The Coherence Spectrum
A Quantitative Discriminator of Fibrillatory and Nonfibrillatory Cardiac Rhythms

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Previous work has suggested that a comparison of electrograms from two or more sites may best differentiate fibrillatory from nonfibrillatory rhythms. The coherence spectrum is a measure by which two signals may be compared quantitatively in the frequency domain. In the present study, the coherence spectrum was used to quantify the relation between spectral components of electrograms from two sites in either the atrium or ventricle during both fibrillatory and nonfibrillatory rhythms. Bipolar recordings of 35 rhythms from 20 patients were analyzed for coherence in the 1–59 Hz band. The 17 nonfibrillatory rhythms were sinus rhythm (six), paroxysmal supraventricular tachycardia (two), atrial flutter (four), and monomorphic ventricular tachycardia (five). The 18 fibrillatory rhythms were atrial fibrillation (12) and ventricular fibrillation (six). Nonfibrillatory rhythms exhibited moderate-to-high levels of coherence throughout the 1–59 Hz band, with peaks concentrated at the rhythm’s fundamental frequency and its harmonics. Fibrillatory rhythms exhibited little coherence throughout the 1–59 Hz band, and harmonics were not evident. The mean magnitude-squared coherence (scale of 0 to 1) for the 1–59 Hz band ranged from 0.22 to 0.86 (mean±SD, 0.52±0.19) for nonfibrillatory rhythms and from 0.042 to 0.12 (0.067±0.021) for fibrillatory rhythms. Separation of fibrillatory and nonfibrillatory rhythms was possible whether signals were recorded by floating or fixed-electrode configurations. These findings indicate that comparison of two electrograms with magnitude-squared coherence measurements differentiates fibrillatory from nonfibrillatory rhythms. A recognition algorithm based on coherence spectra may be robust in the face of major variations in lead configuration. Furthermore, the coherence spectra may provide a means to quantify the “organization” or “disorganization” of a cardiac rhythm. (Circulation 1989;80:112–119)

Fibrillatory rhythms are typically described as “chaotic” and “disorganized.” More specifically, the activity from multiple sites during fibrillation has been described as asynchronous and incoordinate. Allessie et al have suggested that the comparison of activity from two or more sites may best differentiate fibrillatory from nonfibrillatory rhythms. While this “altered spatial arrangement of conduction” is quintessential to fibrillation, this qualitative characteristic remains to be quantified. Previous studies have used frequency domain analysis of intracardiac electrograms to discriminate fibrillatory from nonfibrillatory rhythms. However, such studies only quantify activity from a single recording site. The coherence spectrum is a frequency domain measure that may be used to make a quantitative comparison between activity recorded from two sites.

In the present study, coherence spectra were used to quantify the relation between spectral components of electrograms from two sites in the atrium or two sites in the ventricle during fibrillatory and nonfibrillatory rhythms. It was hypothesized that the coherence spectrum would provide a measure of the synchrony and coordination between multiple sites, and thus be indicative of rhythm organization. Such a measure would be a useful tool in the characterization and detection of fibrillatory rhythms. Coherence measurements may provide a means to quantify the terms “organized” and “disorganized” as applied to cardiac arrhythmias. In addition, tachycardia recognition algorithms via...
coherence criteria may contribute to improved function of antitachycardia devices. Specifically, the rate and probability density function criteria currently used by the automatic implantable cardioverter-defibrillator cannot discriminate rapid but organized ventricular tachycardia from ventricular fibrillation, even though pacing or low-energy shocks may be appropriate initial therapy for tachycardia but not for fibrillation.

