomyopathy (p < 0.05 for ECGs 4 to 12).

**Discussion**

This study shows that analysis of the ECG can usually discriminate between pacing sites as close as 5 mm from...
Each other. The results suggest that the spatial resolution of unipolar pace-mapping is usually <5 mm. If only major differences in QRS configuration are sought, ECGs may be similar when pacing sites are as far as 15 mm apart. However, when ECGs are examined for minor configuration and amplitude differences, at least one lead will show a difference up to 50% of the time when pacing sites are as close as 5 mm apart. Differences in pacing current strength have little effect on the configuration of ECGs recorded during unipolar pacing, with the exception of alterations in the initial portion of the QRS complex produced by pacing at high-current strength. Altering pacing current strength had minor effect on ECG amplitude.

Pace-mapping. Localization of the region of the ventricular myocardium from which a tachycardia emanates may have pathophysiologic and clinical importance. Ablative therapy for arrhythmias using either a localized surgical resection or the delivery of electrical energy through catheters requires anatomic localization of the tachycardia (1-4). The degree of precision required depends on the lesion size produced by the ablative technique. Several methods have been suggested to localize ventricular tachycardia, including activation mapping to determine sites of presystolic activity (9), examination of the configuration of local electrograms during ventricular tachycardia (10), pacing during the tachycardia (11) and pace-mapping (5). Pace-mapping can be performed with the patient in sinus rhythm and thus has the advantage of being applicable in patients who have hemodynamically unstable ventricular tachycardia. However, the degree of anatomic localization provided by pace-mapping had not previously been quantitated.

Josephson et al. (5) compared pace maps in 12 patients with tracings obtained during ventricular tachycardia. Electrocardiograms obtained when pacing near the presumed sites of tachycardia origin were described as “similar” or “different” from the ventricular tachycardia. However, the similarity of pace maps from adjacent sites was described only anecdotally. Holt et al. (12) examined ECG configuration when pacing from a variety of epicardial sites, but were mainly interested in anatomic localization of different configurations rather than in comparing differences when pacing from adjacent sites.

Method of ECG comparisons. Differences in the QRS complex were broadly classified as amplitude and configuration differences. The number of leads with a configuration difference from that of the index electrocardiogram was tabulated for each patient. The results suggest that the spatial resolution of pace-mapping is usually <5 mm. If only major differences in QRS configuration are sought, ECGs may be similar when pacing sites are as far as 15 mm apart. However, when ECGs are examined for minor configuration and amplitude differences, at least one lead will show a difference up to 50% of the time when pacing sites are as close as 5 mm apart. Differences in pacing current strength have little effect on the configuration of ECGs recorded during unipolar pacing, with the exception of alterations in the initial portion of the QRS complex produced by pacing at high-current strength. Altering pacing current strength had minor effect on ECG amplitude.

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Table 6. Number of Patients With One or More Leads With an Amplitude Difference or Any Difference From the Index Electrocardiogram

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The results of this study suggest that the potential effect of altering current strength has only minor effects on the surface ECG. Stimulus intensity had little effect on the number of leads or ECGs that showed amplitude or configuration differences at sites remote from the catheter tip. Enlarging the mass of myocardium that was depolarized in a relatively local area would not necessarily change the surface QRS configuration unless the degree of enlargement was highly asymmetric. Although stimulus intensity had no systematic effect on the number of leads with amplitude differences at sites distant from the catheter tip, pacing with different current strengths at the catheter tip did show occasional differences in the amplitude of at least one of the ECG leads. The larger mass of myocardium directly depolarized by high current strength pacing may occasionally alter the amplitude of the QRS complex.

Effects of pacing site and heart disease. Although the incidence of configuration differences was similar during right and left ventricular pacing, major configuration differences were more common during right ventricular pacing. This was likely due to the shift in axis from directly superior, as occurred during pacing at the right ventricular apex, to a more normal axis during pacing from the more proximal poles along the septum. Left ventricular pacing sites that were not along the septum were probably not associated with such marked shifts in ECG axis. Patients with coronary artery disease had a similar number of configuration differences but fewer amplitude differences than did patients with either dilated cardiomypathy or a structurally normal heart. Pacing sites in patients with coronary disease were chosen in areas of abnormal electrical activity that were presumably within or around zones of infarction. Because electrical
forces from such regions are small, a change in pacing site within such regions may produce little change in surface QRS amplitude unless a marked shift in depolarization of the remaining myocardium occurred.

