Quantitative Analysis of the High-frequency Components of the Terminal Portion of the Body Surface QRS in Normal Subjects and in Patients with Ventricular Tachycardia

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SUMMARY Quantitative analysis of the high-frequency components of the terminal portion of the surface QRS was performed in 42 normal subjects (group 1, ages 18–67 years, mean ± SEM 34.7 ± 2.2 years) and in 12 patients with symptomatic, sustained ventricular tachycardia (VT) (group 2, ages 48–76 years, mean 59 ± 2.3 years). Signal averaging and high-pass, bidirectional digital filtering were used for analysis. The total duration of the QRS, the duration of the low-amplitude signals (< 40 μV) in the terminal portion of the QRS and the amplitude of the signals in the last 40 and 50 msec of the QRS were measured at filter settings of 25 and 40 Hz. Reproducibility of the measurements was tested in 15 normal subjects by comparing results obtained from two consecutive recordings. Significant differences were found between normal subjects and VT patients for all four indexes at both 25- and 40-Hz filters. Specific values for each of the indexes were identified at the 40-Hz filtering, which could separate normal subjects from VT patients (20 μV for the amplitude of last 40 msec; 30 μV for the amplitude of last 50 msec; 120 msec for the total duration; and 39 msec for the low-amplitude signal of the filtered QRS). Using these values for the four indexes, respectively, 90%, 98%, 100% and 90% of the normal subjects and 83%, 83%, 58% and 83% for the VT group were correctly classified. The results show that the high-frequency analysis of the signal-averaged body surface QRS is a reliable, reproducible, noninvasive method for distinguishing patients with VT from normal subjects.

EXPERIMENTAL and clinical evidence reveals that delayed fragmented electrograms can be recorded from the ischemic myocardium.1–6 These areas of delayed activation are associated with the occurrence of ventricular arrhythmias, which are probably reentrant.7–8 Recently, several groups have demonstrated that high-frequency analysis of the signal-averaged surface ECG detects discrete, low-amplitude signals in the terminal portion of the body surface QRS in patients with ventricular tachycardia (VT).9–14 These signals have been labeled as arrhythmogenic ventricular activity, delayed depolarizations or late potentials. These signals correlate well in time with the fragmented activity recorded during epicardial and endocardial mapping in animals and man.3, 8, 9, 11, 15, 16

Thus, analysis of the signal-averaged, high-frequency components of the late QRS appears to be a promising new noninvasive technique for detecting patients with VT. Previous clinical studies have dealt with patients with cardiac disease either with or without VT, and only limited data are available in normal subjects.13, 14

The purposes of this study were to provide a quantitative analysis of the high-frequency components of the terminal portion of the signal-averaged surface QRS in normal subjects, to test the reproducibility of this analysis, to provide a quantitative analysis of the high-frequency components of the terminal portion of the signal-averaged surface QRS in patients with VT, and to compare the findings of normal subjects with those of patients with VT.

Material and Methods

The high-frequency components of the terminal portion of the signal-averaged QRS were analyzed in 42 normal subjects (28 males and 14 females, ages 18–67 years, mean ± SEM 34.7 ± 2.2 years) and in 12 patients (nine males and three females, ages 48–76 years, mean 59 ± 2.3 years) with symptomatic, sustained VT and no evidence of bundle branch block on the resting ECG. Group 1 consisted of 30 normal, healthy young subjects (group 1A, ages 18–33 years, mean 25.9 ± 0.6 years) and 12 patients who underwent cardiac catheterization for evaluation of chest pain (group 1B, ages 43–67 years, mean 56.9 ± 2.0 years). Criteria for inclusion in group 1A were age 33 years or younger, negative cardiovascular history, normal physical examination and normal ECG. Subjects in group 1B were selected on the basis of normal ECG and normal coronary arteries and left ventricular function by cardiac catheterization. Group 2 consisted of 12 patients with a history of documented, sustained VT that required cardioversion or antiarrhythmic drug administration. All patients in group 2 had VT that was inducible by programmed electrical stimulation in the catheterization laboratory. All had a history of myocardial infarction and six had been resuscitated from at least one episode of sudden death.

