Differentiation of Ventricular Tachyarrhythmias

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Implantable devices capable of several modes of therapy will require differentiation of various ventricular tachyarrhythmias. Three methods of arrhythmia analysis, magnitude-squared coherence, ventricular rate, and irregularity of cycle length were performed for 45 episodes of induced ventricular tachyarrhythmia in 15 patients. Differentiation of monomorphic ventricular tachycardia from polymorphic ventricular tachycardia and ventricular fibrillation was possible by mean magnitude-squared coherence, less possible by rate, and not possible by beat-to-beat irregularity. Faster monomorphic ventricular tachycardia overlapped with rates of polymorphic ventricular tachycardia and ventricular fibrillation. Differentiation of polymorphic ventricular tachycardia and ventricular fibrillation was not possible by rate or irregularity. A progressive decrease in mean magnitude-squared coherence from monomorphic ventricular tachycardia to polymorphic ventricular tachycardia to ventricular fibrillation strengthens previous observations that coherence is a measure of rhythm “organization.” (Circulation 1990;82:2035–2043)

Electrical devices have proved to be an effective method of therapy for several tachyarrhythmias. The proper functioning of these devices requires not only that the device be capable of administering effective therapy but that the device also properly identify the presence of an arrhythmia. A new generation of these electronic devices will be capable of several modes of therapy, each appropriate for specific ventricular tachyarrhythmias. Such a device must therefore have some scheme that will allow it to detect the presence of, and differentiate between, these different tachyarrhythmias. Specifically, a device that would administer pacing or cardioversion for monomorphic ventricular tachycardias and high-energy defibrillation for polymorphic ventricular tachycardia and ventricular fibrillation would be desirable. A programmable rate algorithm has been proposed as the detection criteria by which the device will differentiate between these ventricular tachyarrhythmias, but there has been no published formal examination of this proposed criteria in a series of ventricular tachyarrhythmias.

On a more theoretical level, we have proposed that the coherence function might quantify the degree of “organization” of a cardiac arrhythmia. Previously, we have shown that fibrillation in the atria or ventricles, traditionally considered to be unorganized rhythms, have low coherence, whereas sinus rhythm, atrial flutter, paroxysmal supraventricular tachycardia, or monomorphic ventricular tachycardia, traditionally considered to be organized rhythms, have very high coherence.

In the present study, we have applied this analysis to a much larger sample of monomorphic ventricular tachycardia and ventricular fibrillation to confirm our previous observations of high and low coherence for organized and disorganized rhythms, respectively. An important addition is the inclusion of polymorphic ventricular tachycardia, a rhythm subjectively considered to have a level of organization intermediate between that of monomorphic ventricular tachycardia and ventricular fibrillation. If the coherence of polymorphic ventricular tachycardia were also intermediate, our confidence in the coherence function as a useful measure of rhythm organization would be increased.

Therefore, in the present study, we have analyzed a spectrum of ventricular tachyarrhythmias for magnitude-squared coherence (MSC), ventricular rate, and irregularity of cycle length.

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Methods

Recordings

Simultaneous ventricular recordings from two bipolar electrodes were made in those patients who exhibited sustained monomorphic ventricular tachycardia, polymorphic ventricular tachycardia, or ventricular fibrillation, or any combination of these events during electrophysiological testing (EP) or automatic implantable cardioverter/defibrillator (AICD) implantation, or during both. Rhythms were identified by using standard surface electrocardiographic criteria. During electrophysiological testing, two 6F quadripolar temporary pacing catheters (USCI, Billerica, Massachusetts) were introduced percutaneously through a femoral vein and positioned in the right ventricular apex and outflow tract, respectively (12 monomorphic ventricular tachycardia, four polymorphic ventricular tachycardia, and four ventricular fibrillation). The interelectrode spacing was 1 cm and the interbipole spacing was a few centimeters. During AICD (CPI, St. Paul, Minnesota) implantation (six monomorphic ventricular tachycardia, 11 polymorphic ventricular tachycardia, and eight ventricular fibrillation), one bipole consisted of the rate-sensing electrodes, a pair of ventricular screw-in epicardial leads (model 0030, CPI) with approximately 1-cm interelectrode distance. The second “bipole” consisted of right and left ventricular epicardial patches (model 0040 and/or 0041, CPI). The epicardial patch configuration, which encompasses a large surface area of the ventricles, does not record a standard bipolar electrogram. We have nonetheless referred to these recordings as bipolar for simplicity. Previously, our laboratory has shown that coherence measures for both fibrillatory and nonfibrillatory rhythms are similar for the EP bipolar and AICD bipolar lead configurations.

