Electrocardiography Subtraction Method of Detecting Low-Amplitude, High-Frequency Components (L-HFCs) Within the QRS Complex of Patients With Ventricular Tachycardia

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A new method of extracting the low-amplitude and high-frequency components (L-HFCs) was developed and this study investigated its usefulness in 86 subjects: 28 normal subjects (group 1) and 58 patients with a previous myocardial infarction (MI). The patients were classified into 3 groups: group 2 with 38 patients without ventricular tachycardia (VT), group 3 with 13 patients with non-sustained VT, and group 4 with 7 patients with sustained VT. The new electrocardiography (ECG) subtraction method, using a mathematical filtering procedure, was used instead of conventional complex filtering. The continuous L-HFCs within the QRS complex were analyzed using a Z-lead recording. The duration of the continuous L-HFCs was significantly longer in group 4 than in groups 1 (p<0.0001), 2 (p<0.0001) or 3 (p<0.05) with all 3 filters. The ECG subtraction method is a powerful and useful new technique for identifying patients at risk for either sustained or non-sustained VT after MI, and overcomes several of the problems with the conventional signal-averaging method. (Circ J 2002; 66: 649–654)

Key Words: High-frequency components; Late potential; Myocardial infarction; QRS complex; Ventricular tachycardia

The high-frequency components (HFC) of the electrocardiography (ECG) have been classically described using a high-fidelity ECG, not by conventional 12-lead ECG. Recent studies have described a method for the extraction of the low-amplitude and HFC of the ECG (L-HFCs) for the terminal portion of the QRS complex or the early portion of the ST segment of the signal-averaged ECG using high gain amplifications and signal-averaging techniques. These L-HFCs, so-called ‘late potentials’, correspond to the delayed and fragmented endocardial or epicardial electrograms, and are believed to represent the substrate for reentrant ventricular tachycardia (VT). The L-HFCs not only of the terminal portion of the QRS complex, but also within the QRS complex have been detected by analyzing the signals from catheter electrodes inserted into ventricles. However, a potential problem with the signal-averaged ECG is the attenuation of the L-HFCs because of trigger jitter of the biological signals and the beat-to-beat variation in the L-HFCs caused by the complex filtering and repeated summation-averaging required to improve the signal-to-noise ratio. Recent signal-averaged ECG studies have used a variety of high- and low-pass filters, but as these conventional filters were designed only for the terminal portion of the QRS complex or for the early ST segment, some signal distortion and filter artifact have been unavoidable. The low-frequency components dominate the energy of the QRS complex and mask the HFCs. Furthermore, the L-HFCs within the QRS complex were undetectable in most of the previous studies that used the signal-averaging method. We report a novel ECG subtraction method for extracting the L-HFCs from within the QRS complex.

Methods

Subjects
The subjects consisted of 25 healthy volunteers (Healthy group) and 58 patients with a previous myocardial infarction (MI): 21 consecutive patients with acute MI admitted to hospital between January 1995 and December 1997, and 37 patients with VT or suspected VT who were admitted between February 1990 and December 1994. The 58 patients were classified into 3 groups from the results of routine ECG check-ups and clinical Holter ECG studies: 38 patients without a history of VT (noVT-MI group), 13 patients with clinically documented spontaneous non-sustained VT (non-susVT-MI group) and 7 patients with clinically documented spontaneous sustained VT (susVT-MI group) (Table 1). The Healthy group consisted of all males (mean age, 28±2 years), the noVT-MI group had 33 males and 5 females (mean age, 60±12 years; 21 anterior MI and 17 inferior MI), the non-susVT-MI group had all males (mean age, 52±13 years; 10 anterior MI and 3 inferior MI), and the susVT-MI group comprised 6 males and 1 female (mean age, 61±8 years; 3 anterior MI and 4 inferior MI). The left ventricular ejection fraction was significantly less in the susVT-MI group (mean 36.2±5.6%, range 30–48%) than in the noVT-MI group (mean 53.3±12.6%, range 32–78%) and the non-susVT-MI group (mean 48.0±8.7%, range 34–61%). There was no significant difference in left ventricular ejection fraction between the susVT-MI and non-susVT-MI groups.
Non-sustained VT was defined as 5 or more consecutive premature ventricular complexes at a rate of more than 120 beats/min lasting less than 30 s. VT lasting more than 30 s was classified as sustained. Cases of acute MI within 4 weeks prior to the study, bundle branch block, accessory pathways, or atrial fibrillation were excluded. None of the patients were on antiarrhythmic medication at the time of the study. Most of the patients were observed by cardiologists at St Marianna University Hospital or affiliated hospitals every 2–4 weeks, with a mean follow up period of 45 months (range: 2–110 months). Informed consent to participate in the study was obtained from all the subjects.