Methods

Recordings

Simultaneous recordings from two bipoles, both in either the atrium or ventricle, were made in those patients who exhibited fibrillatory or nonfibrillatory rhythms (>8.5 seconds) during hemodynamic catheterization, electrophysiologic testing, automatic implantable cardioverter/defibrillator (AICD) implantation, or a combination. (It should be understood that the epicardial patch configuration, which encompasses a large surface area of the ventricles, does not record a standard “bipolar” electrogram as is routinely recorded. We have, nonetheless, referred to these recordings as “bipolar” for simplicity.) Rhythms were identified with standard surface electrocardiographic criteria. During hemodynamic catheterization or electrophysiologic testing, 6F or 7F quadrupolar temporary pacing catheters (USCI, Billerica, Massachusetts) were introduced percutaneously via a femoral vein and positioned in the right atrium (12 atrial fibrillation, four atrial flutter, and two paroxysmal supraventricular tachycardia [PSVT]) or in the right ventricle (four sinus rhythm, three monomorphic ventricular tachycardia, and two ventricular fibrillation). The interelectrode spacing was 1 cm. The interbipole spacing was 2 cm for recordings made in the atrium. For those recordings made in the ventricle, two separate catheters were used, and the interbipole spacing was on the order of centimeters. During AICD (CPI, St. Paul, Minnesota) implantation, one bipoles 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 ventricle epicardial patches (model 0040 or 0041, CPI) (two sinus rhythm, four ventricular fibrillation, and two monomorphic ventricular tachycardia).

Two unfiltered (0.05–5,000 Hz) bipolar atrial or ventricular electrograms as well as surface leads II and V1, and the two atrial or ventricular electrograms were digitized simultaneously. Up to 60 seconds of continuous data were digitized for each rhythm. All data analysis was performed on a Masscomp MCS-563 computer system (Massachusetts Computer, Littleton, Massachusetts).

Coherence Spectra

The coherence function is a frequency domain measure of the similarity of two signals. The magnitude-squared coherence function (MSC), which is a function of frequency, is defined as

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

where \(x(t)\) and \(y(t)\) are the two simultaneous bipolar recordings, \(S_{xy}\) is the cross-power spectrum of signals \(x\) and \(y\) averaged over several segments of \(x\) and \(y\), and \(S_{xx}\) 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 one at all frequencies, while two random, uncorrelated signals will have a coherence function equal to zero. Additive, uncorrelated noise and system nonlinearities will reduce the coherence function for similar signals. As an example (Figure 1), a coherence function is presented for two signals; signal X consists of a 10 Hz sine wave to which random noise is added, and signal Y consists of a 10 Hz sine wave and a 27 Hz sine wave to which random noise is added. The autopower spectra, \(S_{xx}\) and \(S_{yy}\), for these two signals exhibit peaks at 10 Hz, and at 10 Hz and 27 Hz, respectively. As would be expected, the MSC for these two signals exhibits a large peak at 10 Hz (the only frequency component common to both signals) and very little magnitude throughout the remainder of the spectrum.

The two bipolar atrial or ventricular electrograms for each rhythm were analyzed for coherence spectra. The data were digitally filtered at 60 Hz with a three-pole, low-pass, Butterworth filter. Data were then reduced to 120 Hz by extracting every tenth point. For those rhythms with a duration of 30–60 seconds (23 rhythms: 11 nonfibrillatory, and 12 fibrillatory), the data were divided into 512-point segments for analysis. For rhythms of duration less than 30 seconds (12 rhythms: six nonfibrillatory, and six fibrillatory), the data were divided into 256-point segments. The accuracy of the estimate of the coherence spectrum is dependent on the number of segments averaged. Thus, for rhythms of short duration, the data must be divided into a greater number of shorter length segments to improve the coherence estimate. However, the segments must be of sufficient length to provide adequate resolution in the spectra. The MSC function was determined for each rhythm using 512-point (or 256-point) fast Fourier transforms with a 50% overlap of adjacent segments. The MSC in the 1–59 Hz
Analysis of Short Data Segments

If coherence spectra were to be used in antitachycardia devices, detection would be required in the shortest amount of time possible for hemodynamically unstable rhythms such as ventricular fibrillation. Thus, coherence spectra were recalculated for each rhythm using only 4.27 seconds (512 points) of data for each rhythm (the first 4.27 seconds after onset of the rhythm were used). The data were divided into 16×32-point segments, and the coherence function was determined for each rhythm with 32-point fast Fourier transforms with a 50% overlap of adjacent segments. The mean MSC in the 0–60 Hz band was determined for each rhythm, and a Student's t test was used to compare the mean for fibrillatory rhythms with that of nonfibrillatory rhythms.

