Diagnostic Implications of Spectral and Temporal Analysis of the Entire Cardiac Cycle in Patients With Ventricular Tachycardia

Michael E. Cain, MD; H. Dieter Ambos; Joanne Markham, MS; Bruce D. Lindsay, MD; and R. Martin Arthur, PhD

Background. Available methods for analysis of signal-averaged electrocardiograms (ECGs) have a low-positive predictive accuracy for identifying patients at risk for ventricular arrhythmias. Identification of the spectral and temporal features in ECGs that distinguish patients prone to ventricular tachycardia (VT) is a prerequisite to implementing refinements in methods that increase the diagnostic power of the signal-averaged ECG.

Methods and Results. Fast Fourier transforms and time-domain reconstructions based on inverse fast Fourier transforms were computed over the entire cardiac cycle of signal-averaged ECGs of sinus beats from 40 patients with myocardial infarction and sustained VT, 41 with infarction without VT, and 20 normal controls. Ventricular depolarization and repolarization were analyzed by procedures that obviate limited resolution due to short data segments and window functions. Spectral magnitudes of ECGs from patients in each group were compared, and the phase data were used for time-domain reconstructions to determine the temporal distributions of distinguishing frequency bands during the cardiac cycle. Magnitudes of 1-7-Hz frequencies were increased (from \(p<0.05\) to \(p<0.00001\)), and magnitudes of 13-56-Hz and 70-128-Hz frequencies were decreased (from \(p<0.05\) to \(p<0.00001\)) in the spectra of ECGs from patients with VT compared with patients without VT. Time-domain reconstructions demonstrated that 1-7-Hz frequencies were detectable throughout the QRS complex, ST segment, and T wave in ECGs from each group. The 13-56-Hz and 70-128-Hz frequency bands not only contributed to the terminal QRS and ST segment but were also detectable throughout the QRS complex of ECGs from patients with VT.

Conclusions. Results define new spectral and temporal features in signal-averaged ECGs from patients with VT that are excluded from analysis by available techniques that limit the bandwidth or restrict interrogation to portions of the cardiac cycle. These findings provide an objective basis for developing new indexes for signal-averaged ECG analysis. (Circulation 1991;83:1637-1648)

Time\textsuperscript{1-7} and frequency\textsuperscript{8-17} analysis of the terminal QRS complex of signal-averaged electrocardiograms (ECGs) obtained during sinus rhythm has been a useful first step in the detection of occult electrophysiological abnormalities that distinguish patients with a history of sustained ventricular tachycardia (VT) from patients without a history of VT. Current approaches, however, have a relatively low positive predictive accuracy for prospectively identifying vulnerability to ventricular arrhythmias.\textsuperscript{18-21} Furthermore, there is controversy over the optimal range of frequencies and ECG intervals that should be analyzed. Approaches that limit analysis to the terminal QRS and/or ST segment may, for example, exclude important signals in other ECG intervals that contribute to the differentiation of patient groups. Debate of these issues will continue until the magnitude and phase of frequency components of ECG signals that distinguish patients with from patients without sustained VT are characterized throughout the cardiac cycle with procedures that avoid filters and obviate limited resolution because of short data seg-
Table 1. Characteristics of Patients

<table>
<thead>
<tr>
<th></th>
<th>Normals</th>
<th>No VT</th>
<th>VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>20</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>36±10</td>
<td>58±12</td>
<td>59±10</td>
</tr>
<tr>
<td>Male/female</td>
<td>14/6</td>
<td>24/18</td>
<td>35/5</td>
</tr>
<tr>
<td>MI locus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MI occurrence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote (&gt;4 wk)</td>
<td></td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Recent (2–4 wk)</td>
<td></td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>LV ejection fraction (%)</td>
<td>47±15</td>
<td>32±11</td>
<td></td>
</tr>
<tr>
<td>QRS duration (msec)</td>
<td>120±27</td>
<td>89±11</td>
<td>120±27*†</td>
</tr>
<tr>
<td>Conduction abnormality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBBB</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>RBBB</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>IVCD</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Cardiac cycle length (msec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>805±69</td>
<td>795±96</td>
<td>777±73</td>
</tr>
<tr>
<td>Range</td>
<td>663–984</td>
<td>583–995</td>
<td>639–975</td>
</tr>
</tbody>
</table>

Values are mean±SD. VT, ventricular tachycardia; MI, myocardial infarction; LV, left ventricular; LBBB, left bundle branch block; RBBB, right bundle branch block; IVCD, intraventricular conduction delay (QRS≥120 msec).

