Identification of ventricular tachycardia with use of the morphology of the endocardial electrogram

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ABSTRACT Currently available antitachycardia devices rely primarily on timing information to define abnormal rhythms. It would be useful to have more specific means of automatically identifying pathologic tachycardias. Using unfiltered (0.04 to 500 Hz bandpass) recordings made during electrophysiologic testing in 10 patients with ventricular tachycardia (VT), we studied the differences in electrogram morphology during sinus rhythm and VT. Signals were digitized at 1 kHz. A template of a normal sinus rhythm electrogram was created for each patient by averaging five sinus complexes from the beginning of each study. Ten sinus electrograms just before the onset of VT and 10 electrograms during stable monomorphic VT were compared with this template. The difference in morphology between a given electrogram and its template was quantitated by superimposing the two signals and measuring the area between the curves. There was no overlap in the ranges of these “area of the difference” measurements between sinus and VT electrograms from any of the 10 patients studied, including four with intraventricular conduction disturbances. In contrast, discrete features of the signal, including peak amplitude and maximum dV/dt, did not reliably differentiate sinus from VT electrograms. Bandpass filtering, sample window size, and digitizing rate were manipulated to determine the minimal signal content necessary for the area of difference method to reliably identify VT. These interventions suggest that the low-frequency far-field portion of the signal is primarily responsible for the morphologic differences between sinus and VT electrograms. In conclusion, the morphology of VT electrograms in man is consistently and distinctly different from the morphology of sinus electrograms. Morphologic analysis may be a useful adjunct for the automatic detection of VT by implanted antitachycardia devices.


The automatic implantable defibrillator appears to improve survival in a subset of patients with aborted sudden death.1,2 More sophisticated implantable devices for the treatment of ventricular tachycardia and fibrillation are being developed that combine antitachycardia pacing with backup defibrillation capability. Such devices will offer an even better alternative to antiarrhythmic surgery or long-term drug therapy.

Accurate identification of potentially lethal ventricular arrhythmias is essential for the safe and effective operation of such devices. Reliance on an upper rate limit to define a rhythm requiring treatment is not sufficient since this cannot distinguish between sinus, ventricular, and supraventricular tachycardias of similar rates.3–5 Several antitachycardia devices use more complex timing criteria, such as abruptness of heart rate increase and sustained rapid rate.6 Other proposed solutions also involve detection of timing changes, such as the nature of atrioventricular coupling7 or determination of the direction of depolarization by timing of activation along multielectrode arrays.8 Significant limitations are already recognized for each of these approaches.3,6 The analysis of electrogram morphology is a promising alternative method for differentiating pathologic from nonpathologic tachycardias with the use of simple and easily placed electrodes.

In preliminary animal studies, we investigated the utility of a simple, morphology-based approach to automatic rhythm identification.9 Each electrogram was superimposed on a template of a sinus rhythm electrogram and the area between the two curves was calculated. This “area of the difference” measurement unambiguously identified all ventricular tachycardia beats from six different foci in all animals. The speci-
ficity of this technique was also investigated by analyzing the effects of various perturbations on electrogram morphology. Rapid atrial pacing, atropine, epinephrine, procainamide, and infarction caused relatively minor changes in electrogram morphology and did not interfere with the ability to detect ventricular tachycardia by the area of difference method in instrumented dogs.10

Because of these promising results in animals, we applied this morphologic approach of rhythm identification to electrograms recorded during electrophysiologic study in humans.

Methods

Electrocardiographic (ECG) lead V1, as well as bipolar and unipolar endocardial electrograms from the right ventricular apex were recorded simultaneously during electrophysiologic study in 10 patients. Seven patients had coronary disease with previous myocardial infarction, one had an apical aneurysm without coronary disease, and two had idiopathic dilated cardiomyopathy. Two patients had complete and one incomplete left bundle branch block. One patient had left anterior fascicular block. Standard 6F quadrupolar electrode catheters (USCI, Inc.) with 1 cm interelectrode spacing were used. A 12 cm indifferent electrode (R2, Inc.) applied over the right scapula was used as an indifferent electrode for unipolar recordings. Electrograms were amplified with minimal filtering (0.04 to 500 Hz) with use of ECG/His channels of an Electronics for Medicine VR-16 recorder. High-fidelity analog FM tape recordings were made at 7.5 inches/sec on a Hewlett Packard 3968A instrumentation recorder during periods of sinus rhythm and induced monomorphic ventricular tachycardia. A Data Translation DT 2801A analog-to-digital conversion board was used to digitize the electrograms at a sampling rate of 1 kHz. A Compaq computer and Asyst Scientific software were used to analyze the signals.

