Analysis of Noise Level Effects on Signal-Averaged Electrocardiograms

Chun-Cheng Lin

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***Abstract*—**Noise level has critical effects on the diagnostic performance of signal-averaged electrocardiogram (SAECG), because the true starting and end points of QRS complex would be masked by the residual noise and sensitive to the noise level. Several studies and commercial machines have used a fixed number of heart beats (typically between 200 to 600 beats) or set a predefined noise level (typically between 0.3 to 1.0 μV) in each X, Y and Z lead to perform SAECG analysis. However different criteria or methods used to perform SAECG would cause the discrepancies of the noise levels among study subjects. According to the recommendations of 1991 ESC, AHA and ACC Task Force Consensus Document for the use of SAECG, the determinations of onset and offset are related closely to the mean and standard deviation of noise sample. Hence this study would try to perform SAECG using consistent root-mean-square (RMS) noise levels among study subjects and analyze the noise level effects on SAECG. This study would also evaluate the differences between normal subjects and chronic renal failure (CRF) patients in the time-domain SAECG parameters.

The study subjects were composed of 50 normal Taiwanese and 20 CRF patients. During the signal-averaged processing, different RMS noise levels were adjusted to evaluate their effects on three time domain parameters (1) filtered total QRS duration (fQRSD), (2) RMS voltage of the last QRS 40 ms (RMS40), and (3) duration of the low amplitude signals below 40 μV (LAS40). The study results demonstrated that the reduction of RMS noise level can increase fQRSD and LAS40 and decrease the RMS40, and can further increase the differences of fQRSD and RMS40 between normal subjects and CRF patients. The SAECG may also become abnormal due to the reduction of RMS noise level. In conclusion, it is essential to establish diagnostic criteria of SAECG using consistent RMS noise levels for the reduction of the noise level effects.

***Keywords*—**Signal-averaged electrocardiogram, Ventricular late potentials, Chronic renal failure, Noise level effects.

I. Introduction

FROM the body surface electrocardiogram (ECG) recording, the low amplitude, high frequency ventricular late potentials (VLPs) in the terminal QRS complex is an important noninvasive marker for the detection of patients with high risk ventricular arrhythmias [1-6]. To reduce the effects from the background noise on the detection of VLPs, signal-averaging technique has been widely used in order to reduce the noise level of electrocardiograms [7, 8].

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After signal averaged electrocardiogram (SAECG) is performed, three standardized time-domain parameters in reference to the starting point (onset) and end point (offset) of QRS complex, namely (1) filtered total QRS duration (fQRSD), (2) RMS voltage of the last QRS 40 ms (RMS40), and (3) duration of the low amplitude signals below 40 μV (LAS40), can be used to detect the presence of VLPs [9, 10].

According to the recommendations of an ACC Expert Consensus Document [10] for use of SAECG, the established clinical values are for the stratification of the risk of development of sustained ventricular arrhythmias in patients who are recovering from myocardial infarction, and for the identification of patients with ischemic heart disease and unexplained syncope. Several recent studies also applied time-domain VLP analysis to evaluate the risk of ventricular arrhythmias for symptomatic and asymptomatic patients with Brugada syndrome [11], Chagas disease patients [12] and patients with arrhythmogenic right ventricular cardiomyopathy [13]. SAECG has also been used in the evaluation of hemodialysis effects and shown significant changes in time-domain parameters [14-17]. It is well documented that ventricular arrhythmias and sudden death are much more easily induced during hemodialysis in chronic renal failure (CRF) patients [18]. Nevertheless, there is no consistent trend of changes in these parameters. Therefore, the feasibility of applying SAECG in CRF patients requires further clarification.

Although signal averaging can reduce the residual noises to a certain extent, it cannot eradicate them completely. The true onset and offset of QRS complex would be masked by the residual noise and sensitive to the noise level. The method for determining the noise sample and final noise level have not been unified up to now. Several studies have used a fixed number of heart beats (typically between 200 to 600 beats) or set a predefined noise level (typically between 0.3 to 1.0 μV) in each X, Y and Z lead to perform SAECG, and tried to evaluate their effects on the analysis of SAECG [19-25]. However, different criteria or methods used to perform SAECG would cause discrepant noise levels [24]. This would directly affect the determination of onset and offset, and SAECG parameters.