**ECG Subtraction Method**

In the ECG subtraction method, a mathematical filtering procedure was used instead of the conventional complex filtering, to extract the low-frequency components from the original signals (Fig 1). The first step was to make the low-frequency components [B] from the original waves [A] using signal smoothing with a moving average method. For the second step, the low-frequency components [B] were subtracted from the original waves [A], which allowed only the L-HFCS to remain. For the last step, the L-HFCS were amplified and smoothed by a high-cut filter to reduce the noise in the super high-frequency zone to obtain the subtraction ECG [C]. Changing the filter characteristics, such as the number of smoothing times, subtraction times, point of the moving average and final smoothing times, were very easy with this method. Finally a magnitude display of the subtraction ECG [D] was calculated for each point of the subtraction wave by the following formula:

\[
\text{Magnitude display of the subtraction ECG } (t) = \sqrt{Z(t)^2}
\]

**Data Acquisition**

Recording of data was performed in an electromagnetic shield room. The hair on the chest was shaved as needed for proper electrode attachment. After thorough cleaning and mild abrasion of the skin with a skin cleanser, silver/silver chloride ECG electrodes (Magnerode, Fukuda Denshi, Inc, Tokyo, Japan) were applied for a Z-lead terminal at the fifth intercostal space along the mid-clavicular line (positive electrode) and at an opposite point on the posterior chest (negative electrode). The original ECG signals were obtained using a bipolar Z-lead, amplified approximately 4,000-fold by a preamplifier (LA-804, Fukuda Denshi, Inc) and digitized at 5,000 samples/s by a digital oscilloscope (310B, Nicolet, Inc, WI, USA) with 12-bit accuracy. The digital information stored on a floppy disk was analyzed by the ECG subtraction method with a personal computer system (Vectra-D, Hewlett-Packard, Inc, Sunnyvale, USA and Waveform BASIC) and the calculated wave was printed by an XY plotter (7470A, Hewlett-Packard, Inc).

In all of the patients, the data from 5 beats were averaged and processed. The frequency characteristics of the filters were as follows (Fig 2): the H1-filter ranged from 100 to 450 Hz, and the peak voltage response was obtained at 160 Hz; the H2-filter ranged from 120 to 450 Hz, and the peak voltage response was obtained at 200 Hz; the H3-filter

<table>
<thead>
<tr>
<th>Table 1 Clinical Data</th>
<th>Healthy group (n=25)</th>
<th>svVT-MI group (n=38)</th>
<th>non-susvt-MI group (n=13)</th>
<th>susvt-MI group (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28±2</td>
<td>60±12</td>
<td>52±13</td>
<td>61±8</td>
</tr>
<tr>
<td>Male/female</td>
<td>25/0</td>
<td>33/5</td>
<td>13/0</td>
<td>6/1</td>
</tr>
<tr>
<td>Myocardial infarction (anteroinferior)</td>
<td>–/–</td>
<td>21/17</td>
<td>10/3</td>
<td>3/4</td>
</tr>
<tr>
<td>LVEF (%)</td>
<td>53.3±12.6</td>
<td>48.0±8.7</td>
<td>36.2±5.6</td>
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</tr>
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VT, ventricular tachycardia; MI, myocardial infarction; LVEF, left ventricular ejection fraction.
ranged from 160 to 450 Hz, and the peak voltage response was obtained at 250 Hz. The following mathematical procedures were applied to obtain those filter characteristics.