The peak-to-peak amplitudes and maximal slew rates of 10 sinus electrograms just before the onset of ventricular tachycardia and of 10 electrograms during ventricular tachycardia were measured for each patient. Bipolar and unipolar electrograms were analyzed in an identical fashion.

In addition to these discrete variables, the morphology of the same 10 sinus and 10 ventricular tachycardia electrograms was quantitated by comparing each to a sinus electrogram template. At the beginning of each recording, five sequential electrograms during stable sinus rhythm were aligned at the point of their maximum excursion from baseline and the mean was calculated to form this template. The morphology of each electrogram was compared with the morphology of the template by superimposing them and measuring the area between the two curves (figure 1). The comparison electrogram and sinus template were initially aligned at their points of maximal amplitude. The comparison electrogram was then shifted back and forth in time until the area between the two curves was minimized. This ensured that the “area of difference” was truly representative of morphologic dissimilarity and not of template misalignment. The area of the difference was calculated by adding the absolute values of the algebraic differences between each point on the electrogram and the corresponding point on the template. This value was normalized for electrogram size by expression as a percentage of the total area between the template waveform and the isoelectric line.

Preprocessing of the signal was performed to determine its effects on the accuracy of the area of difference method. The data were reanalyzed by use of every second and every fourth element of the data set to simulate a sampling rate of 500 and 250 Hz. The area of difference for each electrogram was also recalculated after the width of the sample window was reduced from 80 to 40 and 20 msec (figure 1). Finally, the effects of bandpass filtering were examined. All electrograms were reanalyzed after 5 to 80, 10 to 80, and 20 to 80 Hz digital filtering. Digital filters were designed with a gain of 0 ± 0.5 dB in the passband and attenuation of greater than 20 dB for frequencies greater than 2.5 times the upper corner frequency or less than 0.4 times the lower corner frequency of the passband. Each bandpass filter was designed by cascading a digital low-pass
with a digital high-pass stage. Digital filter design was based on Butterworth analog prototypes. All statistical comparisons were made with the t test for paired variables.

**Results**

Mean amplitudes and maximal slew rates for bipolar and unipolar sinus rhythm and ventricular tachycardia electrograms are shown in tables 1A and 1B. Note that there was considerable variability in slew rate and peak amplitude in the majority of patients during monomorphic ventricular tachycardia (figure 2). This appeared to be a function both of respiration and beat-to-beat changes in blood pressure. Amplitudes and slew rates of sinus electrograms were not significantly different from those during ventricular tachycardia. More importantly, as seen in figure 2, A, the range of sinus electrogram amplitude overlapped with the range for ventricular electrograms in seven of 10 patients. Similarly, the range of maximal slew rates for sinus and ventricular electrograms overlapped in eight of 10 patients (figure 2, B). Thus, these discrete variables did not reliably differentiate sinus from ventricular electrograms.

Similar results were seen on analysis of maximal amplitudes and slew rates of unipolar electrograms; overlap occurred between the ranges of sinus and ventricular electrogram amplitudes in eight of 10 patients and in the ranges of slew rates in six of 10 patients.

A morphology-based approach to rhythm identification was assessed by measurement of the area between sinus and ventricular electrograms superimposed on the corresponding sinus electrogram template. The results of this area of the difference measurement are shown in table 2. The area of difference was significantly larger for both bipolar and unipolar ventricular tachycardia electrograms (p < .001). More importantly, there was no overlap in the range of values for bipolar sinus rhythm and ventricular tachycardia electrograms in any of the 10 patients (figure 3, A), allowing unambiguous identification of ventricular tachycardia in all cases. This applied to patients with normal conduction as well as those with chronic left bundle branch block (patients 5 and 9), incomplete left bundle branch block (patient 3), and left anterior fascicular block (patient 8) (table 2). Similar results were seen with unipolar signals (figure 3, B).

Bandpass filtering, sample window size, and signal sampling rate were manipulated to determine the minimal signal content necessary for the area of difference method to reliably distinguish ventricular tachycardia from sinus rhythm electrograms. As seen in table 3, decreasing the sampling rate as low as 250 Hz did not affect the reliability of the area of difference technique. In contrast, high-pass filtering from 5 through 20 Hz progressively degraded the ability of this technique to detect ventricular tachycardia electrograms. Similar effects were seen when the width of the sample window was decreased from 80 to 20 msec. It is important to note that high-pass filtering and reduction of window size had a less pronounced effect on the analysis of unipolar as compared with bipolar electrograms.

