Improved Frequency-Domain Analysis of Ventricular Late Potentials

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Abstract

Many methods of segment selection of various lengths and locations in the high-frequency spectral analysis of ventricular late potentials (VLPs) in signal-averaged electrocardiograms (SAECGs) have been demonstrated to yield conflicting results in clinical applications. This work compares of a new locally developed method with two existing methods for detecting VLPs in the frequency domain.

A total of 154 normal individuals, 94 patients with frequent ventricular premature contraction (VPC) and 26 patients with sustained ventricular tachycardia (VT) were recruited for the study. Two existing methods use a 120 ms time segment, starting from 20 ms before spatial vector velocity < 5 mV/s and vector magnitude < 40 μV at the terminal QRS complex, to analyze the VLPs. A locally developed 80 ms segment, starting from 60 ms before the QRS offset, was shown to outperform these two currently adopted methods. The areas under the receiver operating curves (AUCs) of the root-mean-square amplitude (RMSA) in the 60 to 120 Hz band were 82.2 % versus 60.2 % and 55.2 %, and the AUCs of the RMSA ratio (RMSAR) (100 × [60 to 120 Hz RMSA / 0 to 120 Hz RMSA]) were 77.2 % versus 54.9 % and 53.1 %.

The locally developed method, which uses the QRS offset as a reference for selecting segments is determined substantially to improve VLPs analysis in the frequency domain.

1. Introduction

The ventricular late potentials (VLPs) from high-resolution electrocardiograms have become an important marker in the evaluation of high-risk patients with ventricular tachycardia (VT) [1]. Although the use time-domain analysis of the signal averaged electrocardiogram (SAECG) has been well established in identifying patients with VT in certain clinical settings, no consensus exists for analysis in the frequency domain or other transformations [2,3].

Many studies have developed high-frequency spectral analysis, based on fast Fourier transformation (FFT). The pre-defined segment of SAECG enables the spectral area in the high-frequency band to be used along with the spectral area ratio to identify high-risk VT patients [4-7]. This approach has been claimed to be superior to analysis in the time domain. However, no conclusive method is available for defining the most suitable time segment (including determining its starting point and its length).

The aim of the study is to develop novel segment selection to improve the high-frequency analysis of VLPs in SAECG and to compare it to the two existing methods.

2. Methods

2.1. Materials

Group I (normal group) comprised 154 normal healthy Taiwanese (65 men and 89 women, aged 36±16, ranging from 18 to 81 years old). They were students and teaching staff from Jen-Chi General Hospital and the Chin Min College of Technology and Commerce. All individuals had a normal clinical history, and the results of their physical examination, 12-lead ECG and echocardiogram were normal.

Group II (as VPC group) included 94 ventricular premature contraction (VPC) patients (43 men and 51 women, aged 64±13, ranging from 28 to 88 years old) from the Cardiology Department of Jen-Chi General Hospital. Their total VPC in 24-hour Holter recording exceeded 240 without any history of sustained VT [8].

Group III (as VT group) consisted of 26 patients (13 men and 13 women, aged 65±17, ranging from 30 to 91 years old) from the Cardiology Department of Jen-Chi General Hospital. Their sustained VT was also recorded by 24-hour Holter ECG monitoring [8]. They all suffered from chronic ischemic heart disease and survived clinically documented myocardial infarction.

2.2. High-resolution ECG recording and time-domain SAECG analysis

High-resolution ECGs were recorded using a commercially available Simens-Elema Megacart® machine with a bipolar, orthogonal X, Y and Z, lead system. The raw ECG signal was digitized using an analog-to-digital device in a personal computer at a sampling rate of 2,000 Hz with a 12-bit resolution. Ten

minutes of signals were stored on a hard disk for subsequent analysis.

Signal averaging was performed offline and the final noise level of the SAECG, obtained using a 40 to 250 Hz filter, was set at 0.6 μV [2,3]. After the signals had been averaged and filtered, they were combined into a vector magnitude (VM) $\sqrt{X^2+Y^2+Z^2}$. The following three time-domain parameters were calculated: the filtered total QRS duration (fQRSD), the root-mean-square voltage of the last 40 ms of the QRS complex (RMS40) and the duration of the low-amplitude signals below 40 μV of the terminal QRS complex (LAS40). On both sides of the QRS complex in VM, when the mean amplitude of the 5 ms segment was lower than the mean plus three times the standard deviation of the noise sample, then the midpoints of the 5 ms segment were separately defined as the onset and offset points.

The criteria applied in the time-domain SAECG were fQRSD > 114 ms, LAS40 > 38 ms and RMS40 < 20 μV using a 40 to 250 Hz filter [2,3]. If two or more of these criteria were satisfied, then VLPs were considered to be present.