*P<0.01 vs. no VT; †P<0.005 vs. normals.

ments and the attenuation of data by window functions. Clarification of these issues is paramount not only in the establishment of standards for methods of analysis but also in the maximization of the diagnostic power of the signal-averaged ECG. Accordingly, spectral estimates of signal-averaged ECGs and time-domain reconstructions based on the inverse fast Fourier transform (FFT) were computed throughout the cardiac cycle to determine the specific range of frequencies and their temporal distribution during the cardiac cycle that distinguish patients with from patients without sustained VT.

Methods

Patients Studied

Signal-averaged ECGs were obtained during sinus rhythm from 40 patients with prior myocardial infarction and spontaneous sustained VT (>30 seconds in duration or associated with hemodynamic collapse), 41 patients with prior myocardial infarction without subsequent sustained VT, and 20 normal controls. Episodes of spontaneous sustained VT were not associated with evidence of an acute myocardial infarction based on premonitory symptoms, an elevation of MB-creatine kinase, or ECG criteria. Left ventricular function was determined by radionuclide or contrast ventriculography. The locus of infarction was determined by standard ECG criteria and the results of ventriculography. No patient was receiving treatment with antiarhythmic drugs at the time of signal averaging. Pertinent clinical features of each patient group are summarized in Table 1. The loci of infarction, intervals from infarction, and left ventricular ejection fractions were comparable between the group of patients with and the group without sustained VT. The durations of the cardiac cycle were comparable among all three groups studied. The mean value for QRS duration was significantly greater for the group with VT compared with values for the group without VT and normal controls.

Data Acquisition and Signal Averaging

Frank X-, Y-, and Z-lead ECGs were recorded during sinus rhythm over a bandwidth of 0.05–470 Hz and amplified 1,000-fold using techniques reported previously.8,22 The amplitudes of the analog ECG signals were optimized to encompass the maximum ±2.5-V input range of the analog-to-digital converter. Optimized signals were digitized at 1 KHz with 12-bit accuracy, providing a 72-dB dynamic range.

The X, Y, and Z ECG signals were averaged after passage through a template recognition program generated from a 3-second display of normal sinus rhythm. All subsequent beats were tested against the template and averaged with a cross-correlation technique described previously.8,22 Data from 100 beats were averaged and stored on floppy disk for further processing. A total of 1,024 sample points were stored, enabling display of the entire cardiac cycle in each patient. The X, Y, and Z leads were monitored continuously in real time during averaging to enable detection of changes in amplitude or grossly noisy signals.

Frequency Analysis of the Entire Cardiac Cycle

Spectral estimates of the entire cardiac cycle of each signal-averaged X-, Y-, and Z-lead ECG were computed using the FFT.23 The averaged ECG signals were displayed, and the beginning and end of the cardiac cycle were identified in the TP segment using computer cursors. The extracted signals represented the natural period of the cardiac cycle (Figure 1). The first and last points of the data interval were isopotential. Accordingly, these initial and final isopotential points defined the zero-signal value, which obviated the need for window functions and eliminated spurious contamination of spectra by direct current components.

Durations of the cardiac cycle ranged from 583 to 995 msec. For analysis with the FFT, the data interval was padded with zeros for a total of 1,024 points. Zero padding does not change the shape of the spectrum. The fundamental and therefore the frequency separation between lines in all cases was fixed at 0.997 Hz. This approach assured that, as long as the signal, regardless of its length, was within the 1,024 samples transformed, the signal’s continuous FFT was sampled at the same frequencies in all patients, enabling straightforward comparisons between patient groups. The magnitudes
of the FFTs were computed and used for all further computations (Figure 1). Spectra were plotted on a laser printer (Lasergrafix printer, model 800, Quality Micro Systems).

