A Wavelet-Based High-Frequency Analysis of Fragmented QRS Complexes in Patients with Myocardial Infarction

Chun-Cheng Lin[1], Weichih Hu[2], Yu-Wei Lin[1]

[1]Department of Electrical Engineering, National Chin-Yi University of Technology, Taichung, Taiwan
[2]Department of Biomedical Engineering, Chung Yuan Christian University, Chung Li, Taiwan

Abstract

Fragmented QRS (fQRS) is an important and noninvasive marker for evaluating myocardial scar in patients with coronary artery disease, which is defined as additional spikes within the QRS wave. It is not easy to detect the fQRS accurately because of a variety of fQRS morphologies. This study is to analyze the high-frequency (HF) potentials of fQRS complexes using a continuous wavelet transform-based method in patients with myocardial infarction (MI). The HF parameter is defined as the root-mean-square (RMS) value of wavelet coefficients at the central frequencies of 100Hz, 150Hz, 200Hz, or 250Hz further normalized by the RMS value of the entire QRS complex, which is defined as the HF ratio. There were 76 MI patients and 43 Normal subjects recruited in this study. All of the ECG recordings were obtained from the PTB Diagnostic ECG Database including the conventional 12-lead and Frank XYZ lead ECGs. A signal averaging technology was adopted to reduce the background noise. The fQRS complexes were defined by the presence of an additional R wave, or notching in the nadir of the S wave, notching of the R wave, or the presence of more than one R prime. All of the mean HF ratios of the fQRS complexes are significantly larger than those of the non-fQRS complexes ($p<0.001$). The total accuracy of the HF ratio for detecting the fQRS complex is about 80% (specificity 84% and sensitivity 60%) in the 12-lead ECGs, and about 84% (specificity 88% and sensitivity 65%) in the Frank lead ECGs.

1. Introduction

Myocardial infarction (MI) is a high-risk cardiac disease, and is highly associated with increased risk of cardiac events and mortality. It causes a shortage of blood to the heart muscles, and may lead to permanent heart damage. Several recent studies have revealed that the fragmented QRS (fQRS) is a noninvasive risk indicator for various cardiac diseases, including coronary artery disease (CAD), arrhythmogenic right ventricular cardiomyopathy, and MI [1-4]. The presence of the fragmentations within the QRS complex represent conduction abnormalities induced by the myocardial scars. The fQRS for a narrow QRS complex (<120 ms) is defined as the presence of an additional R wave (R') in the upstroke or of an S wave (S') in the downstroke, and the presence of more than one additional R' or S' in two contiguous leads, corresponding to a myocardial territory on the resting 12-lead ECG [5]. The fQRS for a wide QRS complex (>120 ms) consists of various RSR' patterns, with more than 2 additional R waves (R') or more than 2 notches in the R wave, or more than 2 notches in the downstroke or upstroke of the S wave, and appearing in at least two contiguous leads [6].

Das *et al*. proved that fQRS is a predictor of cardiac events and mortality in patients who have known CAD or who are being evaluated for CAD [5]. Das *et al*. further reported that fQRS in a wide QRS complex had good sensitivity (86.8%), specificity (92.5%), positive predictive value (92.0%), and negative predictive value (87.5%) for the detection of myocardial scars [6]. In order to detect the fQRS automatically, Maheshwari *et al*. proposed a fragmentation detection algorithm to detect the discontinuities present in the QRS complex of a standard 12-lead ECG based on discrete wavelet transform [7]. However it is not easy to detect the fQRS accurately because of a variety of fQRS morphologies. This study is to analyze the high-frequency potentials of the QRS complexes for the detection of the fQRS complexes in MI patients using a continuous wavelet transform-based method. It is expected that the fragmentations within the QRS complex would increase the high-frequency components.

2. Materials and methods

2.1. ECG recordings and signal averaging

All of the ECG recordings used in this study were obtained from the PTB Diagnostic ECG Database [8]. The database contains 549 records from 290 subjects. Each subject is represented by one to five records. Each

record includes 15 simultaneously measured signals: the conventional 12-lead ECG (I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6) together with the Frank-lead ECG (Vx, Vy, Vz). Each signal is digitized at 1,000 samples per second, with 16 bit resolution. There were 76 patients with MI and 43 normal subjects recruited in this study.

Signal averaging was performed to lower the effects of random noise [9,10]. The final noise level of SAECG measured by a bidirectional Butterworth filter with a 40–50 Hz bandpass was less than 0.7μV using the Frank-lead ECG. The onset (starting) and offset (end) of the QRS complex were detected from the vector magnitude (VM) analysis of the Frank-lead ECG.