2.3. High-frequency spectral analysis of SAECG

2.3.1. Selecting time segments

A new locally developed method (method 3) was compared to two methods currently used (methods 1 and 2) in the spectral analysis of SAECG.

Haberl et al. [6] proposed Method 1 in 1988. They defined a 120 ms segment, starting 20 ms before the spatial vector velocity (SVV) < 5 mV/s. The point at which SVV < 5 mV/s was defined as the end of the normal QRS and VLPs were left outside the QRS.

Pierce et al. [7] proposed Method 2 in 1989. They defined a 120 ms segment, starting from VM < 40 μV using a 25 to 250 Hz filter. The point VM < 40 μV was defined as the onset of VLPs.

Basically, methods 1 and 2 focus on finding the starting point of VLPs. They are illustrated as segments {A} in Figs. 1(a) and 1(b). When VLPs were present, the high-frequency components in segment {A} were larger. Their performance was dominated primarily on the accuracy of the determination of the starting point of the VLPs.

When no VLPs were present (as in Fig. 1(a)), the onset of segment {A} was easily determined as the end of the normal QRS. If VLPs were present (as in Fig. 1(b)), they were mixed with the QRS complex and the starting point had to separate them from the QRS complex. However, identifying the starting of segment {A} that clearly separates VLPs from the terminal QRS is relatively difficult.

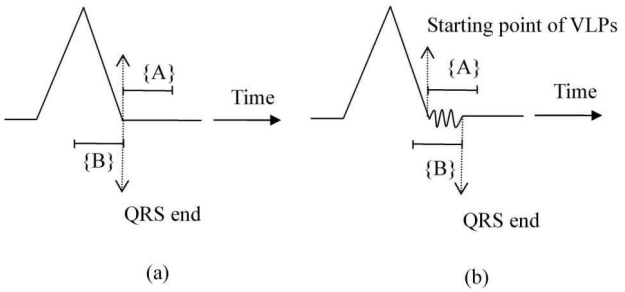

Figure 1. Two segments defined for high-frequency analysis at the terminal QRS complex; (a) QRS complex without VLPs and (b) VLPs in the terminal QRS. The triangular wave represents the high-frequency components of the normal QRS complex.

The new method 3 was developed for high-frequency spectral analysis: an 80 ms segment is defined to start 60 ms before the QRS offset. This segment uses the offset of the entire QRS complex as a reference point which included VLPs; it does not require the onset of VLPs to be determined. The offset was defined as in VM analysis using a 40 to 250 Hz filter. This segment is shown as {B} in Figs. 1(a) and 1(b). When VLPs are present in segment {B}, the offset of the QRS is delayed and the high-frequency components in segment {B} are weakened.

2.3.2. Spectral analysis

Before spectral analysis, the direct current components of the time segments were removed and multiplied by a Blackman Harris window with a -92 dB side lobe, to reduce the high-frequency interference of the edge discontinuity. The windowed signals were then zero-padded to 256 ms to keep the spectral resolution. A spectral calculation, based on the FFT algorithm, was performed as follows.

$$X[k]=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}x[n]e^{-j(2\pi/N)kn},$$

where N is the length of the segment.

2.3.3. Definitions of spectral parameters

The root-mean-square value of spectral amplitude (RMSA, μV) in the range 60 to 120 Hz and the ratio RMSA (RMSAR, %) between 60 to 120 Hz and 0 to 120 Hz (100×[60 to 120 Hz RMSA / 0 to 120 Hz RMSA]) were defined to evaluate the presence or absence of VLPs. RMSA and RMSAR analyses were performed on the composite lead ($\sqrt{X^2+Y^2+Z^2}$).

2.4. Statistical methods

Results were presented as mean ± standard deviation

(SD). The Statistical Package for the Social Sciences (SPSS®) was used to conduct all statistical analysis. Normal distribution tests were performed on all quantitative variables [9]. Paired groups were compared using Student's t test for normally distributed continuous variables. The Mann Whitney U and Wilcoxon Rank Sum tests were employed for non-normally distributed variables [10]. Statistical significance was defined as a p value of less than 0.05.

The receiver operating characteristic (ROC) curve [11] was applied to analyze the global performance. Each point on the ROC plot represents a specificity / sensitivity pair that corresponds to a particular decision threshold. The area under the receiver operating characteristic curve (AUC) was used as an index to quantify the global performance of the diagnosis (0.5 □AUC □1) [11,12].

3. Results

Table 1 lists time-domain parameters for normal, VPC and VT groups. Statistically significant differences are obtained between the non-VT group (normal plus VPC) and VT group with respect to all parameters. By the 1991 AHA/ACC/ESC diagnostic criteria [2], the specificity is 88.9 % and the sensitivity is 46.2 %.