**Data Analysis**

The effect of signal gain, used during ECG acquisition, on the FFT magnitude was removed using three independent methods to normalize the data. The measured voltage in each ECG lead was normalized with respect to its peak-to-peak value, its root mean square value, and the average spectral magnitude of its FFT. The discrete-time (sampled) version of the ith voltage was defined as \( v_{i[j]} \), where \( j \) is the sample number. The normalizations were defined as follows: The peak-to-peak (\( p_{[j]} \)) value is given by

\[
p_{[j]} = \frac{v_{i[j]}}{v_{\text{max}} - v_{\text{min}}} \quad (1)
\]

where \( v_{\text{max}} \) and \( v_{\text{min}} \) are the maximum voltages in the cardiac cycle. The root mean square (\( r_{[j]} \)) value is given by

\[
r_{[j]} = \sqrt{\frac{1}{L} \sum_{j=1}^{L} v_{i[j]}^2} \quad (2)
\]

where \( L \) is the number of samples in the cardiac cycle. The average spectral magnitude (\( m_{[j]} \)) is given by

\[
m_{[j]} = \frac{1}{L} \sum_{k=1}^{L} |V_{[k]}| \quad (3)
\]

where \( V_{[k]} \) represents the FFT of \( v_{i[j]} \).

Within each patient group, FFT magnitudes over the bandwidth (0.05–470 Hz) for each of the three normalized versions of all \( X \), \( Y \), and \( Z \) leads were averaged and then compared statistically. Frequencies with magnitudes that differed significantly between patient groups were then reconstructed in the time domain.
Time-Domain Reconstructions

Both magnitude and phase information in the FFT of those frequencies whose magnitudes differed significantly between patients with and without VT were used to compute their temporal distribution during the cardiac cycle. Optimal zero-phase filters designed by the Remez exchange algorithm were used for the time-domain reconstructions to test the hypothesis that distinguishing frequency bands contribute to portions of the ECG in addition to the terminal QRS complex and ST segment. Zero-phase filters introduce no phase distortion and ensure that frequencies passed by the filter are precisely aligned with the original waveform. These passband filters have 255-point impulse responses. This length is required to provide both passband ripple of less than $\frac{1}{4}$ dB and sharp cutoff at the band edges. Stopband attenuation was greater than 32 dB. The frequency response of each filter was multiplied by the FFT over the cardiac cycle. The length of the FFT was increased to 2,048 points by padding with zeros to ensure that the results of the product of FFTs agreed with that given by linear convolution. The filter output was obtained by computing the inverse FFT of the frequency-domain products (Figure 1).

Statistical Analysis

Data were analyzed with a statistical analysis system. Mean magnitude values over the entire bandwidth from each patient group were compared statistically (unpaired t test) line by line. Results of statistical analysis were plotted as a t statistic. The zero-frequency component was not included in the statistical analysis. Data are reported as mean±SD. Significance refers to a value of $p<0.05$.

Results

Spectral Analysis of the Entire Cardiac Cycle

Raw group spectra of the entire cardiac cycle from patients with and without VT and from normal subjects are shown in Figure 2. Each group spectrum is an arithmetic average of magnitude values of individual X, Y, and Z ECGs normalized to the peak-to-peak voltage, the root mean square voltage, and the average FFT magnitude of the cardiac cycle from the 41 patients without VT (123 ECG leads), the 40 patients with sustained VT (120 ECG leads), and the 20 normal controls (60 ECG leads).

Spectral magnitudes over the entire bandwidth from patients with VT were compared statistically line by line with those from patients without VT. Graphs of the t statistics that compare spectral magnitudes of the cardiac cycle normalized to the peak-to-peak voltage, root mean square voltage, and the average FFT magnitude of the cardiac cycle from patients with sustained VT with those values from patients with infarction without VT are shown in Figure 3. Differences in magnitudes were most marked (from $p<0.05$ to $p<0.00001$), with each method of normalization, for frequencies of 1–7 Hz, 13–56 Hz, and 70–128 Hz.