1. For the H1-filtering, the signals were subtracted by the 40-times smoothed original signals, then finished with one smoothing.

2. For the H2-filtering, the signals were subtracted by the 80-times smoothed original signals. This subtraction process was repeated once, then finished with one smoothing.

3. For the H3-filtering, the signals were subtracted by the 20-times smoothed original signals. This subtraction process was repeated for 20-times, then finished with one smoothing.

Fig 3. A subtraction ECG obtained from a normal subject in the Healthy group. The unfiltered waveforms are shown in the top panel, the subtracted ECG in the middle panel, the magnitude display of the subtracted ECG in the third panel, and the H1-filtered HFCs on the left, H2-filtered HFCs in the middle and H3-filtered HFCs on the right. The L-HFCs were not sustained in any of the 3 filters (range, 13.9–19.0 ms).

Fig 4. A subtraction ECG obtained from a patient with an inferior myocardial infarction and sustained ventricular tachycardia (VT) in the susVT-MI group. The unfiltered waveforms are shown in the top panel, the subtracted ECG in the middle panel, the magnitude display of the subtracted ECG in the third panel, and the H1-filtered HFCs on the left, H2-filtered HFCs in the middle and H3-filtered HFCs on the right. Well-defined continuous L-HFCs (arrow) were present in the recording obtained from the H1, H2 and H3-filters (range, 65.5–70.2 ms).

Fig 5. A subtraction ECG obtained from a patient with an inferior myocardial infarction and non-sustained ventricular tachycardia (VT) in the non-susVT-MI group. The unfiltered waveforms are shown in the top panel, the subtracted ECG in the middle panel, the magnitude display of the subtracted ECG in the third panel, and the H1-filtered HFCs on the left, H2-filtered HFCs on the right. The H3-filter clearly demonstrates continuous L-HFCs (42.9 ms) starting from the QRS complex; however, L-HFCs were not detectable (range, 9.7–32.1 ms) with the H1 or H2-filters.
The signal was considered to be significant when it was more than twice the size of the noise level of the subtracted ECG. The noise level was measured during the ST segment over a 70 ms sample from the magnitude display of the subtraction ECG. The L-HFCs were defined as a low-amplitude signal (<10 μV) recorded from the terminal portion of the subtraction ECG. The mean noise level obtained for the H1-filter was 0.53±0.13 μV, 0.53±0.14 μV for the H2-filter and 0.49±0.13 μV for the H3-filter in the normal subject group. The duration of the L-HFCs and noise level were measured with the H1-, H2- and H3-filters.

Statistical Analysis

All statistical analyses were performed with Statview software (Abacus Concepts, Inc, Calabasas, CA, USA). All data are presented as mean ± 1 SD. A calculated p-value less than 0.05 was considered statistically significant. The duration of the L-HFCs between the clinical groups were compared with nonparametric Kruskal-Wallis testing, and posthoc testing was performed with Scheffe’s F test.

Results

Subtraction ECG of Representative Cases

Representative results of subtraction ECGs from a normal healthy subject (Fig 3), a patient with sustained VT (Fig 4) and a patient with non-sustained VT (Fig 5) are presented. The L-HFCs were not sustained after passing any of the 3 filters for all of the normal healthy subjects (range, 10.7–39.8 ms). All 7 patients with sustained VT had well-defined continuous L-HFCs starting from inside the QRS complex (as shown in Fig 4). The continuous L-HFCs were reproducibly present in all recordings obtained with the 3 filters (H1, H2, H3) in the patients with sustained VT (range, 33.3–72.6 ms with H1-filter, 46.5–72.6 ms with H2-filter and 52.4–78.6 ms with H3-filter); however, the precise amplitude and morphology of the L-HFCs varied slightly from day to day even in the analyses from the same subject. In contrast, well-defined continuous L-HFCs from the signals obtained from all 3 filter recordings were rare (1/13: 8%) in the patients with non-sustained VT. In a representative analysis from a patient with non-sustained VT (Fig 5), the H3-filter clearly demonstrated continuous L-HFCs starting from the beginning of the QRS complex; however, they were undetectable with the H1- and H2-filters. Continuous L-HFCs were detected in 6 of 13 patients with non-sustained VT with the H3-filter, but not with the other filters.