The results of high-frequency spectral analysis (Table 2) show that both RMSA and RMSAR differed significantly ($p<0.001$) between non-VT and VT groups according to method 3, but not method 1 or 2. The mean RMSA and RMSAR of the non-VT group were significantly larger than those of the VT group, according to method 3.

Table 1. Results of time-domain analysis using 40 to 250 Hz filter

Variable	Non-VT		VT (N=26)	p-value*
	Normal (N=154)	VPC (N=94)		
fQRSD (ms)	90.4 ± 8.6	92.1 ± 9.6	95.7 ± 7.8	< 0.01
LAS40 (ms)	30.5 ± 7.4	31.1 ± 7.9	37.0 ± 7.0	< 0.001
RMS40 (μV)	42.2 ± 25.5	35.0 ± 19.8	20.6 ± 9.1	< 0.001

*The p-value is determined by the equivalent non-parametric Mann Whitney U and Wilcoxon Ranked Sum tests to evaluate statistical significance of the difference between non-VT and VT groups.

Table 2. Results of high-frequency spectral analysis

	Non-VT		VT (N=26)	p value*
	Normal (N=154)	VPC (N=94)		
Method 1†,				
RMSA (μV)	0.73 ± 0.17	0.75 ± 0.18	0.67 ± 0.15	NS
RMSAR (%)	1.66 ± 0.57	1.72 ± 0.72	1.63 ± 0.61	NS
Method 2†,				
RMSA (μV)	0.79 ± 0.23	0.85 ± 0.39	0.94 ± 0.52	NS
RMSAR (%)	1.55 ± 0.76	1.59 ± 0.94	1.38 ± 0.63	NS
Method 3†,				
RMSA (μV)	47.0 ± 30.5	39.2 ± 24.3	22.5 ± 10.0	< 0.001
RMSAR (%)	8.30 ± 3.98	7.62 ± 2.74	5.54 ± 2.12	< 0.001

†Methods 1, 2 and 3 defined a 120 ms segment starting from 20 ms before spatial vector velocity (SVV) < 5mV/s, a 120 ms segment starting from vector magnitude (VM) < 40μV at 25 to 250 Hz, and an 80 ms segment starting from 60 ms before QRS offset. *The p-value is determined by the equivalent non-parametric Mann Whitney U and Wilcoxon Ranked Sum tests, to evaluate statistical significance of the difference between non-VT and VT groups. NS: non-significant ($p > 0.05$). RMSA = root-mean-square amplitude in range 60 to 120 Hz. RMSAR = the ratio of RMSA from 60 to 120 Hz to that from 0 to 120 Hz.

The analyzes of ROC curves were performed on all parameters, including RMSA in the 60 to 120 Hz band, RMSAR from 60 to 120 Hz and from 0 to 120 Hz, and the time-domain parameters. The RMSA obtained using method 3 has the best global performance (AUC = 82.2 %), next were the RMS40 in the time-domain analysis (AUC = 79.1 %) and the RMSAR determined by method 3 (AUC = 77.2 %). Neither RMSA nor RMSAR in method 1 or 2, can significantly separate VT from non-VT, so their AUCs are only 53.1 % to 60.2 %. Given 90 %-specificity, the best sensitivity is 46.2 % for RMSA according to method 3. This local performance is similar to time-domain analysis in terms of sensitivity but with a better specificity (88.9 % specificity and 46.2 % sensitivity).

4. Discussion and conclusions

The results demonstrate that neither method 1 or 2 can effectively distinguish VT from non-VT when applied to

the locally recruited study subject. This error might arise from the inaccuracy of the location of the VLP segments, as they are defined. The 120 ms length of the VLPs segment (compared with 6 ms differences of the mean LAS40) would enclose certain non-VLPs signals.

The proposed method, in which an 80 ms segment is used (with the offset of QRS as a reference point) was used to improve the spectral analysis. This method provides the advantage of not requiring the determination of the uncertainty in the onset of VLPs. The spectral parameters of RMSA and RMSAR according to this method can significantly distinguish VT from non-VT with a statistically significant reduction of mean RMSA from the normal group to the VT group (VT < VPC < normal). Therefore, a smaller RMSA corresponds to a higher risk of ventricular arrhythmias.

The results of AUC also indicate that the proposed method exhibits much better clinical performance than the two existing methods (AUCs of RMSA were 82.2 % versus 60.2 % and 55. 2 %, and AUCs of RMSAR were 77.2 % versus 54.9 % and 53.1 %). Hence, the newly introduced segment for the high-frequency spectral analysis of VLPs can improve the clinical performance of frequency-domain analysis, as tested on the subjects in this study.

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