For graphic purposes only, the average magnitude of ECG signals from normal controls at each frequency was set to 0 dB. With each method of

![Figure 2](http://circ.ahajournals.org/)

**FIGURE 2.** Raw group spectra of the entire cardiac cycle normalized to the peak-to-peak voltage, root mean square (RMS) voltage, and average spectral magnitude for patients with ventricular tachycardia (VT) (---), patients without VT (----), and normal controls (---). Each spectrum is an arithmetic average of the fast Fourier transform (FFT) magnitude values of individual X, Y, and Z electrocardiograms from patients in each of the three groups studied. Results of comparison of mean magnitude values over the entire bandwidth from patients with VT and patients with infarction but without VT are shown in Figure 3.
normalization, marked and consistent differences in the spectral plots between patient groups were seen (Figure 4). ECGs from patients with sustained VT showed a marked increase in the magnitudes of 1–7-Hz frequency bands and a marked decrease in the magnitudes of 13–56-Hz and 70–128-Hz frequency bands when compared with ECGs from the group without VT and from normal controls.

These three frequency bands represent the most powerful spectral features that distinguish signal-

Figure 3. Graphs of the t statistics comparing spectral magnitudes from the group of patients with sustained ventricular tachycardia with the group without ventricular tachycardia. Data above or below the shaded portion of each graph identify the individual frequencies with magnitudes that differ significantly (p<0.05) between these groups and distinguish signal-averaged electrocardiograms from patients with sustained ventricular tachycardia from electrocardiograms from patients without ventricular tachycardia. RMS, root mean square.

Figure 4. Group spectra of the entire cardiac cycle normalized to the peak-to-peak voltage, root mean square (RMS) voltage, and average spectral magnitude from patients with and without ventricular tachycardia. Each spectrum is an arithmetic average of the fast Fourier transform (FFT) magnitude values of individual X, Y, and Z electrocardiograms from the group of patients with sustained ventricular tachycardia (lower solid plot) and those without ventricular tachycardia (upper broken plot). For graphic purposes only, the average magnitude of the electrocardiographic signals from normal controls at each frequency was set to 0 dB (dotted line). Electrocardiograms from patients with ventricular tachycardia have more 1–7-Hz frequencies and less 13–56-Hz and 70–128-Hz frequencies compared with electrocardiograms from patients without ventricular tachycardia and normal controls.
Fourier Transform without sustained contributions during VT from 1-7-Hz lead, 1642 Circulation inferi myoccardial without patient Y, excluded from out the time the prior myocardial scalar ECGs.

70-128-Hz frequencies methods.
al-averaging min-estinguishing frequency ECGs averaged Time-Domain Reconstructions 13-56-Hz frequencies, Time-domain reconstructions of 13-56-Hz Representative reconstructions of the 1-7-Hz frequency band. The 1-7-Hz frequency band contributes to the QRS complex, ST segment, and T wave in electrocardiograms from both patients.

averaged ECGs of sinus beats from patients with prior myocardial infarction and subsequent sustained VT from ECGs from patients with prior infarction without sustained VT. Accordingly, these three distinguishing frequency bands were reconstructed in the time domain to determine their temporal distributions during the cardiac cycle.

**Time-Domain Reconstructions Based on the Inverse Fourier Transform**

Representative time-domain reconstructions of 1-7-Hz frequencies that comprise signal-averaged X, Y, and Z ECGs from a patient with and from a patient without VT are shown in Figure 5. In each lead, 1-7-Hz components were detectable throughout the QRS complex, ST segment, and T wave of the scalar ECGs. This distinguishing frequency band is excluded from analysis with currently available signal-averaging methods.

Time-domain reconstructions of 13-56-Hz and 70-128-Hz frequencies that comprise signal-averaged X, Y, and Z ECGs from a patient with remote inferior myocardial infarction and subsequent sustained VT and from a patient with remote inferior infarction without VT are shown in Figure 6. In the X and Y ECGs from the patient with VT, the 13-56-Hz components contributed extensively to the terminal QRS complex. In addition, however, the 13-56-Hz components were also detectable in each lead throughout the QRS complex. These time-domain reconstructions demonstrate not only that the terminal QRS and ST segment of ECGs from patients with VT often contain a relatively large contribution of 13-56-Hz frequencies, consistent with our previous findings based on short segment analysis, but also demonstrate that this distinguishing frequency band contributes to other portions of the QRS complex not analyzed by current signal-averaging methods. The 70-128-Hz components contributed modest energy to the ECG signals of patients with and without VT and were detectable during other portions of the QRS complex in addition to the terminal QRS complex.

