Enhanced Detection of Distinguishing Features in Signal-Averaged Electrocardiograms From Patients With Ventricular Tachycardia by Combined Spatial and Spectral Analyses of Entire Cardiac Cycle

Neal G. Kavesh, MD; Michael E. Cain, MD; H. Dieter Ambos, BS; R. Martin Arthur, PhD

**Background** Signals generated by myocardium responsible for ventricular tachycardia (VT) contribute to the entire QRS complex, ST segment, and T wave and are spatially distributed over the entire torso. However, current methods of signal-averaged ECG analysis restrict interrogation to the terminal QRS complex, do not include data on the body surface distributions of the distinguishing features detected, and have a limited clinical value because of a low positive predictive accuracy. Accordingly, we tested the hypothesis that frequency analysis of the entire cardiac cycle of spatially selected ECGs based on isoharmonic maps of the body surface enhance the detection of the unique spectral features in signal-averaged ECGs that differentiate patients with from those without VT.

**Methods and Results** Isoharmonic maps of the body surface were calculated during sinus rhythm with the use of forward problem solutions for 32 patients with sustained VT, 30 without VT, and 10 healthy subjects and analyzed over a bandwidth of 0.05 to 470 Hz. Spectra of ECGs at the maximum and minimum of each patient’s isoharmonic map of 1 to 7 Hz demonstrated a broadened bandwidth of significant separation \(P<.05\) for patients with from those without VT compared with the separation achieved with the use of Frank ECGs alone. Furthermore, the statistical significance within the bands of separation was greater for spatially selected ECGs compared with the Frank leads. Frank leads separated patients over the band from 11 to 84 Hz with a mean value of \(P=.0094\). ECGs at the maximum of 1-to-7-Hz isoharmonic maps separated patients over the 8-to-111-Hz band with a mean value of \(P=.0062\) (range, \(P<.05\) to \(P<.000001\)). ECGs at the minimum of 1-to-7-Hz isoharmonic maps extended the low-frequency end of the band of separation, which covered 0 to 69 Hz with a mean value of \(P=.0039\) (range, \(P<.05\) to \(P<.000001\)). Subgroup analysis verified that results were independent of QRS duration.

**Conclusions** Spectral analysis of ECGs that are spatially selected for each patient is superior to orthogonal ECGs and augments detection of distinguishing features in ECGs that identify risk of VT. The new data acquired from analysis of spatially selected ECGs from individual patients provide the information on the specific frequency bands and an improved ECG-lead system required to refine methods of analysis of the signal-averaged ECG. (Circulation. 1994;90:254-263.)

**Key Words** • ECG • electrocardiography • mapping • ventricular tachycardia

Detection of abnormalities in the signal-averaged ECG has been shown to prospectively identify patients convalescing from myocardial infarction who are prone to developing life-threatening ventricular arrhythmias. However, only 17% to 29% of patients recovering from myocardial infarction with late potentials detected by signal-averaged ECG analysis of the terminal QRS complex and/or ST segment will experience sustained ventricular tachycardia (VT) or sudden cardiac death within 1 year.1-6 This low, positive-predictive accuracy precludes therapeutic interventions in individual patients and underscores the need for continued refinements of methods of data analysis.

Two strategies for improving the positive-predictive accuracy of the signal-averaged ECG are evolving. First, the signal-averaged ECG has been considered in conjunction with the extent of left ventricular dysfunction, frequency and complexity of ventricular ectopy, heart rate variability, and response to programmed stimulation. Results of prospective studies have demonstrated that when the signal-averaged ECG is used in combination with other determinants of risk, the overall positive-predictive accuracy may be as high as 50%.2-5.7 A second strategy has been to determine the extent to which the terminal QRS complex and ST segment are optimal ECG intervals and whether orthogonal ECGs are the ideal leads for detecting signals that identify patients who are prone to sustained VT.8

We have demonstrated by analysis of three-dimensional activation maps obtained during sustained VT and during sinus rhythm from patients undergoing arrhythmia surgery that available methods of signal-averaged ECG analysis that limit interrogation to the terminal QRS and ST segment exclude detection of
most of the signals generated by the myocardium responsible for sustained monomorphic VT. These data from patients provide a pathophysiological basis to expand the ECG interval analyzed to include more of the cardiac cycle.