Surface Recordings

Bipolar X, Y and Z leads were used. The X lead was between the right and left midaxillary lines at the fourth intercostal space. The Y lead was between the
superior part of the manubrium and the proximal left leg. The anterior and posterior Z electrodes were at the fourth intercostal space, along the left parasternal margin and at the posterior chest, respectively. Positive electrodes were left, inferior and anterior. Each recording was made at the bedside and took approximately 15 minutes.

**Signal Processing**

The signal processing, hardware and methods were identical to those described by Simson. A diagram of the signal processing system is shown in figure 1. Bipolar X, Y and Z lead signals were amplified, pre-filtered and digitally sampled into a Hewlett Packard 9825B microcomputer. Approximately 150 beats per lead were then signal averaged and the averaged signals filtered using two filter frequencies, one with a 3-db corner frequency of 25 Hz and the other with a corner frequency of 40 Hz. A vector magnitude was calculated for each point of the averaged wave, as

\[ V_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2}. \]

Typical signal-averaged and unfiltered QRS complexes are shown in figures 2A and 3A. The corresponding vector complexes are shown in figures 2B and 3B.

The mean noise level (±sd) in the ST segment was 0.8 ± 0.3 μV at 25 Hz and 0.6 ± 0.2 μV at 40 Hz for the normal group and 0.9 ± 0.3 μV at 25 Hz and 0.8 ± 0.3 μV at 40 Hz for the VT group.

Four indexes were then measured with both a 25- and a 40-Hz filter (fig. 2): amplitude (μV) of the signals in the last 40 msec of the QRS; the amplitude (μV) of the signals in the last 50 msec of the QRS; duration (msec) of the filtered QRS; and the duration (msec) of the low-amplitude signals at the end of the filtered QRS (from the QRS end point back to the first point where the signals reached 40 μV of amplitude).

These indexes were selected for several reasons: (1) Filtering at 25 Hz and measurement of the amplitude of the last 40 msec of the QRS was based on Simson’s method. (2) Filtering at 40 Hz was added because in animal experiments (unpublished observations), the 25-Hz filter did not adequately eliminate harmonics of the large-amplitude, low-frequency components of the ECG wave form. These harmonics sometimes obscured the high-frequency, low-amplitude signals at the end of the QRS. (3) A 50-msec interval amplitude measurement was added to detect more consistently delayed potentials of short duration (40 msec or less). (4) The measurement of duration of the low-amplitude signals was used to try to directly quantitate the length of low-amplitude, high-frequency signals in the terminal portion of the filtered QRS. Most investigators have used the duration of the late potentials to detect abnormal recordings. The selection of a 40-μV signal amplitude to indicate onset of the late potential was based on the observation that in normal subjects, the 40-μV point usually occurred near the end of the abruptly descending large-amplitude signal.

Data are presented as the mean ± SEM. Statistical analysis was performed using the t test for unpaired data. To test reproducibility, recording and analysis were repeated in 15 normal subjects 1 week to 1 month after the first recording was taken. Pearson’s correlation coefficient was used to test for reproducibility.

| Table 1. Comparison Between Groups 1A and 1B with the 25- and 40-Hz Filters |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                             | 25 Hz            |                 | 40 Hz           |                 |                 |
|                             | 1A              | 1B              | p               | 1A              | 1B              | p               |
| Last 40 msec (μV)           | 66.9 ± 6.3      | 67.5 ± 9.8      | NS              | 41.5 ± 4.5      | 41.8 ± 5.7      | NS              |
| Last 50 msec (μV)           | 116.0 ± 9.8     | 110.9 ± 15.6    | NS              | 73.9 ± 5.7      | 64.1 ± 7.0      | NS              |
| QRS dur (msec)              | 96.3 ± 1.7      | 94.9 ± 2.9      | NS              | 94.2 ± 1.7      | 92.5 ± 2.5      | NS              |
| LA dur (msec)               | 24.3 ± 1.4      | 20.7 ± 1.8      | NS              | 29.6 ± 1.2      | 29.6 ± 2.6      | NS              |

Values are mean ± SEM.