The temporal distributions of the 13-56-Hz and 70-128-Hz bands during the cardiac cycle in ECGs from patients with VT were independent of the locus
of myocardial infarction. Peak distributions of the 13–56-Hz frequency band were observed during the early, middle, or terminal portion of the QRS complex. Figure 7 shows time-domain reconstructions of these frequency bands in ECGs from a patient with a remote anterior infarction and subsequent VT and from a patient with remote anterior infarction without VT. The 13–56-Hz and 70–128-Hz frequency bands were detectable throughout the QRS complex.

The temporal patterns of the 13–56-Hz frequency band and 70–128-Hz frequency band in ECGs from patients with VT were also consistent irrespective of the presence or absence of conduction abnormalities during sinus rhythm. Data from a patient with sustained VT in whom right bundle branch block was present during sinus rhythm and from a patient with right bundle branch block but without VT are shown in Figure 8. In the X, Y, and Z ECGs from the patient with VT, 13–56-Hz frequencies were distributed throughout the QRS complex with a major proportion occurring during the terminal QRS. The 70–128-Hz frequencies peaked during the initial to middle portion of the QRS complexes in ECGs from both patients.

**Discussion**

The signal-averaged ECG has been shown to prospectively identify patients convalescing from myocardial infarction who are prone to life-threatening ventricular arrhythmias. Based on results of published studies that limit analysis to the terminal QRS complex, 14–29% of patients recovering from myocardial infarction with abnormal signal-averaged ECGs will experience sustained VT or sudden cardiac death within 1 year compared with only 0.8–4.5% of those in whom the signal-averaged ECG is normal. The relatively low-positive predictive accuracy obtained with current approaches underscores the need for continued refinements of methods for data analysis that will increase the diagnostic power of the signal-averaged ECG to detect patients at high risk of developing life-threatening ventricular arrhythmias.

Key issues in refining methods for analyzing the signal-averaged ECG are complete knowledge of the spectral and temporal features of ECGs that distinguish patient groups. We tested the hypothesis that frequency analysis of the entire cardiac cycle and time-domain reconstructions using the inverse FFT

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**Figure 6.** Time-domain reconstructions of signal-averaged X, Y, and Z electrocardiograms from a patient with remote inferior myocardial infarction and subsequent sustained ventricular tachycardia (right panels) and from a patient with inferior infarction without ventricular tachycardia (left panels). In the X- and Z-lead panels, the signal-averaged electrocardiogram of the natural cardiac cycle recorded over a bandwidth of 0.05–470 Hz (top tracing) is shown along with time-domain reconstructions computed using the inverse fast Fourier transform of the 13–56-Hz (middle tracing) and 70–128-Hz (bottom tracing) frequency bands. The Y-lead panels are organized from top to bottom with 70–128-Hz components, 13–56-Hz components, and the electrocardiogram. In each electrocardiogram, the 13–56-Hz band contributes to many portions of the QRS complex including the terminal QRS complex. The 70–128-Hz components are dispersed throughout the QRS complex and contribute extensively to the terminal QRS and ST segment in some leads.
Features

Additional features identified by frequency analysis of the entire cardiac cycle

In previous studies we have computed spectral estimates of the terminal 40 msec of the QRS complex and ST segment of signal-averaged Frank ECGs and reported differences in the contributions of frequencies less than 120 Hz to ECG signals from patients with and without VT. Indexes of the relative contribution of 20–50-Hz components to the terminal QRS and natural ST segments of individual X, Y, and Z ECGs have been found to be end points that distinguish ECGs from patients with VT and patients without VT irrespective of the presence or absence of bundle branch block patterns during sinus rhythm.

The power of spectral analysis for distinguishing patients with VT has been confirmed by some but not all studies. Worley and coworkers computed the power spectral density and measured the contribution of 20–50-Hz frequencies of several fixed 140-msec data intervals of bipolar X, Y, and Z ECGs beginning at 0, 40, 50, and 60 msec after QRS onset and at 40 and 50 msec before QRS offset. In ECGs from patients with VT, data intervals beginning at 0 and 40 msec after QRS onset had less and the data interval beginning 60 msec after QRS onset had more 20–50-Hz components compared with corresponding ECG intervals from patients without VT. These spectral differences, however, were not powerful discriminators of patient groups.