**Discussion**

This study examined right ventricular endocardial electrograms recorded during electrophysiologic study.
Characteristics of the signal were analyzed to determine their utility for automatic rhythm identification. Discrete features of the electrogram including amplitude and slew rate (dV/dt) were not reliable discriminators. In contrast, a simple method of estimating morphologic changes in the electrogram unambiguously distinguished complexes of ventricular origin from sinus rhythm in all patients, including four with abnormal intraventricular conduction in sinus rhythm.

Several other studies have examined the utility of a morphology-based approach to rhythm identification. Davies et al.\textsuperscript{12} used the first derivative of the right ventricular endocardial electrogram to differentiate supraventricular from ventricular rhythms. Pannizzo et al.\textsuperscript{13} computed the ratio of peak electrogram amplitude to cycle length as well as the ratio of positive peak amplitude to negative peak amplitude. The discriminating power of these indexes for detecting ventricular tachycardia or fibrillation was examined in six patients. Tronstad et al.\textsuperscript{14} used an autocorrelation technique in which each electrogram was compared with a 100 msec time-delayed copy. The phase angle between these two signals served as an estimate of electrogram width and correctly identified ventricular tachycardia or fibrillation in nine patients.

These techniques involve processing of the signal to assess specific morphologic features of the endocardial electrogram. In contrast, the area of difference method quantitates the overall morphologic similarity of a giv-
en complex to the corresponding template and does not depend on any single feature of the signal. This may explain the reliability of this template-matching technique over a wide range of electrogram amplitudes and tachycardia morphologies.

The genesis of the endocardial electrogram can be conceptually divided into contributions from the far field, or distant electrical activity, and those from local myocardial depolarization adjacent to the electrode. Both the pattern of activation over the ventricles and local conduction variables may be dramatically altered during ventricular ectopy. The relative contributions of near- and far-field activity to the morphologic difference between sinus and ventricular tachycardia electrograms are uncertain. Blanchard et al. have developed a canine preparation with an electrically isolated right ventricular free wall. By pacing the ventricles in both a synchronous and asynchronous fashion, they demonstrated a significant contribution of distant activation to locally recorded electrogram configuration. Neilsen et al. have shown a close correlation between electrogram duration and total ventricular activation time during multiple activation patterns, suggesting that far-field activity is being detected by the endocardial electrode. Other data suggest that local conduction variables, including velocity and orientation of the activation wavefront, may also be critical determinants of electrogram morphology. Such differences in local conduction could arise because ventricular ectopic beats are not conducted via the His-Purkinje system.

To mimic clinically used lead systems, relatively large surface area electrodes and spacing were chosen for this study. This would tend to enhance the contribution from far-field effects. With use of a 40 msec sampling window, unipolar electrograms unambiguously distinguished ventricular tachycardia from sinus rhythm, whereas some overlap occurred when bipolar signals were used. This suggests that significant information is contained in the far field, which is more readily “seen” by the unipolar configuration.

Waveform morphology is used in the automatic detection of ventricular ectopy on the surface electrocardiogram. Morphologic differences between complexes of ventricular and supraventricular origin may be less pronounced on the endocardial electrogram than on the surface electrocardiogram. However, the endocardial signal also has inherent advantages. The endocardial electrogram has a more rapid maximal dV/dt, allowing for more reproducible alignment than with the corresponding electrocardiogram. In addition, the endocardial signal-to-noise ratio is superior.

Reducing the sampling rate to 250 Hz did not affect the discriminating power of the area of difference method. This suggests that most of the signal information content is well below 250 Hz, and that the low-frequency, far-field signal is primarily responsible for the morphologic dissimilarity of sinus and ventricular electrograms. This observation is consistent with Fourier transform analyses of endocardial signals.

High-pass filtering from 5 through 20 Hz progressively degraded the accuracy of the algorithm, rein-

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**TABLE 2**

Area between electrograms and a template of sinus rhythm expressed as a percent of the total area of the template

