A Comparative Study of Abnormal Intra QRS Potentials and High-Frequency Components in Signal-Averaged Electrocardiogram

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Abstract

Abnormal intra-QRS potentials (AIQP) have been proposed as a promising new index for evaluating the risk of ventricular arrhythmias. However the clinical results are still inconsistent. Our previous study showed that the mean AIQP parameters of ventricular tachycardia (VT) patients were significantly lower than those of normal subjects. Because several previous studies have reported that myocardial infarction and ischemic heart disease could reduce the high-frequency components within the QRS complex, this study will be devoted to comparing the clinical results of AIQP and high-frequency parameters in the diagnosis of VT, and analyzing whether the reduced AIQPs in VT patients are correlated to the changes in high-frequency components.

The study results demonstrated that the reductions of AIQP and high-frequency components in VT patients were consistent, and the correlation coefficients between the AIQP and high-frequency parameters were all significant, and ranged from 0.40 to 0.83 ($p<0.05$). In conclusion, the significant correlations between the AIQP and high-frequency parameters imply that the reduced AIQP in VT patients is correlated with the reduction of high-frequency components.

1. Introduction

The signal-averaged electrocardiogram (SAECG) is an important, non-invasive tool for the evaluation of high-risk patients with ventricular arrhythmias [1-3]. The conventional ventricular late potentials (VLP) analysis focuses on the detection of abnormal low-amplitude signals at the terminal QRS complex. Time-domain VLP parameters can provide the advantage of high reproducibility and excellent negative predictive accuracy for the stratification of the risk of development of sustained ventricular arrhythmias in patients who are recovering from myocardial infarction (MI), and for the identification of patients with ischemic heart disease and unexplained syncope [3].

The main limitations of VLP analysis are an incomplete characterization of reentrant activity [4] and a low positive predictive accuracy [3]. The delayed abnormal signals may be completely contained within the normal QRS period [5,6]. Hence Gomis *et al.* [7] proposed the use of an autoregressive moving average (ARMA) model to extract the abnormal intra-QRS potentials (AIQP) which are considered as low-amplitude notches and slurs with sudden changes in slope. The study results demonstrated that the mean AIQP values of the VT patients (N = 59) in leads X, Y and Z were significantly higher than those of the non-VT subjects (N = 73) ($p < 0.05$), and that the AIQP parameters can enhance the diagnostic performance of SAECG.

However, the clinical results of AIQP analysis are still inconsistent. Lander *et al.* [8] applied the same method to 16 patients with ventricular arrhythmias and 157 subjects without ventricular arrhythmias. The mean AIQP of the arrhythmic-event group in lead X significantly exceeded that of the non-event group ($p < 0.05$); however, no significant difference of the AIQP in leads Y or Z existed between the two groups. Our previous study [9] showed that the mean AIQP of VT patients (N=23) in lead Y was significantly lower than that of the normal subjects (N = 130) ($p < 0.05$), but that no significant differences in leads X and Z existed between the two groups.

The reduced AIQP of VT patients in our database may be related with MI and ischemic heart disease [10]. Several previous studies [11-13] have reported that MI reduces the high-frequency components within the QRS complex. Bhargava and Goldberger [14], and Talwar *et al*. [15] further showed that MI attenuates both low- and high-frequency QRS potentials. From a pathophysiological viewpoint, myocardial necrosis leads to a general decrease in electromotive potentials. Tragardh *et al*. [16] showed that the summed 12-lead high-frequency (150–250 Hz) components within the QRS interval in patients with ischemic heart disease were significantly smaller than those in normal subjects. Hence it is possible that MI and ischemic heart disease reduced the broadband AIQP.

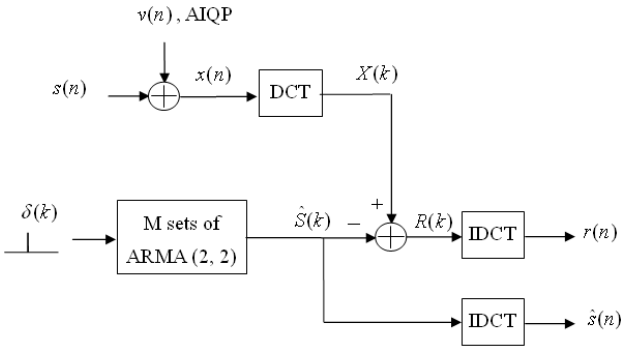

Figure 1. Block diagram of AIQP analysis using an ARMA model in the DCT domain.