Comparison of the Duration of the Continuous L-HFCs for Each Group

The duration of the continuous L-HFCs with the H1-filter (Fig 6) was significantly longer in the susVT-MI group than in groups Healthy, noVT-MI or non-susVT-MI. The continuous L-HFCs duration was significantly longer in the susVT-MI group than in the Healthy group. VT, ventricular tachycardia.

The duration of the continuous L-HFCs for the H2-filter was significantly longer in the susVT-MI group than in groups Healthy, noVT-MI or non-susVT-MI. The continuous L-HFCs duration was significantly longer in non-susVT-MI group than in Healthy group. VT, ventricular tachycardia.

The duration of the continuous L-HFCs for the H3-filter was significantly longer in group susVT-MI group than in groups Healthy, noVT-MI or non-susVT-MI. The continuous L-HFCs duration was significantly longer in non-susVT-MI group than in Healthy group. VT, ventricular tachycardia.
(Fig 7) was significantly longer in the susVT-MI group (54.4±8.8 ms) than in the Healthy group (24.7±6.0 ms, p<0.0001), noVT-MI group (29.1±12.0 ms, p=0.0001) or non-susVT-MI group (37.2±18.5 ms, p=0.006). Furthermore, the duration of the continuous L-HFCs with the H2-filter was significantly longer in the non-susVT-MI group than in the Healthy group (p=0.024).

The duration of the continuous L-HFCs with the H3-filter (Fig 8) was significantly longer in the susVT-MI group (61.4±9.8 ms) than in the Healthy group (26.5±7.3 ms, p<0.0001), noVT-MI group (34.2±12.4 ms, p=0.0001) or non-susVT-MI group (44.6±17.1 ms, p=0.034). Furthermore, the duration of the continuous L-HFCs with the H3-filter was significantly longer in the non-susVT-MI group than in the Healthy group (p=0.0004). There was no significant difference in the duration of the continuous L-HFCs between the noVT-MI group and non-susVT-MI group for the H1-filter (p=0.377), H2-filter (p=0.198) or H3-filter (p=0.064).

**Discussion**

The high-frequency (>80 Hz) components of the QRS complex are less than 3% of the total voltage11 but some investigators have suggested that these components might be helpful in the prediction of VT in certain patients.14-17 In previous studies, the HFCs were estimated by counting the number of notches and slurs of the QRS complex on a high-fidelity ECG.1-3 but recently, high gain amplifications and signal-averaging techniques have been reported in the evaluation of the quantitative magnitude of the L-HFCs of the terminal portion of the QRS complex or the early portion of the ST segment on the signal-averaged ECG.4-8 The L-HFCs of the terminal portion of the QRS complex or the early portion of the ST segment are considered 'late potentials' and are associated either directly or indirectly with the presence of a non-sustained VT substrate.9,10,12 It has been suggested that these signals could be a non-invasive predictor of sustained VT11,12,18,19 or of the risk for sudden cardiac death9,10,12,19,20 particularly in patients with a history of MI.