Two bipolar ventricular electrograms (0.05–5000 Hz) as well as surface leads II and V1 were amplified and recorded with an electrophysiological recorder (Honeywell VR16, Electronics for Medicine, Honeywell, Pleasantville, New York). The data were stored on frequency modulation tape (Honeywell 101, Electronics for Medicine, Honeywell).

Preprocessing

Data were played back through an antialiasing filter with a cutoff frequency of 200 Hz, given appropriate gain, and digitized at 1,200 Hz. Surface leads II and V1 and the two ventricular electrograms were digitized simultaneously. Up to 60 seconds of continuous data were digitized for each rhythm. Data analysis was performed on a Masscomp MCS-563 computer system (Concurrent Computer, Triton, New Jersey) and a Macintosh IIX (Apple Computer, Cupertino, California).

Rhythm Classification

The digitized rhythms were labeled, using surface leads II and V1 by two independent observers, as monomorphic ventricular tachycardia, polymorphic ventricular tachycardia, and ventricular fibrillation. The observers were blinded to the intracardiac electrograms. Monomorphic ventricular tachycardia was defined as ventricular tachycardia having a constant QRS morphology, and polymorphic ventricular tachycardia was defined as ventricular tachycardia having variable QRS morphology but with discrete QRS complexes on the surface electrocardiogram. Ventricular fibrillation was defined by undulations that were irregular in timing and morphology without discrete QRS complexes, ST segments, or T waves.

Intracardiac Lead Morphology

Once the tachycardia was classified by using surface electrocardiographic criteria, the two intracardiac leads for each rhythm were inspected. Specifically, the morphology (existence of discrete ventricular electrograms) and timing in each intracardiac lead were compared with that of the surface leads, and qualitative differences between the three rhythm classes were noted.

Coherence Analysis

The coherence function is a frequency domain measure of the similarity of two signals. The MSC, which is a function of frequency, is defined as follows:

\[ MSC(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \]

where \( x(t) \) and \( y(t) \) are the two simultaneous bipolar recordings, \( S_{xx} \) is the cross-power spectrum of signals \( x \) and \( y \) averaged over several segments of \( x \) and \( y \), and \( S_{xy} \) and \( S_{yy} \) are the individual power spectra of signals \( x \) and \( y \) averaged over the same segments. Two linearly related signals (in the absence of noise) will have a coherence function equal to 1 at all frequencies, whereas two random uncorrelated signals will have a coherence function equal to 0.

The two ventricular electrograms for each rhythm were analyzed for coherence spectra as previously described for our laboratory. The data were digitally filtered at 60 Hz by using a three-pole, low-pass Butterworth filter. Data were then reduced to 120 Hz by extracting every 10th point. For each rhythm, the first 4.27 seconds after onset of the rhythm (and stabilization of the intracardiac signals) were analyzed for MSC. The data were divided into 31 \( \times \) 32-point segments, and the coherence function was determined for each rhythm by using 32-point fast Fourier transforms with a 50% overlap of adjacent segments. The MSC in the 0–60 Hz region was retained for analysis. The mean MSC in the 0–60 Hz band was then determined for each rhythm.

Rate and Irregularity Analysis

For each rhythm, the same 4.27-second segment analyzed for MSC was additionally analyzed for rate and irregularity. The data recorded from the right ventricular apex or the rate-sensing leads were ana-
alyzed for rate (in the case of the electrophysiological lead configuration, rate calculated from the right ventricular outflow tract did not alter the results). For each rhythm, the digitized data were first high-pass filtered at 30 Hz and then reduced to 240 Hz by extracting every fifth point. The mean of the data was subtracted in each 4.27-second segment, and the absolute value of each data point was used for rate calculation. Rate was calculated as previously described.25,26 Briefly, an amplitude threshold was set to 10% of the third maximum electrogram amplitude above which electrograms were detected as previously described. Rate was initially calculated by using two different thresholds (10% and 30%) in combination with three different blanking periods (50 msec, 100 msec, and 150 msec). Blanking period is defined as that portion of the signal after the detection of an electrogram during which detection is inhibited. The results for rate calculated by using the 10% threshold in combination with the 150-msec blanking period will be reported here because the authors found that this combination provided the best separation between monomorphic ventricular tachycardias versus the polymorphic ventricular tachycardias and ventricular fibrillation. Additionally, this combination did not result in any “double counting” for the monomorphic rhythms. The mean cycle length between detected electrograms was determined as well as the standard deviation from this mean. Rate was defined as the reciprocal of mean cycle length. Irregularity was defined by the ratio of cycle-length standard deviation to mean cycle length, expressed as a percentage.