In support of expanding the ECG interval analyzed, we have demonstrated, in a stepwise fashion, previously undefined magnitude, phase, and spatial features over the entire cardiac cycle of sinus beats that distinguish signal-averaged ECGs from patients with or without sustained VT. Ultimately, refinements in analyses of the signal-averaged ECG are expected to be based on the synthesis of methods of signal processing that maximize the detection of the most powerful spectral, temporal, and spatial components in the ECG that identify patients who are prone to VT. The purpose of the present study was to test the hypothesis that frequency analysis of spatially selected ECGs based on isoharmonic maps of the body surface enhances the detection of the unique spectral features in signal-averaged ECGs that distinguish patients with from those without life-threatening ventricular arrhythmias compared with the separation achieved by analysis of Frank ECGs alone.

Methods

Patients Studied

Signal-averaged ECGs were obtained during sinus rhythm from 32 patients with healed myocardial infarction and spontaneous sustained VT (>30 seconds in duration), 30 patients convalescing from a recent myocardial infarction (8 to 10 days) without sustained VT, and 10 healthy subjects. Episodes of spontaneous sustained VT were not associated with evidence of an acute myocardial infarction based on premonitory symptoms, elevation of creatine kinase–MB, or ECG criteria. No patient was receiving treatment with antiarrhythmic drugs at the time that the signal-averaged ECG was recorded. Left ventricular function was determined in each patient by radionuclide or contrast ventriculography or by echocardiography. Individual estimates of left ventricular ejection fraction were scored (on a scale of 1 to 4) to enable patient-to-patient comparisons where 1 is normal (ejection fraction, >55%), 2 is mild dysfunction (ejection fraction, 46% to 54%), 3 is moderate dysfunction (ejection fraction, 31% to 45%), and 4 is severe dysfunction (ejection fraction, <30%).

Pertinent clinical features of each patient group are summarized in Table 1. Patient age, heart rate during sinus rhythm, and loci of infarction were comparable between patients with and those without VT. Patients in the group with VT were significantly more likely to be male, have more extensive left ventricular dysfunction, and have signal-averaged ECGs with a longer QRS duration than patients in the group without VT.

Table 1. Characteristics of Subjects With and Without VT

<table>
<thead>
<tr>
<th></th>
<th>Non VT</th>
<th>VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>Age, y</td>
<td>64±11</td>
<td>63±9</td>
</tr>
<tr>
<td>Male/female</td>
<td>20/10</td>
<td>27/5</td>
</tr>
<tr>
<td>Left ventricular function</td>
<td>1.9±0.9</td>
<td>3.4±0.9*</td>
</tr>
<tr>
<td>QRS duration, ms</td>
<td>106±18</td>
<td>121±251</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>72±11</td>
<td>75±16</td>
</tr>
<tr>
<td>Infarct locus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Inferior</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>Anterior+inferior</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Non-Q wave</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Unknown</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

VT indicates ventricular tachycardia; bpm, beats per minute. *P=.009 non-VT vs VT.
†P=.0001 non-VT vs VT.

Estimation of Signal Distribution on Body Surface

Estimation of the body surface distribution of signals of interest was performed with the use of forward-problem solutions for unit dipoles at the x-ray center of the heart in an adult male torso. Unit-dipole solutions, weighted by Frank-lead estimates of the actual cardiac dipole, permit reconstruction of potentials at any surface location. Estimated body surface signals can be reconstructed in the time domain as the ECG at any given site or as an isopotential map over the entire torso and in the frequency domain as the spectrum of the ECG at a given site or as an isoharmonic map over the torso surface.