According to the 1991 ESC, AHA and ACC Task Force consensus on SAECG standards [9], final noise level was measured by root mean square (RMS) method from summation vector magnitude (VM) of the X, Y, and Z leads and should be less than 1 μV or 0.7 μV by using 25 Hz or 40 Hz Butterworth filter, respectively. In order to having consistent noise level in the VM analysis, this study would try to perform SAECG using consistent RMS noise levels among study subjects instead of using a fixed number of heart beats or a predefined noise level in each lead for analyzing the noise level effects on SAECG parameters. Another purpose of this study is to analyze the differences between normal subjects and CRF patients in the time-domain SAECG parameters.

II. Materials and Methods

A. Materials

The study subjects were composed of 50 normal Taiwanese (49 men and 1 woman, aged 23 ± 8 years old) and 20 CRF patients (11 men and 9 women, aged 56 ± 13 years old). All of the normal subjects had a normal medical history, physical examination, chest X-ray, 12-lead ECGs, echocardiograms and renal function test (creatinine, uric acid and BUN). The CRF patients were undergoing regular long-term maintenance hemodialysis therapy at Jen-Chi General Hospital in Taiwan. Thrice weekly maintenance hemodialysis therapy using Althin® artificial kidneys were performed with bicarbonate dialysate fluid for an average of four hours period among these CRF patients.

B. High resolution electrocardiogram recording

The high resolution electrocardiograms were recorded at rest in a supine position using a commercially available Simens-Elema Megacart® machine. A bipolar, orthogonal X, Y and Z lead system was used [9] and a sample of 10 min raw ECG with 12-bit resolution at 2 kHz was stored on computer hard disk for subsequent analysis. The time-domain SAECG analyses under different RMS noise levels were performed offline.

C. Signal averaging and noise measurement methods

Offline signal averaging procedure in our program followed the standards of 1991 ESC, AHA and ACC Task Force [9]. Before signal averaging was performed, the first template, which was 48 points in length and spanned for 384ms, was chosen automatically by the computer program for alignment. The fiducial point was the maximum point of QRS complex. The X lead served as a reference for all processing. Each incoming heartbeat was aligned with the template waveform. An alignment was accepted when the correlation coefficient is larger than 0.98. The template was then updated every eight beats averaged to prevent any possible corruption from proliferation. Assume the *i*th aligned beat $b_i(n)$ can be expressed as follows

$$b_i(n) = s(n) + d_i(n)\ , \tag{1}$$

where $s(n)$ denotes the deterministic noise-free ECG signal including VLPs, and $d_i(n)$ is the *i*th background noise. The SAECG with *N*-beat averaged can be calculated as

$$\text{SAECG} = \frac{1}{N}\sum_{i=1}^{N} b_i(n) = s(n) + \frac{1}{N}\sum_{i=1}^{N} d_i(n) \tag{2}$$

If the background noise is a random signal and uncorrelated with itself or the deterministic signal $s(n)$, the signal-to-noise ratio can be reduced by a factor of $\sqrt{N}$ [7, 8]. In order to quantify the noise level and analyze the time-domain SAECG parameters, each averaged ECG of lead X, Y and Z was filtered with a four-pole 40-250 Hz high-pass Butterworth filter working with the bi-directional mode. The filtered X, Y and Z signals were further combined to form a vector magnitude, also called the filtered QRS complex, defined as

$$\text{VM} = \sqrt{\text{X}^2 + \text{Y}^2 + \text{Z}^2} \tag{3}$$

The noise level was quantified by the RMS value of a 40 ms noise segment where the RMS voltage was smallest in the ST segment of the filtered QRS complex. The onset and offset of SAECG were defined as the midpoint of the 5-ms segment in which the mean voltage exceeded the mean noise level plus three times the standard deviation of the noise sample. Three time domain parameters in reference to the onset and offset of QRS complex (fQRSD, RMS40 and LAS40) are used in detecting the presence of VLPs. Specifically, they were defined as (a) fQRSD > 114 ms, (b) RMS40 < 20 μV and (c) LAS 40 > 38 ms [9,10].