Statistics

Student’s t tests were used to compare the calculated mean MSC, rate, and irregularity in cycle length between the three classes of ventricular arrhythmias for both lead configuration combined and within each lead configuration.

Results

Fifteen patients comprised the study population. The patients’ ages ranged from 43 to 75 years (mean, 62±9 years). Clinical diagnoses, indications for study, the presence or absence of antiarrhythmic drugs, and the clinical procedure (and thus, the nature of the bipoles) are described in Table 1.

Forty-five rhythms from the 15 patients were analyzed for MSC and ventricular rate. Overall interobserver agreement for rhythm classification was 84%. Although there was 100% agreement for the 18 of these rhythms classified as monomorphic ventricular tachycardia, there was initially only 74% agreement on those rhythms classified as polymorphic ventricular tachycardia or ventricular fibrillation. Thus, for seven cases, there was not a clear morphological division between rapid polymorphic ventricular tachycardia and coarse ventricular fibrillation. Consensus was reached between the two observers, yielding 15 examples of polymorphic ventricular tachycardia and 12 examples of ventricular fibrillation. Figure 1 provides an illustration of typical recordings for each rhythm class.

Endocardial and Epicardial Lead Morphology

For those rhythms classified as monomorphic ventricular tachycardia, both endocardial or epicardial leads showed discrete electrograms of constant morphology in all cases. As expected, the ventricular electrograms in the rate-sensing lead were much narrower than the ventricular electrograms of the patch leads. For the polymorphic ventricular tachycardias, the leads usually demonstrated discrete electrograms with a changing electrogram morphology in both leads (nine examples). In four cases, however, one of the two leads demonstrated electrograms of constant morphology. In two examples classified as polymorphic ventricular tachycardia, one of the intracardiac leads showed the absence of both discrete electrograms and an isoelectric baseline. Conversely, for those rhythms classified as ventricular fibrillation, one or both leads showed either the absence of discrete electrograms or discrete electrograms of changing morphology. In no example did a single intracardiac lead show monomorphic electrograms.

Coherence Analysis

Monomorphic ventricular tachycardias typically exhibited moderate to high levels of coherence throughout the 0–60-Hz band (Figure 2). Coherence spectra for the polymorphic ventricular tachycardias tended to have low to moderate levels of coherence (Figure 2), intermediate between monomorphic ventricular tachycardia and ventricular fibrillation. Ventricular fibrillation typically exhibited low levels of coherence throughout the 0–60-Hz band (Figure 2).

The mean MSC for the 0–60-Hz band ranged from 0.12 to 0.87 (mean±SD, 0.56±0.19) for the 18 monomorphic ventricular tachycardias, from 0.06 to 0.29 (0.13±0.07) for the 15 polymorphic ventricular tachycardias (p<0.0005 compared with monomorphic ventricular tachycardia), and from 0.03 of 0.09 (0.05±0.02) for the 12 examples of ventricular fibrillation (p<0.0005 compared with monomorphic ventricular tachycardia, and p<0.005 compared with polymorphic ventricular tachycardia) (Figure 3).

As is evident in Figure 3, only one example of monomorphic ventricular tachycardia had a mean coherence that was less than the upper limit of mean MSC for the polymorphic ventricular tachycardias. This example of monomorphic ventricular tachycardia was more rapid than the others (rate, 333 beats/min). Despite this one example, there was no overlap in mean MSC between any of the monomorphic ventricular tachycardias and those examples of ventricular fibrillation.

An additional observation was the spontaneous degeneration of polymorphic ventricular tachycardia to ventricular fibrillation in one episode of ventricular tachyarrhythmia in one patient (Figure 4). Note that the mean MSC decreases from 0.10 to 0.04 as the
TABLE 1. Patient and Procedure Description

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yr)</th>
<th>Diagnosis</th>
<th>Antiarrhythmic medication</th>
<th>Clinical event</th>
<th>Rhythm recorded</th>
<th>Lead</th>
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<td>MVT</td>
<td>VF</td>
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<td>VF</td>
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<td>VF</td>
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<td>MVT</td>
<td>AICD</td>
</tr>
<tr>
<td>15</td>
<td>71</td>
<td>CAD</td>
<td>None</td>
<td>MVT</td>
<td>EP</td>
<td></td>
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</tbody>
</table>

MVT, monomorphic ventricular tachycardia; VF, ventricular fibrillation; AICD, automatic implantable cardioverter/defibrillator; CAD, coronary artery disease; Abort SD, aborted sudden death; PMVT, polymorphic ventricular tachycardia; EP, electrophysiology testing.