The purpose of this study is to compare the clinical results of AIQP and the high-frequency parameters in the diagnosis of VT, and to analyze whether the AIQPs are correlated with the high-frequency components.

2. Methods

2.1. Materials and data acquisition

Two groups were recruited for the present study. Group I (the normal group) consisted of 42 normal healthy Taiwanese (20 men and 22 women, aged 58±14), while Group II (the VT group) consisted of 30 patients (15 men and 15 women, aged 63±16). Their sustained VT was documented by 24-hour Holter ECG monitoring, and they all suffered from chronic ischemic heart disease after surviving clinically documented MI.

High-resolution ECGs were recorded by a commercially available Simens-Elema Megacart® machine with a bipolar, orthogonal X, Y and Z lead system. The raw ECG signal was digitized by a 2,000 Hz sampling rate and 12-bit resolution. SAECG was performed offline using template selection, alignment and averaging [2,3]. The final noise level of the SAECG, when a 40 to 250 Hz filter was used, was set below 0.7 μV. The onset and offset of the QRS complex were obtained from vector magnitude analysis.

2.2. AIQP analysis

Figure 1 displays the block diagram of AIQP analysis using an ARMA model in the discrete cosine transform (DCT) domain. The input QRS complex $x(n)$ is assumed to contain two parts - (1) the normal QRS complex, $s(n)$, and (2) the AIQP, $v(n)$. The normal QRS complex and the AIQP are also assumed to be independent of each other. Their corresponding DCT coefficients are $X(k)$, $S(k)$ and $V(k)$, respectively.

Suppose the length of the input QRS complex $x(n)$ is N. The DCT coefficients of $x(n)$ can be calculated by [17]

$$X(k) = \sqrt{\frac{2}{N}} C_k \sum_{n=0}^{N-1} x(n) \cos \frac{(2n+1)k\pi}{2N} \tag{1}$$

where

$$C_K = \begin{cases} 1/\sqrt{2}, & k = 0 \\ 1, & k \neq 0 \end{cases}, \text{ for } k = 0, 1, 2, \cdots, N-1$$

The corresponding inverse DCT (IDCT) of $X(k)$ is defined as follows [17]:

$$x(n) = \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} C_k X(k) \cos\left[\frac{(2n+1)k\pi}{2N}\right] \tag{2}$$

After the input QRS complex $x(n)$ is transformed into the DCT domain, M sets of ARMA (2, 2) transfer functions are combined to estimate the normal QRS complex $S(k)$ by the modeling output $\hat{S}(k)$ and then to extract the AIQP $V(k)$ by the modeling residuals $R(k)$ in the DCT domain. The system function of the ARMA model in the z transform domain can be expressed as follows:

$$H(z^{-1}) = \frac{B_0 + B_1 z^{-1} + \cdots + B_{2M} z^{-2M}}{1 + A_1 z^{-1} + \cdots + A_{2M} z^{-2M}} \tag{3}$$

where $A_1, A_2, \cdots, A_{2M}, B_0, B_1, \cdots, B_{2M}$ are the model coefficients. Given a specific model order, the iterative least square error algorithm of Steiglitz-McBrige [18] was adopted to estimate the optimal model coefficients.

Because the IDCT of the impulse response of an ARMA (2, 2) model can generate a bell-shaped biphasic signal [9,10], the IDCT of the modeling output $\hat{S}(k)$, $\hat{s}(n)$, is a synthetic M-biphasic signal and is an estimate of the normal QRS complex in the time-domain.

The modeling residual in the DCT domain is $R(k)$, and can be expressed as follows:

$$\begin{aligned} R(k) &= X(k) - \hat{S}(k) \\ &= [S(k) - \hat{S}(k)] + V(k) \end{aligned} \tag{4}$$

The IDCT of $R(k)$ can further obtain the modeling residual in the time domain, $r(n)$, which is given by

$$\begin{aligned} r(n) &= [s(n) - \hat{s}(n)] + v(n) \\ &= e(n) + v(n) \end{aligned} \tag{5}$$

where $e(n)$ is the estimation error that originates from the estimate of the normal QRS complex. Accordingly, the modeling residuals $r(n)$ consist of two parts - the estimation error of the normal QRS complex, $e(n)$, and the AIQP, $v(n)$. If the estimation error can be reduced as much as possible, the modeling residual can be used to evaluate the AIQP.