Abbreviations: QRS dur = duration of the filtered QRS; LA dur = duration of the terminal low-amplitude signals.
S.S. 19-17-81

S.S. 26y.o. 9-17-81

Results

Comparison Between Normal Groups (1A and 1B)

The data for the two normal groups are presented in

Table 1. We compared the young normal subjects (group 1A) with the older patients who had normal cardiac findings (group 1B) to determine if aging had an effect on the high-frequency components of the terminal portion of the filtered QRS. All four indexes were compared using both 25- and 40-Hz filters. No significant differences were found between groups 1A and 1B for any of these indexes, at either 25- or 40-Hz filter. In fact, the means of the comparable indexes in groups 1A and 1B were remarkably similar. However, the values in the older group were more variable, as reflected by the larger standard error of the mean for each index at both frequencies.

Reproducibility

The reproducibility of the various measurements was tested by comparing the results obtained from two consecutive recordings (see analysis) in 15 subjects from group 1A. The analysis was performed using both 25- and 40-Hz filters. The individual data points for all measurements in each subject are shown in
The coefficient of reproducibility for all signals varies considerably (fig. 5).

Comparison Between Normal and VT Groups (1 and 2)

Group 1 and group 2 were compared to determine if there were significant differences in the values of the indexes (table 2). All four indexes were compared using both 25- and 40-Hz filters. Significant differences existed between the groups for all measured indexes determined at both frequencies. In group 2, the amplitude of the signals in the terminal portion of the QRS was markedly lower and the duration of the low-amplitude signals was longer than in group 1.

The measured indexes of normal subjects and VT patients were also examined to determine if specific values could be found that effectively separated the two groups.

The distribution of the individual data points for group 1 and 2 using either 25- or 40-Hz filters is shown in figure 7. The high degree of overlap in the values of each index observed at 25 Hz markedly decreased when a 40-Hz filter was used. Defining values of 25 \( \mu V \) at 25 Hz as normal for the amplitude of the last 40 msec, as suggested by Simson, \(^{12} \) 96% of group 1 and 58% of group 2 were correctly identified (table 3). Defining greater than 20 \( \mu V \) at 40 Hz as normal for the amplitude of the last 40 msec, 90% of group 1 and 83% of group 2 were correctly identified (table 3). Defining values greater than 40 \( \mu V \) at 25 Hz as normal for the amplitude of the last 50 msec, 98% of group 1 and 50% of group 2 were correctly identified (table 3). Defining values of 30 \( \mu V \) at 40 Hz as normal for the last 50 msec, 98% of group 1 and 83% of group 2 were cor-
rectly identified (table 3). Defining values less than 120 msec at 25 Hz as normal for the filtered QRS duration as suggested by Simson,12 100% of group 1 and 58% of group 2 were correctly identified (table 4). Identical results were obtained at 40 Hz. Defining values less than 30 msec at 25 Hz for the terminal low-amplitude signals, 79% of group 1 and 58% of group 2 were correctly identified (table 4). While using a normal value of 39 msec for the same index at 40 Hz, 90% of group 1 and 83% of group 2 were correctly identified. Thus, the use of a 40-Hz filter improved the ability to correctly categorize normal subjects and VT patients.