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Infranodal conduction</th>
<th>Sinus rhythm electrograms</th>
<th>Ventricular tachycardia electrograms</th>
<th>Sinus rhythm electrograms</th>
<th>Ventricular tachycardia electrograms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bipolar</td>
<td>Unipolar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Normal</td>
<td>84.5</td>
<td>232</td>
<td>98.1</td>
<td>423</td>
</tr>
<tr>
<td>2</td>
<td>Normal</td>
<td>28.3</td>
<td>101</td>
<td>26.1</td>
<td>109</td>
</tr>
<tr>
<td>3</td>
<td>ICLBBB</td>
<td>40.2</td>
<td>117</td>
<td>28.5</td>
<td>236</td>
</tr>
<tr>
<td>4</td>
<td>Normal</td>
<td>25.9</td>
<td>193</td>
<td>8.4</td>
<td>83.3</td>
</tr>
<tr>
<td>5</td>
<td>LBBB</td>
<td>53.3</td>
<td>203</td>
<td>56.4</td>
<td>210</td>
</tr>
<tr>
<td>6</td>
<td>Normal</td>
<td>14.9</td>
<td>230</td>
<td>33.9</td>
<td>367</td>
</tr>
<tr>
<td>7</td>
<td>Normal</td>
<td>7.65</td>
<td>50.1</td>
<td>2.72</td>
<td>128</td>
</tr>
<tr>
<td>8</td>
<td>LAFB</td>
<td>28.6</td>
<td>82.3</td>
<td>15.8</td>
<td>98.5</td>
</tr>
<tr>
<td>9</td>
<td>LBBB</td>
<td>15.6</td>
<td>80.5</td>
<td>1.4</td>
<td>16.7</td>
</tr>
<tr>
<td>10</td>
<td>Normal</td>
<td>16.0</td>
<td>56.6</td>
<td>27.9</td>
<td>146</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>31.5</td>
<td>135</td>
<td>29.9</td>
<td>182</td>
</tr>
</tbody>
</table>

p<.0001  p<.0001

ICLBBB = incomplete left bundle branch block; LBBB = left bundle branch block; LAFB = left anterior fascicular block.
forcing the importance of the low-frequency, far-field portion of the signal. The size of the sampling window used in this study was 80 msec (40 msec before and after the point of maximal amplitude). Sampling intervals less than 80 msec made the area of difference algorithm less reliable, suggesting once again that the far-field activity occurring at the beginning and end of this signal contributes to the morphologic difference between ventricular and sinus electrograms.

Limitations of the study. An important limitation of this study is the exclusive use of electrograms recorded from temporary electrode catheters. The evolution of the electrogram from a permanent pacing lead has been characterized and involves a decrease in amplitude and slew rate. Preliminary data from our laboratory suggest that the discriminating power of the area of difference method is maintained with permanent pacing leads implanted in animals. The technique needs to be evaluated in patients with implanted leads.

The utility of frequency spectra as a method of detecting ventricular rhythms was not analyzed in this study. Although there is a significant difference between the center frequencies of ventricular and sinus electrograms, there is considerable overlap for individual patients, limiting the reliability of this variable. Moreover, real-time analysis of frequency spectra is currently beyond the capability of implantable devices.

The sensitivity of the area of difference method was 100% in the 10 patients we studied. A high specificity is also mandatory if such an algorithm is to be useful in an implanted device. Although effects of rate-related aberration were not assessed directly in this study, chronic bundle branch block did not impair the sensi-
TABLE 3
Effects of sample rate, filtering, and window size on the reliability of the area of difference method of rhythm identification

<table>
<thead>
<tr>
<th>Sample rate</th>
<th>Bipolar electrograms</th>
<th>Unipolar electrograms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>500 Hz</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>250 Hz</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Filtering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.04–5 kHz</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>5–80 Hz</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>10–80 Hz</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>20–80 Hz</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Sample window size (msec)</td>
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<td></td>
</tr>
<tr>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>+ 20 b</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>− 20 c</td>
<td>60</td>
<td>90</td>
</tr>
</tbody>
</table>

aPercentage of patients for whom all ventricular tachycardia electrograms were unambiguously identified.
bSample window from 20 msec before the point of peak amplitude to the point of peak amplitude.
cSample window from the point of peak amplitude to 20 msec after the point of peak amplitude.

tivity of the technique. In addition, animal studies have shown that electrogram morphology during rate-related bundle branch block is different from both sinus rhythm and ventricular tachycardia. Therefore, if a template of a bundle branch block electrogram were used along with the sinus rhythm template, all electrograms could be correctly classified.

In conclusion, discrete characteristics of the endocardial electrogram are not sufficient to unambiguously differentiate ventricular from supraventricular complexes. By quantitating the difference in morphology between a given electrogram and a template of a sinus complex, ventricular tachycardia could be unambiguously differentiated from sinus rhythm in all 10 patients we studied. Such morphologic techniques may be useful methods for recognition of ventricular tachycardia by implantable devices.

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