To evaluate the effects of noise level on SAECG analysis, this study adopted four RMS noise levels of 1.1, 0.9, 0.7 and 0.5 μV as the threshold to perform SAECG. If the RMS noise level of SAECG is below the predefined threshold, the program immediately terminated the signal averaging process.

D. Statistical methods

All statistical analysis was done with Statistical Package for the Social Sciences®. Data are presented as mean ± standard deviation (SD). The methods used consisted of Student's t test for comparing means of two independent variables, F test for the variance comparisons between variables, analysis of variance (ANOVA) for comparing means and seeking the existence of any significant differences among more than two independent variables, and linear regression to test for correlation between variables. A highly significant correlation was regarded as present, when the cross correlation coefficient, *r*, is greater than 0.7 or less than -0.7. Statistical significance was defined as *p* value less than 0.05.

III. Results

A. Effects of RMS noise level reduction

Figure 1 compares the analytical results of VM for one normal subject including onset, offset, fQRSD, RMS40, LAS40, final RMS noise level and the 40 ms noise segment with smallest RMS value in ST segment using different threshold values of RMS noise levels. The final RMS noise levels were reached at 1.06, 0.85, 0.69 and 0.49 μV in Figs. 1(a), 1(b), 1(c) and 1(d), respectively, as the threshold of RMS noise level for performing SAECG were set at 1.1, 0.9, 0.7 and 0.5 μV, respectively.

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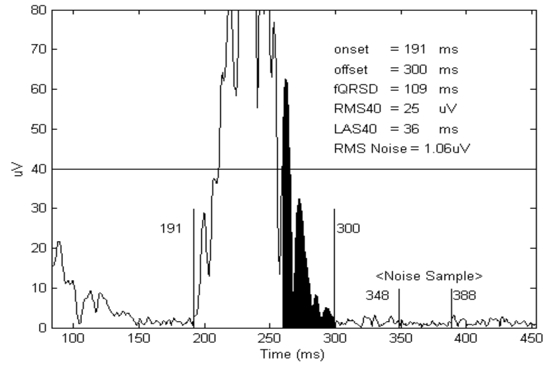
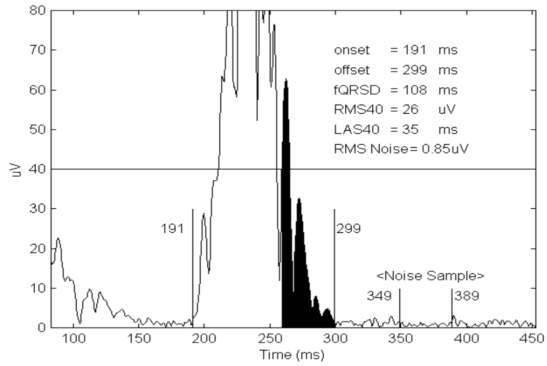
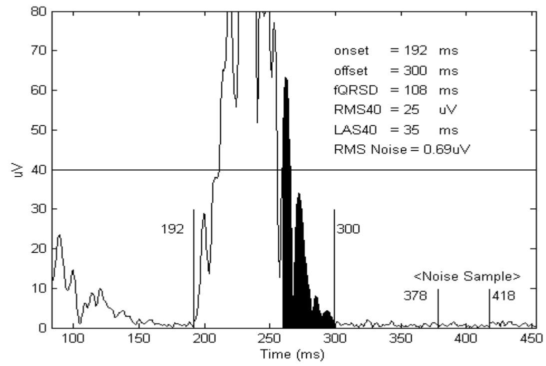


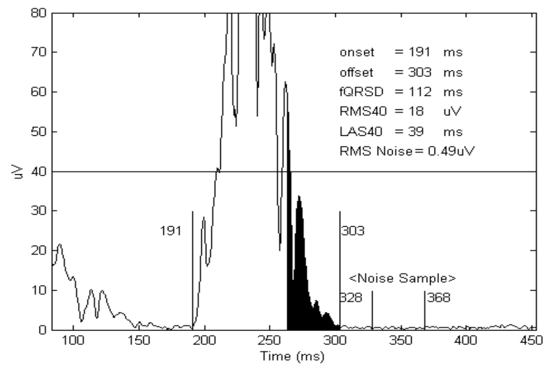
(a)



(b)



(c)



(d)

Fig. 1 Analytical results of VM for one normal subject using the RMS noise levels of (a) 1.1, (b) 0.9, (c) 0.7 and (d) 0.5 μV as the threshold to perform SAECG.