The signal-averaged ECG is a well-established technique for improving the signal-to-noise ratio on the body surface ECG. The level of noise will be reduced by a factor of \( \frac{1}{\sqrt{N}} \), where \( N \) is the number of averaged beats. The typical signal-averaged ECG is obtained from the analysis of 100–600 beats, and no less than 64 beats.22 The conventional signal-averaged ECG studies have some inherent limitations for the analysis of the L-HFCs. First, the HFCs tend to be attenuated because of trigger jitter, which can operate as a low-pass filter and mask the L-HFCs. Even with a 100-beat signal-averaged ECG system with a reference jitter of ±1 ms, the –3 dB cut-off point falls at 134 Hz. Other investigators have reported a jitter value of 0.5–2.0 ms.6,11,18 These observations suggest that high-frequency signals greater than 140 Hz are likely to be attenuated. Secondly, repeated signal averaging causes somewhat variable L-HFCs because of the beat-to-beat variation. The third limitation is the difficulty in changing the filter characteristics. Previous signal-averaged ECG studies utilized various high- and low-pass filters, but these filters were designed to detect the L-HFCs in the terminal portion of the QRS complex and were not suitable for detection of the L-HFCs within the QRS complex.

In contrast, our method has 4 novel aspects. First, the subtraction ECG method requires fewer ECG signals to be averaged than the conventional signal-averaging method: in the present study an analysis of the recordings from as few as 5 beats successfully revealed L-HFCs. Secondly, there is an extremely low level of noise. The amplitude of the clinically important signals (ie, the continuous L-HFCs in patients with VT) is only 10 μV, and the accepted guideline for signal-averaging is 0.7 μV.23 However, with our method, the noise levels were only from 0.49–0.53 μV for all 3 filters, which allowed us to clearly distinguish the signals from noise. In order to reduce the noise, we recorded the original signals from the Z-lead with careful application of the electrodes so that the L-HFCs are hardly attenuated and respiratory movement and electromyograms have little effect on the recordings.24 Thirdly, conventional complex filtering is not necessary, which allows us to avoid a possible source of signal distortion and filter artifact. Finally, the filter characteristics can be easily modified by simply changing the number of smoothing passes and subtractions, as well as the number of moving average points. We tried several patterns of filtering maneuvers to determine the optimal characteristics of the filters to detect the L-HFCs not only in the terminal portion of the QRS complex as reported in the previous studies, but also within the QRS complex.25,26 The advantages of the ECG subtraction method enabled us to detect continuous L-HFCs starting from the inside the QRS complex and so we believe our method is better than the conventional signal-averaging method.

With regard to clinical application, the continuous L-HFCs were present in all recordings made with the 3 filters in the patients with sustained VT, whereas they were absent in the normal healthy subjects. The duration of the continuous L-HFCs in the patients with subsequent sustained VT was significantly longer than in the non-sustained VT patients, patients without VT or the normal healthy subjects. From these results, the patients with sustained VT can quite easily be differentiated. The frequency band of the late potential was reported by Cain et al to have a peak below 120 Hz; however, we have more distinctive features with the sharpest low-cut H3-filter. Some of the present patients with non-sustained VT had well-defined continuous L-HFCs only with the H3-filter and they were undetectable with the H1- and/or H2-filters. Those results suggest that the details of the HFCs within the QRS complex were clarified by our new method and we could differentiate patients with and without VT by the detection of L-HFCs using the H3-filter. The following 3 mechanisms may be involved: (1) low-frequency components may dominate the energy of the QRS complex, masking the continuous L-HFCs, (2) alteration of the HFCs is the remains of the QRS complex and (3) the alteration of the signal bands of the HFCs is caused by variation in the individual’s myocardial substrate.27

Our new ECG subtraction method appears to be a powerful and useful new technique for identifying patients at risk for sustained VT and non-sustained VT after MI, and overcomes several of the problems of the conventional signal-averaging method. Further prospective studies with a large number of patients are warranted. L-HFCs may drift with time after MI, with circadian rhythm or with day-to-day changes in condition, so further and detailed analysis is needed.

**References**


2. Langner PH. The value of high fidelity electrocardiography using the...
cathode ray oscillograph and an expanded time scale. *Circulation* 1952; 5: 249 – 256.