Results

Twenty patients comprised the study population. The patients' ages ranged from 31 to 76 years (mean, 57 years). Clinical diagnosis, indications for study, the presence or absence of cardioactive drugs, and the clinical procedure (and, thus, the nature of the bipoles) are described in Table 1.

Thirty-five rhythms from the 20 patients were analyzed for MSC. Seventeen of these rhythms were nonfibrillatory (six sinus rhythm, two paroxysmal supraventricular tachycardia, five monomorphic ventricular tachycardia, and four atrial flutter). The remaining rhythms were fibrillatory (12 atrial fibrillation and six ventricular fibrillation). The length of data available for analysis for the 35 rhythms ranged from 8.5 to 60 seconds (mean±SD, 43.3±21.7 seconds).

Nonfibrillatory Rhythms

The nonfibrillatory rhythms typically exhibited moderate-to-high levels of coherence throughout the 1–59 Hz band (Figure 2). The regular tachycardias exhibited peaks of coherence at the rhythm's fundamental frequency (i.e., rate) and its harmonics throughout the 1–59 Hz band. Sinus rhythm exhibited high coherence at the lower range and midrange frequencies. The individual peaks (harmonics) were not as clearly discernable in sinus rhythm as they were for regular tachycardias.

The mean MSC for the 1–59 Hz band for the 17 nonfibrillatory rhythms ranged from 0.22 to 0.86 (mean±SD, 0.52±0.19) (Figure 3).

Fibrillatory Rhythms

The coherence spectra for the fibrillatory rhythms typically exhibited little coherence throughout the 1–59 Hz band (Figure 4), and harmonics were not...
TABLE 1. Patient and Procedure Description

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age</th>
<th>Diagnosis</th>
<th>Medications</th>
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<th>Procedure</th>
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<td>1</td>
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<td>Digoxin, amiodarone</td>
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CAD, coronary artery disease; RHD, rheumatic heart disease; WPW, Wolff-Parkinson-White syndrome; PSVT, paroxysmal supraventricular ventricular tachycardia; EP, electrophysiologic testing; Cath, hemodynamic catheterization; AICD, automatic implantable cardioverter/defibrillator.

evident. The mean MSC for the 1–59 Hz band for the 18 fibrillatory rhythms ranged from 0.042 to 0.12 (0.067±0.021) (p<0.0005 compared with nonfibrillatory rhythms) (Figure 3). For this data set, there was no overlap in the mean MSC between fibrillatory and nonfibrillatory rhythms.

Effect of Lead Configuration

Nonfibrillatory rhythms and fibrillatory rhythms were each recorded with floating and fixed-electrode configurations. Thus, the effect on the MSC of recording with very different lead configurations could be examined. The mean MSC for those rhythms recorded with quadripolar pacing catheters ("floating") ranged from 0.22 to 0.86 (0.53±0.18) for nonfibrillatory rhythms and from 0.042 to 0.12 (0.063±0.022) for fibrillatory rhythms (p<0.0005). Similarly, the mean MSC for those rhythms recorded with epicardial screw-in and patch leads ("fixed") ranged from 0.25 to 0.75 (0.46±0.21) for nonfibrillatory rhythms, and from 0.073 to 0.096 (0.082±0.01) for fibrillatory rhythms (p<0.01) (Figure 5). Despite the use of two very different lead configurations, differentiation of fibrillatory from nonfibrillatory rhythms by coherence measurements was maintained.