Discussion
Electrocardiographic studies have demonstrated specific alterations (notching) of the high-frequency components of the ECG in the presence of myocardial disease.18, 19 Recently, several authors, using new ECG processing techniques, have shown that signal-averaged surface ECG recordings can identify patients with VT.9, 14 Low-amplitude, high-frequency signals have been observed in the terminal portion of the QRS or in the early ST segment of the signal-averaged and filtered ECG of these patients. These low-amplitude, high-frequency signals also correlate with the fragmented electrograms detected during epicardial and endocardial mapping.3, 5, 9, 11, 15, 16. The fragmented electrograms represent areas where conduction is slow and
**FIGURE 5.** Two tracings from a normal subject recorded at different times and analyzed using a 25-Hz filter.

**FIGURE 6.** The same tracing as in figure 5 analyzed using a 40-Hz filter.
reentry can occur. Signal-averaging techniques and high-pass filtering allow detection of these low-amplitude, high-frequency signals. Signal averaging reduces random noise by the square root of the number of beats averaged and allows the detection of repetitive signals. High-pass filtering is necessary to reject the low-frequency activity present in the ST segment and in the T wave. A common problem with conventional high-pass filters is filter ringing; this can be eliminated from the regions of interest by using a bidirectional digital filter. The technique reported by Simson has additional advantages: high-frequency analysis of the signal averaged QRS is performed on a vector amplitude, incorporating characteristics of all filtered X, Y, and Z leads; analysis of the signal-averaged and filtered QRS is based entirely on computer algorithms that determine QRS endpoints, amplitude and duration; and the noise level in the ST segment is quantitated. This allows for quality control of the recording and also for differentiation between noise and true signal.

Berbari et al. recorded arrhythmogenic ventricular activity in dogs after acute myocardial infarction. The delayed activity was confirmed by direct epicardial mapping. Rozanski et al. described eight patients with chronic, recurrent VT and ventricular aneurysm in whom delayed wave form activity was present in the filtered QRS extending beyond the end of the surface QRS. However, in eight patients with VT but without a ventricular aneurysm, these potentials were not recorded. They concluded that the delayed activity was related to the presence of an aneurysm. Fontaine documented the presence of delayed activity on chest wall recordings in 11 patients with VT unrelated to myocardial ischemia. Breithardt et al. studied patients with and without VT. They observed that 71% of patients with documented VT or fibrillation demonstrated late potentials. They also reported that in patients without VT who underwent cardiac catheteriza-

<table>
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<th>TABLE 2. Comparison Between Normal and Ventricular Tachycardia Groups with the 25-Hz and 40-Hz Filters</th>
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<td>25 Hz</td>
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<tr>
<td>-------</td>
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<tr>
<td>Last 40 (μV)</td>
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<tr>
<td>Last 50 (μV)</td>
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<tr>
<td>QRS dur (msec)</td>
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<td>LA dur (msec)</td>
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Abbreviations: N = normal subjects; VT = patients with ventricular tachycardia; other abbreviations as in table 1.

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<th>TABLE 3. Separation of Normal and Ventricular Tachycardia Patients Using 25-Hz and 40-Hz Filters for the Last 40 Msec and 50 Msec</th>
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<td>Last 40 msec</td>
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<td>Pos (&lt; 25 μV)</td>
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<tr>
<td>Neg (&gt; 25 μV)</td>
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<tr>
<td>Total</td>
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</table>

Last 50 msec | 25 Hz | VT | | 40 Hz | VT | |
| Pos (< 40 μV) | 1/42 (2%) | 6/12 (50%) | | Pos (< 30 μV) | 1/42 (2%) | 10/12 (83%) |
| Neg (> 40 μV) | 41/42 (98%) | 6/12 (50%) | | Neg (> 30 μV) | 41/42 (98%) | 2/12 (17%) |
| Total | 42 (100%) | 12 (100%) | | Total | 42 (100%) | 12 (100%) |

Abbreviations: Pos = positive; Neg = negative; other abbreviations as in table 2.