Machac and coworkers estimated the spectra of the terminal 40 msec of the QRS complex either...
alone or with 216 or 150 msec of the ST segment to determine the contributions of 0–20-Hz, 20–50-Hz, 50–70-Hz, 70–120-Hz, and 120–500-Hz components to these ECG intervals. Spectra of the terminal 40 msec of the QRS complex from patients with VT demonstrated a uniform decrease in energy of all frequency bands compared with spectra from patients without VT. Spectral magnitudes of the terminal QRS plus ST segment did not distinguish patient groups.

In contrast, studies by Haberl and coworkers14 and Pierce and colleagues16 analyzed a fixed 120-msec data interval that comprised the terminal QRS complex and ST segment. Although methods used to define the end of the QRS complex differed, both groups reported that spectra from patients with VT had a marked increase in 60–120-Hz frequencies compared with spectra from patients without VT. These spectral features were powerful discriminators of patient groups. Buckingham and coworkers15 have reported a profound increase in the contribution of 20–50-Hz frequencies to a 140-msec ECG interval that began 60 msec after QRS onset from patients with compared with patients without VT. Recently, Haberl and colleagues17 confirmed altered frequency components over a bandwidth of 50–200 Hz in a 120-msec ECG data interval beginning 20 msec before the end of the QRS complex.

Factors that have contributed to controversies with approaches in the frequency domain have been reviewed recently28 and include analysis of corrected and noncorrected ECG lead systems, limited resolution due to short data segments and window functions, lack of consensus regarding the definition of the terminal QRS complex, analysis of fixed and variable length data intervals, and uncertainty over the appropriate reference for measuring direct current components during the terminal QRS and ST segment. Methodological differences have precluded determination of whether discordant results are due to differences in data processing or conceptual deficiencies with individual approaches.

Results of this study, based on spectral analysis of the entire cardiac cycle, demonstrate distinguishing frequency bands of 1–7-Hz, 13–56-Hz, and 70–128-Hz components in signal-averaged ECGs from
patients with VT. Indexes proposed in each of the earlier studies\textsuperscript{8-17} incorporate some but not all of these altered frequency components. Indexes that we have relied on previously,\textsuperscript{10} for example, exclude 1–7-Hz and 70–128-Hz frequency bands. Time-domain reconstructions based on the inverse FFT demonstrate that these distinguishing frequency bands also contribute to ECG intervals in addition to the terminal QRS complex and ST segment.

A factor that was uncontrolled in this study was QRS duration. The mean duration of the QRS complex was longer and the incidence of conduction abnormalities was greater in ECGs from the group of patients with sustained VT (Table 1). Previous publications from our group\textsuperscript{10} and from others\textsuperscript{14-16} have demonstrated, however, that spectral changes in signal-averaged ECGs distinguish patients with VT regardless of the presence or absence of bundle branch block patterns during sinus rhythm. In addition, line interference precluded definitive determination of the extent to which 60-Hz components also distinguish ECGs from patients with VT. Notch filters were purposely avoided. In other environments it might be possible to test whether 60-Hz components also differentiate patient groups.

We\textsuperscript{8} and others\textsuperscript{12,13,15} have previously analyzed additional ECG regions that include the QRS complex, T wave, and variable portions of the QRS complex and ST segment. Results are inconsistent and reflect the limitations encountered during short segment analysis using window functions as well as limitations of applying end points developed from analysis of one region of the cardiac cycle to other ECG intervals. It is clear, based on the results of this study, that the alterations in both the magnitude and phase of these frequency bands preclude reliance on the same index for different ECG data intervals.

**Additional Features Identified by Time-Domain Reconstructions of the Entire Cardiac Cycle**

Time-domain analysis of the signal-averaged ECG has focused on the detection of occult delayed ventricular activation that persists beyond the end of the scalar QRS complex.\textsuperscript{1-7} Many methods limit analysis to the terminal 40 msec of a filtered, vector magnitude QRS complex. Low-amplitude signals that extend beyond the end of the conventional QRS complex have been detected with 25–250-Hz, 40–250-Hz, 80–250-Hz, and 100–300-Hz bandpass filters. Attempts to optimize the sensitivity and specificity of these methods have been limited to varying the passband. An 80–250-Hz or 100–250-Hz passband maximized sensitivity, whereas specificity was highest with a 25–250-Hz or 40–250-Hz passband.\textsuperscript{7}