Calculation of forward-problem solutions and construction of body surface maps were made with a model of an adult male torso comparable to the adult male torso used to define the Frank lead system. The model, which had uniform conductivity, consisted of 2048 triangular surface elements. Potentials were computed for unit dipoles in the X, Y, and Z directions from a discrete approximation to an iterative solution of Poisson’s equation at each of the triangular surface elements. These three sets of calculated potentials were scaled for the torso conductivity to yield coefficients that relate the actual X, Y, and Z dipoles at any instant to the surface potential each produces:


where, for example, $T[i]$ is the X-dipole transfer coefficient for torso site i, and x[n] is the X dipole at discrete time n as estimated by the Frank X lead. In the frequency domain, Equation 1 becomes:

$$V[k] = X[k] x[k] + Y[k] y[k] + Z[k] z[k]$$

where $V[k]$ is the Fourier transform of $V[n]$ over, in this case, the cardiac cycle, and $X[k]$, $Y[k]$, and $Z[k]$ are the FFTs of sequences $x[n]$, $y[n]$, and $z[n]$, respectively. The transfer coefficients are constants and therefore not affected by the FFT.

Construction of Isoharmonic Maps

Isoharmonic maps, which represent the body surface distribution of a frequency band or sum of harmonics, were constructed by summing the magnitude spectrum at each surface site i over the frequency band of interest. The contri-
Frank X, Y, and Z ECGs from patients with VT were compared with those from patients without VT as described previously.10 Second, magnitude spectra of ECGs at the maximum and minimum of each of the isoharmonic maps were computed for each patient and healthy subject. Third, the extent to which analysis of these spatially selected ECGs augmented the detection of the unique spectral features that distinguish patients with VT compared with that achieved from the arithmetic average of the magnitude spectra of Frank X, Y, and Z ECGs was quantified by calculating difference spectra.

To graphically display the improved separation of groups of patients using spatially selected leads compared with the performance of Frank leads, difference spectra were calculated. Difference spectra for leads at the maxima and minima of each patient's isoharmonic maps were calculated as a function of frequency k from the group magnitude spectra from patients with and without VT as follows:

\[
D_{\text{max}}[k] = |V_{\text{max}}[k]|_{\text{vt}} - |V_{\text{max}}[k]|_{\text{vtl}}
\]

\[
D_{\text{min}}[k] = |V_{\text{min}}[k]|_{\text{vt}} - |V_{\text{min}}[k]|_{\text{vtl}}
\]

where, for example, \(|V_{\text{max}}[k]|_{\text{vt}}\) is the mean magnitude spectrum of signal-averaged ECGs at the maximum of each patient's isoharmonic map from patients without VT.

**Statistical Analysis**

Groups of patients with VT and without VT were identified prospectively for comparison. Accordingly, an unpaired t test was used to characterize the separation of these two groups. Mean values of the magnitude spectra of ECGs from all patients with VT were compared by line with the mean values of the spectra of equal ECGs from patients without VT using the unpaired, two-tailed t test. Results of the statistical analysis were plotted as the P value as a function of frequency. Data are reported as mean±SD. Significance refers to a value of P<.05. Data acquired from healthy subjects were used for graphical purposes only, as reported previously,10 and were not compared statistically with patient groups.

**Results**

**Spectral Analysis of Frank Leads Over the Entire Cardiac Cycle**

Group magnitude spectra of the entire cardiac cycle from patients with VT (n=32), without VT (n=30), and healthy subjects (n=10) are shown in the top panel of Fig 3. For graphical purposes only, the average magnitude from normal controls was set to 0 dB at each frequency, and the other spectra were adjusted accordingly. Each group spectrum is the arithmetic average of magnitude values of individual Frank X, Y, and Z leads. ECGs from patients with sustained VT showed a decrease in spectral magnitude of as much as 6 dB over a broad band of frequencies relative to ECGs from the group without VT and to healthy subjects.

Spectral magnitudes over the entire bandwidth from patients with VT were compared statistically line by line at 0.977-Hz frequency intervals with those from patients without VT. When each Frank X, Y, and Z lead was considered as a distinct observation, as has been previously described,10 the 32 patients with VT and the 30 patients without VT provided 96 and 90 observations, respectively. Results of this analysis, plotted as the P
value as a function of frequency, reveal significant separation (from $P<.05$ to $P<.000001$) of the ECGs from the patients with VT from those without VT over the continuous frequency band from 9 to 141 Hz (Fig 3, middle). The frequency band of maximal separation was 14 to 35 Hz ($P<.000001$).