Analysis of Short Data Segments

Coherence spectra were recalculated for each of the 35 nonfibrillatory and fibrillatory rhythms with a single 4.27-second epoch of data for each rhythm. Although the resolution of the coherence spectra was greatly reduced (3.75 Hz) using such short data segments, the separation of fibrillatory and nonfibrillatory rhythms was similar to that obtained with the long segments of data described above (Figure 6). The mean MSC for the 0–60 Hz band ranged from 0.26 to 0.77 (0.53±0.14) for the 17 nonfibrillatory rhythms and from 0.022 to 0.11 (0.062±0.026) for the 18 fibrillatory rhythms (p<0.0005). There was no overlap in the means between the two groups.

Discussion

Current arrhythmia detection algorithms use single unipolar or bipolar electrode techniques to characterize electrograms.8–13,17–27 These algorithms use shape, duration, and frequency information to characterize waveforms, but their performance is often hampered by overlap between fibrillatory and nonfibrillatory rhythms. Most detection algorithms that incorporate multiple unipolar or bipolar electrode techniques do not attempt to characterize the elec-
FIGURE 2. Shown is the coherence spectra for nonfibrillatory rhythms. The magnitude-squared coherence (MSC) is plotted for examples of sinus rhythm (A), paroxysmal supraventricular tachycardia (PSVT) (B), and ventricular tachycardia (V Tach) (C).

trograms but merely measure relative timing of depolarization between sites or the ratio of atrial events to ventricular events.28-30 Dufault and Wilcox31 proposed a dual lead fibrillation detection system that uses a least-mean square algorithm to measure the relation between electrical activity at two sites.

The coherence spectrum is a technique by which two signals may be compared quantitatively in the frequency domain and is not dependent on actual rate or specific morphology of the signals. Coherence functions are used in the study of electroencephalograms32,33 and electromyograms34 to quantify the relation between signals from multiple sites; how-

FIGURE 3. Shown is the mean magnitude-squared coherence (MSC) for the 1–59-Hz band for the 18 fibrillatory (FIB) and 17 nonfibrillatory rhythms. The fibrillatory rhythms are categorized as atrial fibrillation (AFIB) and ventricular fibrillation (VFIB). The nonfibrillatory rhythms are categorized as sinus rhythm (SR), paroxysmal supraventricular tachycardia (PSVT), atrial flutter (AFLT), and ventricular tachycardia (VT).

ever, this frequency domain measure has received little attention in cardiac arrhythmia analysis.

Coherence as a Quantitative Measure of Rhythm Organization

What is meant by the term “organized” as a descriptor of cardiac rhythms is unclear. However, if it means that there exists temporal synchrony and harmony between multiple sites, then the MSC

FIGURE 4. Shown is the coherence spectra for fibrillatory rhythms. The magnitude-squared coherence (MSC) is plotted for examples of atrial fibrillation (A) and ventricular fibrillation (B).
function may provide a quantitative measure of that organization. The MSC spectrum is insensitive to phase differences between two signals, so long as the phase relations are constant over time. During nonfibrillatory rhythms, multiple sites are being activated in an orderly, coordinated fashion by one or more wavefronts, and the phase relation between activity from two sites is relatively unchanged. Thus, one would expect high coherence for these rhythms. If the mechanism of fibrillation is that of multiple circulating wavelets, then the activity observed at one site would most likely be unrelated (in both timing and morphology) to the activity observed at other distant sites. One would then predict that the coherence between two such sites would be very low at all frequencies due to a continually changing phase relation. In the present study, the MSC was confirmed to be significantly greater for nonfibrillatory rhythms (especially at the fundamental frequency and its harmonics) than for fibrillatory rhythms, thus demonstrating the potential for this type of analysis for automatic recognition of arrhythmias.