Rhythm changes from polymorphic ventricular tachycardia to ventricular fibrillation.

Rate and Irregularity Analysis

As expected, the calculated rates for most examples of monomorphic ventricular tachycardia were considerably lower than those for polymorphic ventricular tachycardia or ventricular fibrillation. Unlike mean MSC, however, there was considerable overlap between the rapid monomorphic ventricular tachycardias and both polymorphic ventricular tachycardia and ventricular fibrillation. Most overlap in rate among the three groups occurred with faster monomorphic tachycardias induced during defibrillation testing of the AICD.

The calculated ventricular rate ranged from 114 to 333 beats/min (230±55 beats/min) for the 18 monomorphic ventricular tachycardias, from 152 to 373 beats/min (317±54 beats/min) for the 15 polymorphic ventricular tachycardias (p<0.0005 compared with monomorphic ventricular tachycardia), and from 274 to 384 beats/min (329±35 beats/min) for the 12 examples of ventricular fibrillation (p<0.0005 compared with monomorphic ventricular tachycardia but p>0.1 compared with polymorphic ventricular tachycardia) (Figure 3).

There was no significant difference in calculated beat-to-beat irregularity between the three rhythm classes. The calculated irregularity in beat-to-beat intervals ranged from 2% to 27% (12±9%) for the 18 monomorphic ventricular tachycardia, from 2% to 32% (16±10%) for the 15 polymorphic ventricular tachycardia (p>0.1 compared with monomorphic ventricular tachycardia), and from 8% to 30% (14±6%) for the 12 examples of ventricular fibrillation (p>0.1 compared with monomorphic ventricular tachycardia and p>0.1 compared with polymorphic ventricular tachycardia) (Figure 3).

Discussion

The ideal implantable antiarrhythmia device should be capable of several modes of therapy including antiarrhythmia pacing, low-energy cardioversion, and high-energy defibrillation. Patients often experience more than one form of ventricular tachyarrhythmia (e.g., both monomorphic ventricular tachycardia and ventricular fibrillation), and these different arrhythmias may require different therapies. Having several modes of therapy is only advantageous if an accurate decision can be made regarding which therapy to use in a given instance. This requires sensitive and accurate detection algorithms that can differentiate among the various tachyarrhythmias.
Presently, a major limitation of automatic devices is relatively primitive arrhythmia detection schemes. A proposed strategy for antitachycardia devices is to apply a programmable rate criterion to separate ventricular tachycardia from ventricular fibrillation.20,21 Overlap in rates between pathological and nonpathological tachycardias and the sensitivity of rate measurements to signal amplitude and morphology, however, result in these devices inappropriately administering therapy for supraventricular tachycardias, atrial fibrillation, sinus tachycardia, and other spurious indications.9,16,18,19,28–38

Thus, devices using a rate criterion may or may not be sophisticated enough to differentiate between monomorphic ventricular tachycardia, polymorphic ventricular tachycardia, and ventricular fibrillation.

Our data suggest that such a strategy may be reasonable because most polymorphic ventricular tachycardia and ventricular fibrillation have detected rates faster than most monomorphic ventricular tachycardia. The overlap in rates between these three groups was minimal, and we suspect that such a simple measure may indeed work well in a device with a combination of therapies. The overlap in rates occurred between
the faster monomorphic ventricular tachycardias and polymorphic ventricular tachycardia/ventricular fibrillation. With such a strategy, the device might occasionally deliver a high-energy shock, when rapid pacing or a low-energy shock would have sufficed. Because very rapid monomorphic ventricular tachycardia will tend to be hemodynamically unstable, this is not unreasonable. Burst pacing or cardioversion, however, may be quite effective for these rapid tachycardias. Winkle\textsuperscript{17} reports that 80% of stable morphology ventricular tachycardias can be terminated by using energies of 1–5 J. If low-energy cardioversion were the therapy of choice for those faster rate monomorphic ventricular tachycardias, then rate criteria would fail to separate such rhythms from ventricular fibrillation, polymorphic ventricular tachycardia (for which low-energy cardioversion is much less likely to be successful), or both, whereas coherence may succeed. Our study does not address the efficacy of different modes of therapy in relation to coherence spectra.