The arithmetic average of the Frank leads from a given individual as a single observation reduces the number of observations by a factor of 3 and provides an assessment of separation of patients rather than separation of leads in different arrhythmic groups. As illustrated in Fig 3 (bottom), analysis of the arithmetic average of the data from each patient's X, Y, and Z lead confirms significant differences in the magnitude spectrum from the group of patients with VT compared with the group without VT over the continuous frequency range from 10 to 82 Hz ($P<.05$ to $P<.001$).

To determine the contribution of each of the Frank X, Y, and Z leads to the observed separation between patients with and without VT, the group spectra of each lead were individually analyzed. Results, plotted as the $P$ value as a function of frequency, are shown in Fig 4.

The individual lead with the broadest bandwidth of separation was the X lead (7 to 106 Hz; $P<.05$ to $P<.001$). The Z lead provided better separation of patient groups over a more narrow frequency range (9 to 82 Hz; $P<.05$ to $P<.00001$). The Y lead was the least powerful discriminator of arrhythmia group (15 to 21 Hz; $P<.05$ to $P<.01$).

**Spatial Selection of ECGs Using 1-to-7-Hz Isoharmonic Maps**

As illustrated by Fig 4, results of analysis of the entire cardiac cycle of Frank X, Y, and Z ECGs were not equally useful for separating patients with VT from those without VT. To adjust for the spatial distribution of distinguishing frequencies and to test the hypothesis that improved separation of patient groups could be achieved by spatially selected leads. ECGs at the maximum and minimum of isohermonic maps were analyzed.

Isoharmonic maps were constructed and analyzed over several frequency bands. Results obtained from analysis of isohermonic maps constructed using the
band from DC to the frequency at which 99% of the entire spectral energy was included, 1 to 100 Hz, and 1 to 7 Hz were found to be equivalent. These three bands were more successful than other bands tested at separating patient groups. Because computation time is directly proportional to the width of the frequency band selected, the results were based on 1-to-7-Hz isoharmonic maps.

**Spectral Analysis of Spatially Selected ECGs Over the Entire Cardiac Cycle**

Fig 5 illustrates results from the analysis of the magnitude spectrum of the reconstructed lead at the maximum of each patient’s 1-to-7-Hz isoharmonic map. For illustrative clarity only, the group spectrum of the normal controls was set to 0 dB at each frequency line, and the spectra of the other groups were adjusted accordingly. Spectral magnitude of the ECGs at the maxima of the 1-to-7-Hz isoharmonic maps from patients with VT was diminished relative to spectral magnitude of patients without VT over a broad frequency range (8 to 108 Hz; P<.05 to P<.0000001). Although qualitatively similar to the results obtained using the arithmetic average of Frank leads (Fig 3, bottom), separation using the maximum of the 1-to-7-Hz isoharmonic map was improved (Table 2).

Spectral analysis of the lead at the minimum of each patient’s 1-to-7-Hz isoharmonic map is shown in Fig 6. Analysis of ECGs at the minimum of the isoharmonic map revealed a low-frequency band of separation not seen in the Frank leads or by using the ECG at the maximum of the 1-to-7-Hz isoharmonic map. In contrast to analysis of both Frank lead and ECGs at the maximum of isoharmonic maps, the magnitude spectrum of the group of patients with VT was found to exceed that of the patients without VT. The bandwidth of separation extended from 1 to 66 Hz (P<.05 to P<.0000001). Spectral differences were as large as 20 dB.

**Loci of 1-to-7-Hz Isoharmonic Map Maximum and Minimum**

The spatial distributions of the maxima and minima of each patient’s 1-to-7-Hz isoharmonic map are shown in Fig 7. The maxima of the isoharmonic maps of the patients without VT occurred exclusively over the left anterior precordium. In patients with VT, the maxima were observed over the left, right, and mid precordia. In contrast, the distribution of the minima of the 1-to-7-Hz isoharmonic maps from patients with VT was spatially heterogeneous in marked distinction to the uniformity of the spatial distribution of isoharmonic minima from patients without VT.
Fig 4. Statistical comparison of group spectra of the entire cardiac cycle from patients with and without ventricular tachycardia (VT) subgrouped by Frank lead. A continuous band of significant separation is observed from 7 to 108 Hz (P<.05 to P<.00001) for the X lead (top), 15 to 21 Hz (P<.05 to P<.01) for the Y lead (middle), and 9 to 82 Hz (P<.05 to P<.00001) for the Z lead (bottom).