The RMS value of the modeling residuals within the entire QRS complex was defined to quantify the AIQP as follows:

$$\text{AIQP\_}l = \sqrt{\frac{1}{QRSD}\sum_{n=n_1}^{n_2}\hat{v}^2(n)} \quad (6)$$

where l denotes lead X, Y or Z, and n_1 and n_2 are the onset and offset of the QRS complex, respectively.

2.3. High-frequency analysis

The high-frequency components of the QRS complex were extracted using a fourth-order bi-directional Butterworth filter with a frequency band of 150 to 250Hz. The filtered QRS complex is denoted as. The RMS value of the filtered QRS complex within the QRS period was defined to quantify the high-frequency components as follows:

$$\text{HF\_}l = \sqrt{\frac{1}{QRSD}\sum_{n=n_1}^{n_2}{x_f}^2(n)} \quad (7)$$

where l denotes lead X, Y or Z, and n_1 and n_2 are the onset and offset of the QRS complex, respectively.

2.4. Statistical analysis

Data were presented as mean ± standard deviations. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS)®. The F test was adopted to compare the variances of different variables, and the Student's t test with two tails was adopted to compare the means of two independent variables. Statistical significance was defined as $p < 0.05$. Pearson's product moment coefficient was determined to evaluate the degree of linear correlation between two variables.

3. Results

Table 1 lists the results of the AIQP and high-frequency parameters. The AIQPs were estimated using the ARMA models with a low-order of (6, 6) and a high-order of (12, 12), respectively. The high-frequency components were extracted using a fourth-order bi-directional Butterworth filter with the frequency band of 150 to 250Hz. Both the mean AIQPs using the order of (6,6) and the mean high-frequency parameters of the VT patients were significantly lower than those of the normal subjects in leads Y and Z, but not in lead X. The mean AIQP using the order of (12,12) of the VT patients was significantly lower that of the normal subjects in lead Z, but not in leads X and Y. Table 2 further demonstrates the results of the correlation analysis between the AIQP and high-frequency parameters for the normal and VT groups, respectively. The high-frequency parameters were positively and significantly correlated with the AIQP using the orders of (6,6) and (12,12), and the correlation coefficients ranged from 0.40 to 0.83 (p<0.05). The correlation coefficients between the high-frequency parameters and the AIQP using the order of (12,12) were higher than those between the high-frequency parameters and the AIQP using the order of (6,6).

Table 1: Summary results of AIQP and high-frequency analyses

	Normal	VT
AIQP_X(6,6)	10.6±3.7	10.0±4.4^{NS}
AIQP_Y(6,6)	17.4±6.6	14.7±4.5*
AIQP_Z(6,6)	18.2±7.5	14.6±2.9**
AIQP_X(12,12)	3.6±1.7	4.1±1.2 ^{NS}
AIQP_Y(12,12)	7.6±4.2	6.2±3.0 ^{NS}
AIQP_Z(12,12)	7.9±4.1	6.5±1.6*
HF_X	4.4±2.0	4.7±1.8 ^{NS}
HF_Y	6.3±2.6	4.9±3.2*
HF_Z	6.0±2.2	5.2±1.3*

NS, not significant ($p > 0.05$); *, $p < 0.05$; **, $p < 0.01$

Table 2: Results of correlation results between AIQP and high-frequency parameters in the normal and VT groups

Parameters	Correlation coefficients	
	in normal subjects	in VT patients
HF_X vs. AIQP_X(6,6)	0.58	0.70
HF_Y vs. AIQP_Y(6,6)	0.61	0.50
HF_Z vs. AIQP_Z(6,6)	0.61	0.40
HF_X vs. AIQP_X(12,12)	0.58	0.75
HF_Y vs. AIQP_Y(12,12)	0.83	0.82
HF_Z vs. AIQP_Z(12,12)	0.81	0.51

All correlation coefficients are significant (p<0.05).

4. Discussion and conclusions

This study presents a comparative study between the AIQP and high-frequency analyses in the identification of VT patients with high-risk ventricular arrhythmias. The ARMA model for extracting the AIQP can be seen as a special filter, and the model order determines the cut-off frequency. A higher order corresponds to a higher cut-off frequency. The study results showed that the AIQPs estimated by a higher order of (12,12) were all smaller than those estimated by a lower order of (6,6). The study results further demonstrate that the reductions of the AIQP and high-frequency components in the VT patients are consistent, and the AIQP parameters are all positively and significantly correlated with the high-frequency parameters. The significant correlations between the AIQP and high-frequency parameters imply that the reduced AIQP in VT patients is correlated with the reduction of high-frequency components.

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