<table>
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<tr>
<th>TABLE 4. Separation of Normal and Ventricular Tachycardia Groups Using 25- and 40-Hz Filters for the Duration of the QRS and of the Terminal Low-amplitude Signals</th>
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<tr>
<td>25 Hz</td>
</tr>
<tr>
<td>QRS dur</td>
</tr>
<tr>
<td>Pos (≥ 120 msec)</td>
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<tr>
<td>Neg (&lt; 120 msec)</td>
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<td>Total</td>
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| LA dur | | | |
| Pos (≥ 30 msec) | 9/42 (21%) | 7/12 (58%) | | Pos (≥ 39 msec) | 4/42 (10%) | 10/12 (83%) |
| Neg (< 30 msec) | 33/42 (79%) | 5/12 (42%) | | Neg (< 39 msec) | 38/42 (90%) | 2/12 (17%) |
| Total | 42 (100%) | 12 (100%) | | Total | 42 (100%) | 12 (100%) |

Abbreviations are as in tables 1, 2 and 3.
tion for diagnosis of organic heart disease, 34% showed late potentials. There was a close correlation between the presence of late potentials and left ventricular dysfunction. In a subsequent study, they showed that post-myocardial infarction patients with late potentials of longer than 40 msec had an increased incidence of sudden death. Simson demonstrated that signal processing of the surface QRS by computer can separate patients with VT from patients without complex ventricular ectopy after myocardial infarction. The sensitivity and specificity of the test were 92% and 93%, respectively. Simson et al. confirmed that delayed ventricular activation can be detected on the body surface recording in dogs during acute ischemia. The delayed activation was confirmed by epicardial mapping.

Based on these previous studies, body surface detection of delayed depolarization appears to be a promising noninvasive technique for detecting patients at high risk of life-threatening ventricular arrhythmia and sudden death.

In Simson’s original article, the high-pass filter frequency was set at 25 Hz. He measured the amplitude of high-frequency signals in the last 40 msec of the filtered QRS and also the duration of the filtered QRS. In the other studies, the delayed activity was defined on the basis of the presence or absence of a delayed low-amplitude wave form that extended beyond the duration of the surface QRS.

In the present study, we concentrated on the characteristics of a normal population and on the development of methods to differentiate this population from patients with VT. When the analysis of the signal-averaged QRS was performed using a 25-Hz filter, the amplitude and, to a lesser extent, the duration of the signals in the terminal portion of the QRS (last 40 and 50 msec) were extremely variable (fig. 7). When specific values were sought to separate normal subjects from VT patients using the 25-Hz filtered signals, a high degree of overlap was present and an accurate separation between normal subjects and VT patients could not be found for any of the indexes (tables 3 and 4). The use of a 40-Hz filter markedly improved the separation between the two groups, reduced the degree of variability in the values of the measured indexes.
(table 2, fig. 7) and improved reproducibility (fig. 4). The comparison between groups 1A and 1B (table 1) failed to show significant differences at the 25- or 40-Hz filter setting, suggesting that age, in the absence of cardiac disease, has no effect on the characteristics of the high-frequency signal of the late portion of the QRS. In group 1, the start of the QRS was represented by an abrupt onset of high-amplitude, high-frequency signals. The terminal portion of the QRS demonstrated a steep decay of the amplitude of the depolarization process, occasionally extending by low-amplitude signal that did not extend beyond the duration of the surface QRS. In contrast, patients with VT had low-amplitude signals of longer duration, sometimes extending far beyond the end of the surface QRS (fig. 3). We believe that quantitation of the duration of the low-amplitude signals at the end of the filtered QRS is the most direct approach to the recognition of an abnormally delayed ventricular depolarization.

In conclusion, a quantitative analysis of the high-frequency components of the terminal portion of the ventricular activation of the normal heart showed great variability of patterns and amplitude. This variability, as well as the reproducibility of the measurements, was markedly improved by the use of a 40-Hz filter. This analysis also reliably differentiated normal subjects from patients with sustained, inducible VT.

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