**Difference Spectra**

The improvement in the separation of group spectra using ECGs selected from isoharmonic maps (Figs 5 and 6) compared with results obtained from the arithmetic average of the magnitude spectra of Frank X, Y, and Z leads (Fig 3) was quantified by calculating difference spectra. The advantage of using spatially selected ECGs was found using Equations 4 and 5 (see “Methods”) and is plotted in Fig 8. The extent to which this figure of merit exceeds zero reflects improved separation of patient groups as the result of spatial selection compared with arithmetic averaging of the spectral magnitudes of Frank X, Y, and Z leads. As seen in Fig 8, there is an improvement of as much as 2 dB using ECGs from the maximum of the 1-to-7–Hz isoharmonic maps over the band from 15 to 190 Hz. Markedly improved separation, of as much as 20 dB,
over the low-frequency band from 1 to 50 Hz was observed using ECGs at the minima of the 1-to-7-Hz isoharmonic maps. These improvements are summarized in Table 2.

**Effect of QRS Duration**

The group of patients with VT had a longer mean QRS duration than the group without VT (121±25 and 106±18 milliseconds, respectively; \(P<.01\)). To determine whether the observed spectral differences in ECGs from patients with and without VT are dependent on QRS duration, subgroup analysis was performed on patients with QRS durations ≤120 milliseconds. QRS durations in the subgroups with VT (n=17) and without VT (n=24) were 103.3±8.4 and 98.6±7.6 milliseconds, respectively (\(P=.07\)). Results of this subgroup analysis verified that significant spectral separation and improvement using spatially selected ECGs in comparison of patients with and without VT are demonstrable independent of QRS duration (Table 2).

**Discussion**

The clinical use of the signal-averaged ECG for predicting risk of development of life-threatening ventricular arrhythmias in individual patients convalescing from myocardial infarction has been limited by positive-predictive accuracies that range from only 17% to 29%.1-6 We believe that further refinements in methods of signal-averaged ECG analysis are essential and require signal processing techniques that maximize the detection of the most powerful spectral, temporal, and spatial components in the ECG that are unique to patients who are prone to VT.

The purpose of the present study was to test the hypothesis that synthesis of the spectral and spatial information in ECGs enhances detection of features in signal-averaged ECGs that distinguish patients with prior myocardial infarction and sustained VT. Novel features of this study include estimation of the body surface distribution of temporal and spectral components of ECG signals in the form of isoharmonic maps, analysis of spatially selected ECGs that were individualized to each patient and identified using isoharmonic maps, and spectral analysis of the entire cardiac cycle over a passband of 0.05 to 470 Hz. Results demonstrate the successful synthesis of spectral and spatial informa-

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**Table 2. Performance of Spatially Selected ECGs Versus Frank Leads for Subjects With and Those Without VT**

<table>
<thead>
<tr>
<th></th>
<th>Bandwidth of Significant Separation, Hz</th>
<th>Band of Maximal Separation, Hz</th>
<th>Maximal Separation, dB</th>
<th>Confidence of Maximal Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean of Frank leads</td>
<td>10 to 82</td>
<td>17 to 23</td>
<td>6</td>
<td>(P&lt;.001)</td>
</tr>
<tr>
<td>Isoharmonic maximum</td>
<td>8 to 108</td>
<td>17 to 23</td>
<td>6</td>
<td>(P&lt;.0000001)</td>
</tr>
<tr>
<td>Isoharmonic minimum</td>
<td>1 to 66</td>
<td>1 to 5</td>
<td>20</td>
<td>(P&lt;.0000001)</td>
</tr>
</tbody>
</table>

QRS ≤120 ms

|                      |                                        |                               |                        |                                  |
| Mean of Frank leads  | 13 to 50                                | 17 to 23                      | 6                      | \(P<.005\)                      |
| Isoharmonic maximum  | 11 to 80                                | 19 to 23                      | 10                     | \(P<.0001\)                     |
| Isoharmonic minimum  | 1 to 60                                 | 2 to 7                        | 15                     | \(P<.0001\)                     |

VT indicates ventricular tachycardia.
tion to achieve superior separation of groups of patients with VT from those without VT compared with Frank leads.