TABLE I
SUMMARY OF TIME-DOMAIN SAECG PARAMETERS FOR NORMAL SUBJECTS AT DIFFERENT RMS NOISE LEVELS

Normal subjects					
Threshold	RMS Noise Level	No. of Averaged Heart Beats	SAECG parameters		
			fQRSD	RMS40	LAS40
1.1	1.03 ± 0.06	88 ± 52	91 ± 9	63 ± 43	26 ± 9
0.9	0.85 ± 0.04	128 ± 69	93 ± 8†	57 ± 36*	27 ± 8*
0.7	0.67 ± 0.03	194 ± 107	95 ± 8‡	53 ± 34†	28 ± 9‡
0.5	0.49 ± 0.01	280 ± 112	97 ± 8‡	50 ± 30‡	28 ± 8‡

*: p <0.05, †: p <0.01, ‡: p <0.001 compared to the parameters with the threshold of 1.1 μV.

TABLE II
SUMMARY OF TIME-DOMAIN SAECG PARAMETERS FOR CRF PATIENTS AT DIFFERENT RMS NOISE LEVELS

CRF patients					
Threshold	RMS Noise Level	No. of Averaged Heart Beats	SAECG parameters		
			fQRSD	RMS40	LAS40
1.1	1.00 ± 0.07	53 ± 47	88 ± 9	81 ± 43	23 ± 7
0.9	0.84 ± 0.04	83 ± 57	89 ± 9†	80 ± 42^{NS}	23 ± 7^{NS}
0.7	0.66 ± 0.03	127 ± 81	90 ± 10‡	76 ± 44*	24 ± 7†
0.5	0.43 ± 0.03	230 ± 90	92 ± 10‡	73 ± 43†	25 ± 7‡

*: p <0.05, †: p <0.01, ‡: p <0.001, ^{NS}: p>0.05 compared to the parameters with the threshold of 1.1 μV.

It is worth to note that all time-domain SAECG parameters including fQRSD, RMS40 and LAS40 were in normal range as the RMS noise level was set at 1.1, 0.9 or 0.7 μV, but SAECG became abnormal as the RMS noise level was reduced to be 0.5 μV. Comparing the results when the RMS noise levels were reduced from 1.1 to 0.5 μV, both fQRSD and LAS40 were prolonged from 109 to 112 ms and 36 to 39 ms, and RMS40 was reduced from 25 to 18 μV. Table 1 and 2 further summarize the time-domain SAECG parameters for normal subjects and CRF patients using different RMS noise levels. The standard deviations of final RMS noise levels corresponding to the thresholds of 1.1, 0.9, 0.7 and 0.5 μV were only ranged from 0.07 to 0.01 μV. It is also obvious to observe that both the mean values of fQRSD and LAS40 were prolonged and the mean RMS40 was reduced along with the reduced RMS noise levels. The increase of fQRSD and LAS40 and the decrease of RMS40 were all significant in comparison with the results of 1.1 μV RMS noise level.

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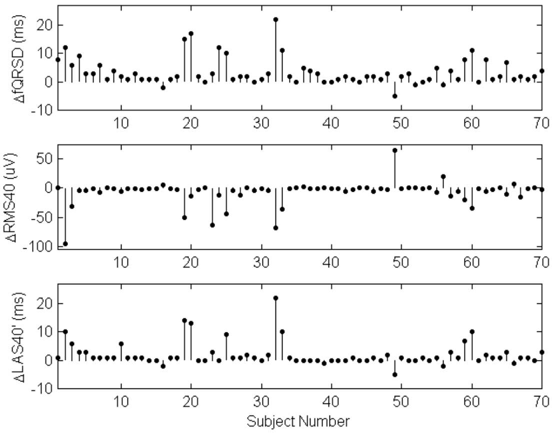

Fig. 2 Increased values of three time-domain parameters as the RMS noise level was reduced from 1.1 to 0.7 μV for all normal subjects and CRF patients.