Limitations. Although we tried to position the catheter so that pacing thresholds from all four electrode poles were equal, stimulus intensity was slightly higher at the most proximal pole. Thus, in some patients, contact with the endocardium may not have been maintained with this electrode. However, the progressive increase in the number of amplitude and configuration differences as the distance between pacing sites increased suggests that this effect was minimal. Since pacing was performed for a prolonged period, a pacing cycle length of 500 ms was used so that the protocol could be tolerated. Ventricular tachycardia may occur at a variety of rates, and rates at several pacing cycle lengths were not compared in this study.

To analyze both amplitude and configuration differences, data were obtained from only one catheter site in each patient. Thus, the spatial resolution of pace-mapping of different sites in the right or the left ventricle was not compared. However, in all patients, regardless of the ventricular pacing site, clear-cut configuration differences were seen within 10 mm of the pacing site, suggesting that the spatial resolution of pace-mapping that we have demonstrated is independent of the location in the ventricle.

The classifications of types of configuration change was arbitrary and may not have had physiologic significance. However, the classification system provided a reproducible method of classifying ECG changes that was, in general, observer independent.

Finally, ventricular pacing was used in this study to simulate a site of ventricular tachycardia origin. Because reentry is the most common cause of ventricular tachycardia, pacing at a point source has inherent limitations in simulating this arrhythmia. However, pacing at a single site can reproduce the exit site of a reentrant circuit (16). Performing this study in patients with spontaneous ventricular tachycardia would do little to overcome these limitations. An arbitrary single point for the catheter tip would still need to be selected and this would have a variable relation to the entire reentrant circuit. In addition, this study was not designed to address the inherent limitations of pace-mapping because pacing model of ventricular tachycardia was used. A potential limitation of pace-mapping is that areas of functional block during ventricular tachycardia may alter the pattern of impulse propagation from an endocardial site (17). Further studies are needed to determine how often this limitation interferes with the use of pace-mapping.

Clinical implications. This study shows that when major configuration differences alone are evaluated, ECGs recorded when pacing at sites as far as 15 mm apart may be similar. However, if amplitude differences and small differences in configuration are carefully noted, the 12 lead ECG during ventricular pacing can discriminate pacing sites as close as 5 to 10 mm apart. Examination of all 12 leads is crucial because in some cases only a single lead may show a difference. Our results suggest that if target sites for catheter or surgical ablation are identified on the basis of results of pace-mapping, an area 1 to 4 cm² would have to be ablated for optimal results.

Catheter ablation of ventricular tachycardia with direct-current shocks is not uniformly successful even when pace maps appear to be identical to the ventricular tachycardia configuration for several possible reasons: 1) The amount of myocardium destroyed by the catheter shock procedure may be less than the 1 to 4 cm² region identified by pace-mapping; 2) For reentrant ventricular tachycardias, ablation of the "exit" site of the ventricular tachycardia circuit may not necessarily interrupt a critical part of the reentrant circuit; 3) Pace maps may not have been examined closely enough for amplitude and minor configuration changes. Application of the configuration criteria proposed in this study allows the third possibility to be distinguished from the other two. In addition, because a high current strength may distort the configuration of the initial portion of the QRS and because no differences were found among pace maps at different current strengths, pace-mapping should be performed at the lowest stimulus intensity that provides consistent capture.

Bipolar pace-mapping has been used by several investigators. Although the stimulus artifact produced by bipolar pacing is smaller, bipolar pacing has the potential for shifting the effective area of impulse origin as a result of an anodal contribution to depolarization (18). Because we have shown that the spatial resolution of unipolar pace-mapping is likely to be within 5 mm, this shift may be significant. Further studies are required to compare bipolar with unipolar pace-mapping.

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References