Selection and analysis of signal-averaged ECGs at the site on the body surface corresponding to the maximum of the 1-to-7-Hz isoharmonic map resulted in the broadest bandwidth of significant separation (8 to 108 Hz) and the greatest statistical confidence associated with the band of maximal separation (17 to 23 Hz, $P<.05$ to $P<.000001$). The group magnitude spectra of the ECG leads at the site of the minimum of each individual's 1-to-7-Hz isoharmonic map from patients with VT differed by as much as 20 dB compared with ECGs from patients without VT, particularly at low frequencies (band of maximal separation, 1 to 5 Hz; $P<.05$ to $P<.000001$). The sign of the difference spectrum from ECGs at the minima of 1-to-7-Hz isoharmonic maps was inverted from 1 to 60 Hz compared with the difference spectrum at the maximum of the maps. The spatial distributions of both the maxima and minima of the 1-to-7-Hz isoharmonic maps from patients with sustained VT were heterogeneous compared with the distributions of extrema from patients without VT. Finally, subgroup analysis of patients with matched QRS durations verified that the observed spectral differences that separated patients with from those without sustained VT were robust.

Rationale for Analysis of the Cardiac Cycle

Most methods of analysis of the signal-averaged ECG have been based on the concept that occult electrophysiological derangements that are a hallmark of reentrant VT are produced as a consequence of myocardial infarction and are detectable by analysis of the terminal QRS complex of orthogonal ECGs. We have recently demonstrated that present methods of analysis of the signal-averaged ECG that limit interrogation to the terminal QRS complex and/or ST segment exclude most of the signals generated by the myocardium responsible for VT, establishing a pathophysiological basis for expansion of the window of analysis to include more of the cardiac cycle. In support of expanding the ECG interval interrogated, we have recently demonstrated in a stepwise series of studies previously unrecognized magnitude, phase, and spatial features over the entire cardiac cycle of sinus beats that distinguish signal-averaged ECGs from patients with a healed myocardial infarction and sustained VT. In the present study, results of spectral analysis of the entire cardiac cycle of Frank X, Y, and Z ECGs from a new group of patients confirmed that ECGs from patients with VT contain significantly smaller magnitudes over a continuous band from 8 to 141 Hz ($P<.05$ to $P<.000001$) compared with ECGs from patients without VT. The absence of an obfuscating peak at 60 Hz in the present data is attributable to the use of a uniform gain of 1000 rather than variable gain, which was used previously to optimize the input to the analog-to-digital converter.

Spatial Analysis and Vulnerability to Ventricular Arrhythmias

Current approaches to temporal and spectral analyses of the terminal QRS complex and/or ST segment of
X, Y, and Z signal-averaged ECGs do not include data on the body surface distributions of the distinguishing features detected. Several lines of evidence indicate that the spatial distributions of abnormalities detected in ECGs provide additional data relevant to patient vulnerability to sustained ventricular arrhythmias. Berbari and coworkers analyzed data from 24-lead precordial recordings and reported that orthogonal ECGs do not accurately measure the total QRS and late potential durations. Faugere and colleagues identified additional information about the distribution and extent of late potentials on the torso surface with the use of time-averaged, 25-Hz high-pass filtered ECGs from 63 thoracic leads. Further characterization of the spatial distribution of ventricular late potentials was achieved by comparison of body surface isopotential maps to endocardial and epicardial recordings in patients undergoing surgery for VT. The isopotential maps generated by Lacroix and coworkers of time-averaged, 55-Hz high-pass filtered thoracic and intracardiac signals demonstrated a close spatial correlation. Shibata and colleagues analyzed the terminal 20 milliseconds of the QRS complex of time-averaged ECGs over a passband of 80 to 250 Hz obtained from 87 body surface leads and determined that the spatial distributions of the ECG features that distinguished patients with VT were dependent on the locus of infarction. Most recently, Ho and coworkers found that a 28-lead body surface array improved sensitivity in the analysis of late potentials from signal-averaged ECGs.