B. Correlation analysis among variations of time-domain parameters

This study also tried to analyze the correlations among variations of time-domain parameters because of the reductions of RMS noise level. Figure 2 plots the increased values of three time-domain parameters as the RMS noise level was reduced from 1.1 to 0.7 μV for all normal subjects and CRF patients. The ΔfQRSD, ΔRMS40 and ΔLAS40 denote the increased values of fQRSD, RMS40 and LAS40, respectively. Figure 2 shows a similar trend among the variations of three time-domain parameters. The linear regression method was further adopted to statistically analyze their correlations. Table 3 shows the results of correlation analysis for the variations of time-domain parameters while the RMS noise level was reduced from 1.1 to 0.7 μV. The results of correlation analysis demonstrate that a highly significant negative correlations exists ($r < -0.7$, $p < 0.01$) between ΔRMS40 and ΔfQRSD, and between ΔRMS40 and ΔLAS40, whereas a highly significant positive correlation exists ($r > 0.7$, $p < 0.01$) between ΔfQRSD and ΔLAS40.

C. The differences of time-domain SAECG parameters between normal subjects and CRF patients

From Table 1 and 2, it can be found that mean fQRSD of normal subjects was longer than that of CRF patients from 3 to 5 ms following the reductions of RMS noise level, but these differences were not statistically significant ($p > 0.05$). The differences of mean LAS40 between normal subjects and CRF patients are also not statistically significant ($p > 0.05$). However the mean RMS40 value of CRF patients was significantly larger than that of normal subjects and CRF patients when the RMS noise levels were set at 0.9, 0.7 and 0.5 μV. Figure 3 further plots the distribution of RMS40 for normal subjects and CRF patients at the RMS noise levels of 1.1 and 0.7 μV. The reduction of the RMS noise level is helpful to show the significant difference of RMS40 between normal subjects and CRF patients.

TABLE III
RESULTS OF CORRELATION ANALYSIS FOR THE VARIATIONS OF TIME-DOMAIN PARAMETERS WHILE THE RMS NOISE LEVEL WAS REDUCED FROM 1.1 TO 0.7 μV

	Correlation coefficient (r value)
ΔfQRSD vs. ΔRMS40	–0.71
ΔfQRSD vs. ΔLAS40	0.87
ΔRMS40 vs. ΔLAS40	–0.78

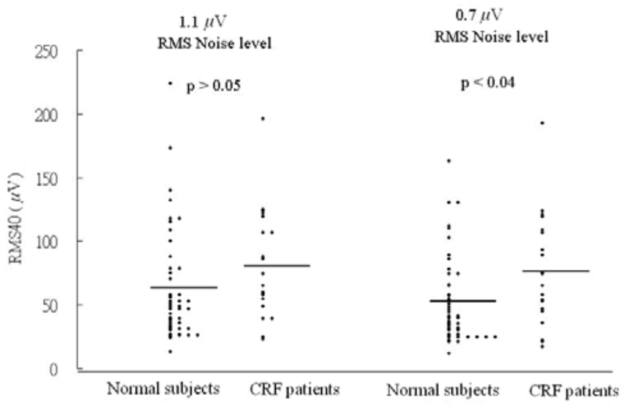

Fig. 3 Distribution of RMS40 for normal subjects and CRF patients at the RMS noise levels of 1.1 and 0.7 μV.