Olson and colleagues\textsuperscript{39} and Ripley et al\textsuperscript{40} propose that the addition of irregularity criteria can increase the specificity of rate criterion for differentiation of ventricular tachycardia from ventricular fibrillation. In this study, we were surprised to find that irregularity did not differ significantly between the three rhythm groups. In those cases in which there was overlap in rate between monomorphic ventricular tachycardia and the other two rhythm classes, irregularity did not allow further differentiation in all cases. The reason for this surprising finding is unclear. Our measurements were made during the early periods after onset of the tachycardia (which is when a device would have to function). Geibel and coworkers\textsuperscript{41} suggest that at the onset of many tachycardias, the cycle length is unstable. This may explain the irregular monomorphic ventricular tachycardia. Additionally, the fixed blanking period combined with the rapid rates for ventricular fibrillation may limit the irregularity measured for this rhythm.

In this study, we used coherence spectra to differentiate between these three classes of ventricular tachyarrhythmias and compared the potential of this technique to the potential of rate analysis. Unlike rate analysis, probability density functions and several other proposed algorithms,\textsuperscript{25,42–54} coherence spectra are not dependent on amplitude and morphology. Additionally, coherence spectra may perform better than traditional power spectra because information is being gathered from more than a single site. We found that for several polymorphic ventricular tachycardias, one of the intracardiac leads (the rate-sensing lead for the AICD configuration) showed discrete electrograms of constant morphology, which may be interpreted by rate or power spectral analysis as monomorphic ventricular tachycardia. Such a tachycardia, however, may be unlikely to respond to pacing. We found that mean MSC provided a better separation of monomorphic ventricular tachycardia from polymorphic ventricular tachycardias and ventricular fibrillation than rate analysis.

**Rhythm Organization**

Our interest in coherence goes beyond any potential practical application for antiarrhythmic devices. We have proposed that MSC might provide a measure of the organization of a cardiac rhythm. Previously, we have shown that mean MSC was very high for those rhythms typically considered to be organized (sinus rhythm, atrial flutter, paroxysmal supraventricular tachycardia, and monomorphic ventricular tachycardia), and very low for those rhythms considered to be disorganized (atrial fibrillation and ventricular fibrillation).\textsuperscript{22} In this study, we extended these observations to a much larger
sample of ventricular arrhythmias. We further investigated the use of coherence in measuring rhythm organization by including a ventricular rhythm, namely, polymorphic ventricular tachycardia, that is subjectively thought of as intermediate in organization. Results indicate that although there was some overlap in mean MSC between polymorphic ventricular tachycardia and ventricular fibrillation, there was a significantly higher coherence for polymorphic ventricular tachycardia than for ventricular fibrillation. Figure 4 illustrates the decrease in mean MSC as one patient’s tachycardia degenerates from polymorphic ventricular tachycardia to ventricular fibrillation. This intermediate coherence for polymorphic ventricular tachycardias suggests that the clinical impression of intermediate organization in polymorphic ventricular tachycardia is correct. Conversely, these results strengthen our impression that MSC quantifies rhythm organization, and that the concept of coherence may therefore prove useful in a number of other areas of electrophysiological research.

**Potential Problems**

Although rate analysis lacks sophistication, it appears simple to implement and requires little computation time and energy. Its dependence on amplitude and morphology, however, will require considerable tailoring of the rate algorithm for each patient. Automatic gain control has been necessary in implantable devices because the progression of ventricular fibrillation is associated with a pronounced decrease in signal amplitude.\textsuperscript{36,55} Automatic gain control, however, has itself introduced occasional problems.\textsuperscript{36} Additionally, we have recently shown that calculated “rate” during fibrillation is quite sensitive to lead configuration and antiarrhythmic drug administration.\textsuperscript{26,56} This will introduce potential problems because any specific rate algorithm may require adjustment for each rate-sensing lead configuration and adjustment for new leads as they are developed.

In contrast, we have shown previously that coherence spectra are not sensitive to lead configuration.\textsuperscript{22} Furthermore, coherence measurements do not require explicit event detection as rate does. Calculation of coherence spectra may require considerable more time and energy than calculation of rate. The magnitude of this requirement necessitates further technological advances before such a method can be practical. We have shown, however, that a 4.27-second segment is adequate for analysis. As fast Fourier transforms are implemented in hardware\textsuperscript{57} and as battery technology improves, it may become practical to implement MSC. Additionally, simplifying the numerical computation of coherence and reducing the number of frequencies analyzed might reduce the time and energy requirements of this technique. Our laboratory is currently addressing these issues.

Like rate analysis, coherence measurements fail to explain hemodynamic consequences during ventricular tachyarrhythmias. Sophisticated antiarrhythmic devices will have to incorporate hemodynamic measurements into their decision-making processes. For example, a high-energy shock may be more appropriate than pacing for a rapid monomorphic ventricular tachycardia that results in syncope, whereas such a shock would be inappropriate and
painful for the patient who remains conscious during accelerated tachycardias.

Acknowledgment
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