Although studies that have focused on analysis of the terminal QRS complex have improved the understanding of late potentials, the methods of signal processing used have been limited by restriction of analysis to the terminal QRS complex, which excludes signals generated by most of the myocardium responsible for VT; lack of a consensus regarding identification of the end of the QRS complex; and imposition of high-pass filters of arbitrary cutoff frequency that exclude useful low-frequency signals.

Some of these limitations in signal processing were obviated by Hosoya and colleagues, who computed area maps of the QRS complex of 0 to 25, 25 to 40, 40 to 80, 80 to 150, and 150 to 250 Hz that were derived from 87-lead, time-averaged, body surface ECGs. Frequency ranges of interest were identified by Fourier transformation and application of optimal, zero-phase filters, followed by inverse Fourier transformation and time domain QRS isoarea analysis. Values for the QRS areas of 40 to 80 and 80 to 150 Hz in ECGs from patients with a history of VT were significantly less compared with ECGs from patients without VT. Although the results of the study from Hosoya and coworkers are in general agreement with those reported in the present and our previous studies, the methods of signal processing differ in several important regards. First, we used the forward problem solution to estimate from Frank leads both isopotential and iso-harmonic body surface maps, obviating the need for laborious collection and analysis of data from 87 (or more) leads per patient. Second, our analysis interrogated the entire cardiac cycle (depolarization and repolarization) rather than only the QRS complex (depolarization). Third, our analysis avoided the imposition of artificial frequency ranges of interest, whereas Hosoya and colleagues used zero-phase filters with arbitrarily designated frequency ranges to interrogate the composite range from 0 to 250 Hz. Finally, our analysis used the spatial information from iso-harmonic maps rather than from QRS area maps.

**Source of 1-to-7-Hz Frequency Bands**

Isoharmonic maps were constructed and analyzed to determine whether spatially selected ECGs at sites on the body surface corresponding to the extrema of several frequency bands maximized detection of the spectral features in ECGs unique to patients prone to sustained VT. The spatial distribution of the 1-to-7-Hz frequency band was a powerful determinant of the body surface site at which differences in the spectra of ECGs from patients with and without sustained VT were most marked. We have previously demonstrated in patients with the use of time-domain reconstructions and optimal, zero-phase filters that the 1-to-7-Hz frequency band contributes not only to the QRS complex but also extensively to the ST segment and T wave. Thus, signals in the frequency range of 1 to 7 Hz include information pertinent to both depolarization and repolarization and are excluded from detection by current methods of analysis that restrict the bandwidth and/or limit interrogation to the terminal QRS or even the entire QRS complex. Results of studies in experimental animals and in humans demonstrate that repolarization is important to the pathogenesis of reentrant VT. Elucidation of the specific abnormalities of repolarization responsible for the observed alterations in the magnitude and spatial distributions of the 1-to-7-Hz frequency band in ECGs from patients with sustained VT is unknown.

**Future Studies**

This study relied on a single-torso model and a single-forward problem solution to derive transfer coefficients for application to all patients for estimation of the signal distribution on the body surface. The accuracy of the forward problem solution can be improved by taking into account each subject's body surface geometry. Performance may be further improved with direct measurement of body surface maps or with forward problem solutions that control for intrathoracic conductance inhomogeneities such as the lung boundaries, anisotropic skeletal muscle, and intracardiac blood pool.

**Conclusions**

We believe that refinements in methods of analysis of the signal-averaged ECG will be best accomplished by a two-stage process that includes (1) identification and characterization of the spectral, temporal, and spatial features in ECGs of the entire cardiac cycle that are unique to patients with ischemic heart disease and sustained ventricular arrhythmias to objectively define the specific frequencies of interest, the ECG intervals to be analyzed, and the optimal ECG-lead system to be analyzed; and (2) implementation and prospective testing of a new index that incorporates the most powerful spectral, temporal, and spatial features in the signal-averaged ECG that distinguish patients prone to life-threatening ventricular arrhythmias. Analysis of the data acquired in the present study demonstrates for the
first time that the combination of spectral information from the entire cardiac cycle with spatial information estimated by isoharmonic maps enhances detection of the abnormal components in ECGs from patients with sustained VT. The new data obtained by analysis of spatially selected ECGs from individual patients provide information on the frequency bands of interest along with an improved ECG-lead system that is required to refine the methods of analysis of the signal-averaged ECG.

References
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