IV. DISCUSSIONS

Three time domain parameters, including fQRSD, RMS40 and LAS40, are standardized indices on time-domain analysis of SAECG [9, 10]. However the reliability of these estimated parameters is mainly based on the selection of reference points: the onset and offset of the filtered QRS complex. According to 1991 ESC/AHA/ACC standards of SAECG analysis, the key criteria concerning the determination of the onset and offset are: (A) the end of vector magnitude is defined as the midpoint of a 5 ms segment in which mean voltage exceeds the mean noise level plus three times the standard deviation of the noise sample, (B) the noise sample is measured of at least 40 ms in the ST or TP segment, (C) RMS noise level from vector magnitude should be less than 1 μV or 0.7 μV by a 25 Hz or 40 Hz Butterworth filters separately [9]. Because the determinations of onset and offset are related closely to the mean and standard deviation of noise sample, this study proposed the use of RMS value of the noise sample as threshold to perform SAECG and evaluate the effects of noise level on time-domain SAECG parameters instead of using a fixed number of heart beats or a predefined noise level in each lead.

Several end point definitions for SAECG and a number of final noise levels had been proposed in studying the effects of different noise level selection [19-25]. Steinberg et al. [19] had

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used a predefined noise level of lead X, Y and Z (0.3 and 1.0 μV) calculated by a signal variance method to discuss the importance of the endpoint of noise reduction. The final RMS noise levels are 0.58 ± 0.28 and 1.36 ± 0.57 μV using a 40-300Hz filter. It has been shown that noise level of 1.0 μV recording has a lower sensitivity than noise level of 0.3 μV. Christiansen et al. [20, 21] evaluated immediate SAECG reproducibility at noise levels of 0.2 and 0.4 μV. The final RMS noise levels are 0.42 ± 0.23 and 1.04 ± 0.36 μV using a 40-250Hz filter. From this study, the temporal variation of fQRSD was significantly lower at the noise level of 0.2 μV than at the noise level of 0.4 μV.

Maounis el al. [22] had used different noise standard deviations (SD) at 25 and 40 Hz high pass filter to evaluate the parameters on time-domain, frequency-domain and spectrotemporal analysis. It has been demonstrated that the parameters of time-domain SAECG analysis became more abnormal with the lower level of noise, while in spectral and spectrotemporal analysis lower noise levels yield less abnormal results. At the 40 Hz high pass filter the noise SD was 0.65 ± 0.04, 0.44 ± 0.05 and 0.23 ± 0.04 μV, the final RMS noise levels were not indicated.

Lander et al. [23] adopted a fixed number of heartbeats (from 200 to 600) to analysis the effects of noise level on SAECG analysis. It has been shown that a significantly correlation exists between RMS40 and residual noise level in patients with ventricular tachycardia (VT). Another study performed by Lander et al. [24] has introduced an optimal filtering technique to reduce noises only with 64 heart beats. Three different methods of noise measurement were also used, such as the signal variance estimation, the mean RMS noise level in three filtered leads XYZ of SAECG, and the RMS noise level of VM. Goldberger et al. [25] set the noise levels from 0.2 to 0.8 μV, the final RMS noise levels were not indicated.

Due to these different methods using by many SAECG researches, the inconsistent final RMS noise levels would lead to difficulties in the interpretation of SAECG results obtained from different study groups [24]. In comparison with the previous studies, the results of this study had very low standard deviations of final RMS noise level ranged from 0.07 to 0.01 μV. In another word, the final RMS noise levels were highly consistent among study subjects in this study.

Lower noise levels result in increase fQRSD [19-25] had also been shown even within the acceptable noise range as suggested by ESC/AHA/ACC task force [9]. This assertion can easily be verified from the data obtained from the present study. Based on this study, when RMS noise levels reduced, the fQRSD and LAS40 increased, whereas RMS40 decreases. Furthermore, from the analysis of correlation by linear regression, there were high significant correlations among these changes. The study results also demonstrated that the SAECG may also become abnormal due to the reduction of RMS noise level.

Although the pathophysiological basis of VLPs in CRF patients has not been well documented, this study tried to analyze the differences between normal subjects and CRF patients in the time-domain SAECG parameters. Observed from the results of the present study, the mean RMS40 of normal subjects is lower than CRF patients, and RMS noise level reduction is helpful to distinguish RMS40 differences between normal subjects and CRF patients.

In conclusion, it is suggested that the diagnostic criteria of SAECG should be established in a consistent RMS noise level.

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