Based on results of FFT analysis and time-domain reconstructions during the entire cardiac cycle, distinguishing features during this 40-msec interval of signal-averaged ECGs from patients with VT include 1–7-Hz, 13–56-Hz, and 70–128-Hz frequencies. Only a portion of these distinguishing frequencies are detectable by passbands used with current methods. Moreover, these frequency bands contribute substantially to other portions of the cardiac cycle that are not detectable when analysis is restricted to just the terminal 40 msec of a filtered QRS complex.

**Pathophysiology**

Late potentials on the body surface are a manifestation of delayed activation of myocardium.\textsuperscript{29-31} They have been well characterized in the time and frequency domains. However, the extent to which the alterations in the magnitude and phase of 1–7-Hz, 13–56-Hz, and 70–128-Hz frequencies detected during the terminal QRS complex as well as during other portions of the cardiac cycle are a measure of delayed activation or even the same pathophysiological process has not yet been determined.

Electrophysiological alterations that result from myocardial infarction are complex. Structural changes that are produced by infarction are critical determinants of delayed activation and altered recovery.\textsuperscript{32-37} Clinically, most myocardial infarctions do not result in complete transmural necrosis. The increased separation of myocardial bundles and the disruption of their parallel orientation by fibrosis may result in a heterogeneous distortion of ventricular activation during multiple portions of the QRS complex. The observed dissociation in the temporal distributions of 13–56-Hz and 70–128-Hz frequencies during the cardiac cycle in patients with VT, particularly those with bundle branch block, underscores the potential value of detecting electrophysiological abnormalities in addition to the total duration of ventricular activation. Late potentials, for example, have been defined as all low-amplitude signals detectable during the terminal 40 msec of the vector magnitude QRS filtered at 25–250 Hz. Based on time-domain reconstructions in this study, the 13–56-Hz and 70–128-Hz frequency bands, which previously have been considered together as components of late potentials, are not always distributed together, are detectable during portions of the cardiac cycle in addition to the terminal QRS, and therefore may reflect different pathophysiological phenomena. Thus, delayed ventricular activation may be only one hallmark of any anatomic/electrophysiological substrate conducive to the development of sustained VT and should not be viewed as the sole generator of altered frequency components.

Several investigators have reported that distinguishing time and frequency components are detectable in ECG signals during many portions of the cardiac cycle from patients with other conditions that include remote myocardial infarction,\textsuperscript{38-40} occult coronary artery disease,\textsuperscript{41,42} or transient myocardial ischemia.\textsuperscript{43} Alterations of myocardial depolarization and repolarizations have been well documented in patients prone to sustained VT.\textsuperscript{44-46} These electrophysiological derangements contribute to the QRS complex, ST segment, and T wave of signal-averaged ECGs; therefore, it is not surprising...
that they appear detectable by frequency analysis of the entire cardiac cycle.

**Summary**

The purpose of this study was to define the frequency bands that distinguish signal-averaged Frank ECGs from patients with sustained VT and determine whether they contribute to ECG intervals in addition to the terminal QRS complex. Based on spectral and temporal analysis of the entire cardiac cycle, additional distinguishing frequency bands were identified that are excluded from detection with available techniques that limit the passband or restrict interrogation to the terminal QRS complex.

Our results do not represent a new index for signal-averaged ECG analysis. Rather, they provide an objective basis and strong rationale for the development of new methods of analysis that incorporate all of the distinguishing spectral and temporal features in ECGs from patients with sustained VT. Further studies are required to implement procedures to maximally extract and quantitate these features and to test the extent to which new indexes that encompass these altered spectral and temporal features improve the prospective identification of patients at risk for life-threatening ventricular arrhythmias compared with time- and frequency-domain approaches relied on currently.

The procedures used in this study are also applicable to other ECG leads as well as other pathophysiological conditions, such as acute rejection of cardiac transplants or myocardial reperfusion in patients with acute infarction treated with thrombolytic agents. Results may differ because the frequency content of ECGs is lead dependent and because altered frequency components that result from one pathophysiological process may not reflect changes elicited during other disease states.

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