Lead Configuration

A major concern for antitachycardia devices is whether changes in lead configuration will hamper performance of their detection algorithms. In particular, there is question as to whether the signals recorded with floating catheters, which are often used for algorithm development, reflect the activity recorded by fixed catheters, which are used in the implanted device. As lead technology improves, with the advent of devices such as the AICD, where the final lead configuration is not known until intraoperative testing, and with the introduction of nonthoracotomy placement of the AICD, it will be inefficient at best to require a new algorithm for each type of lead.

To our knowledge, this is the first study to address this issue by examining coherence of signals recorded with a wide variety of lead configurations. Of special concern were those recordings made with the epicardial patch configuration because it differed so greatly from the usual bipolar recordings. Differences in frequency characteristics due to differences in lead configuration (e.g., patch electrodes versus screw-in electrodes) can be expected to lower coherence estimates. Nonetheless, coherence estimates for all four nonfibrillatory rhythms recorded with the AICD configuration had much higher mean coherence than the fibrillatory rhythms recorded with either the AICD or floating electrode configuration. Such high levels of coherence suggest that the frequency content of signals recorded with the patch electrodes and epicardial screw-in electrodes have enough overlap to give rise to high coherence values for nonfibrillatory rhythms. In the present study, a key feature of the coherence function was that its ability to differentiate nonfibrillatory from fibrillatory rhythms was not altered by changes in lead configuration.

**Analysis of Short Data Segments**

In the first part of our study, we chose long data segments for coherence estimates because we were interested in the details of the coherence spectra that require long segments of data for adequate resolution and accuracy. However, such long segments are clinically impractical for detection of hemodynamically unstable rhythms. Thus, we reanalyzed coherence for these same rhythms using a clinically more practical and uniform segment length. As indicated by the data, the coherence function was able to differentiate nonfibrillatory from fibrillatory rhythms with these short data segments.

We chose to use the mean of the MSC function to quantify differences between nonfibrillatory and fibrillatory rhythms. While the mean is simple to implement and is sufficient to differentiate nonfibrillatory from fibrillatory rhythms, this measure
overlooks a great deal of detailed information within the MSC function.

Potential Limitations

Theoretically, added noise decreases the coherence estimate. The fact that coherence was high in all our nonfibrillatory rhythms suggests that the noise level in our recordings was relatively low. Clearly, any algorithm based on signal analysis will have difficulty performing in the presence of a low signal-to-noise ratio. The presence of interference (e.g., myopotential interference) as opposed to noise may affect coherence very differently than noise, depending on whether the interference is sensed equally by both bipoles. In this case, coherence might even increase because the added frequency content would be similar for both bipoles. How much this interferes with algorithm performance remains to be seen.

Clinical Implications

There has been some question as to whether frequency domain measurements will ever be practical for real-time medical devices because of the requirement for considerable computing resources (time and energy). However, analysis in the frequency domain is a ubiquitous requirement of modern science and it seems reasonable to expect that technology will soon be available to solve these temporary difficulties. For example, TRW LSI Products has introduced a signal-processor chip that can execute a 1024-point FFT in 0.5 msec.36 We have taken the approach that optimizing the hardware to perform real-time analysis is secondary to developing the signal analysis techniques that can accurately detect specific cardiac arrhythmias.

As antiarrhythmic devices become more sophisticated in their ability to deliver several modes of therapy (e.g., pacing, cardioversion, and defibrillation), depending on the specific rhythm and its hemodynamic consequences, accurate discrimination of fibrillation from rapid, potentially pace-terminable tachycardias will be critical. Although we as well as other laboratories have shown that the rate and probability density function currently used in devices can discriminate these rhythms under some circumstances,8,11 these time domain measures have a number of problems, including amplitude threshold dependence,8,11,37-40 breakdown in the presence of antarrhythmic drugs,17 and critical dependence on lead configuration.31,42 As a result, spurious or asymptomatic shocks (or both) remain among the most common clinical problems facing patients with implanted devices.33-45 Because of its independence of amplitude, morphology, and lead configuration, the coherence spectrum is a promising alternative to current detection algorithms.

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