2.2. High-frequency analysis of the QRS complex using continuous wavelet transform

The study introduced the continuous wavelet transform to extract the high-frequency components of the QRS complexes for the detection of fQRS complexes. A continuous wavelet transform can divide a continuous-time signal into wavelets with different scales and translational values. A dilated and translated wavelet can be expressed as follows:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-b}{a}) \tag{1}$$

where $\psi(t) \in L^2(\Re)$ denotes the mother wavelet with zero mean $\int_{-\infty}^{\infty}\psi(t)dt = 0$, and a and b denote the scaling and translation parameters, respectively. The Morlet wavelet was chosen as the mother function in this study. Suppose the QRS complex $x(t)$ belongs to $L^2(\Re)$, the continuous wavelet transform of $x(t)$ at scale a and translation b is defined as follows.

$$Wx(a,b) = \int_{-\infty}^{\infty} x(t)\frac{1}{\sqrt{a}}\psi^*(\frac{t-b}{a})dt \tag{2}$$

where * denotes the operation of the complex conjugate, and $1/\sqrt{a}$ is to ensure that $\psi_{a,b}(t)$ has the same energy at different scales and translations as follows:

$$\int_{-\infty}^{\infty}\left|\psi_{a,b}(t)\right|^2 dt = \int_{-\infty}^{\infty}\left|\psi(t)\right|^2 dt \tag{3}$$

The center frequency f_a of $\psi_{a,b}(t)$ can be derived as follows:

$$f_a = f_0 / a \tag{4}$$

where f_0 is the center frequency of the mother wavelet.

The wavelet coefficients $Wx(a,b)$ with various high central frequencies were used to extract the high-frequency components of the QRS complex in the study. Two high-frequency parameters were defined for further quantification analysis. The first one calculated the mean-square (RMS) value of the high-frequency components corresponding to a particular central frequency as follows.

$$\mathrm{HF}(f_a) = \sqrt{\frac{1}{\mathrm{QRSD}}\sum_{b=onset}^{offset} Wx(a,b)^2} \tag{5}$$

where QRSD denotes the QRS duration. The second one named the high-frequency ratio (HFR) is defined to normalize the HF RMS value by the RMS value of the QRS complex as follows:

$$\mathrm{HFR}(f_a) = \mathrm{HF}(f_a) / \sqrt{\frac{1}{\mathrm{QRSD}}\sum_{n=onset}^{offset} x[n]} \tag{7}$$

where $x[n]$ denotes the discrete version of the signal-averaged ECG signal.

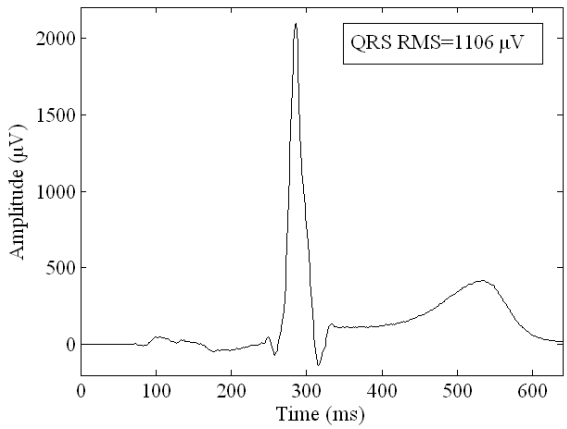
2.3. Statistical methods

Data are presented as mean ± standard deviation. The Student's t test was applied to compare the means of two independent variables, and the F test was used to compare the variances of the variables. Statistical significance was defined as a p value of less than 0.05. Three clinical performance indices including specificity, sensitivity and total prediction accuracy (TPA) [11] were calculated to evaluate the accuracy of the diagnosis of the MI patients.

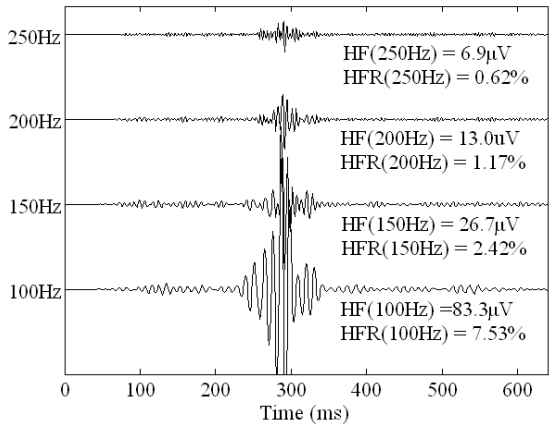
3. Results

Figures 1 and 2 illustrate the QRS waveforms and their corresponding wavelet coefficients with center frequencies of 100Hz, 150Hz, 200Hz and 250Hz for a non-fQRS of a normal subject and an fQRS of an MI patient, respectively. Both the RMS values of the QRS complex and the high-frequency components of the non-fQRS in Fig. 1 are larger than those of the fQRS in Fig. 2. However if the high-frequency components are normalized by the RMS value of the QRS complex, the fQRS demonstrates a larger high-frequency ratio in comparison with the non-fQRS.

Tables 1 and 2 summarize the results of the high-frequency ratios of fQRS and non-fQRS for MI patients and normal subjects in 12-lead and Frank-lead ECGs, respectively. All of the mean high-frequency ratios of fQRS complexes are significantly larger than those of non-fQRS complexes (p<0.001) in 12-lead or Frank-lead ECGs of MI patients or normal subjects. The total accuracy of the HF ratio for detecting the fQRS complex is about 80% (specificity 84% and sensitivity 60%) in the 12-lead ECGs, and is about 84% (specificity 88% and sensitivity 65%) in the Frank lead ECGs.

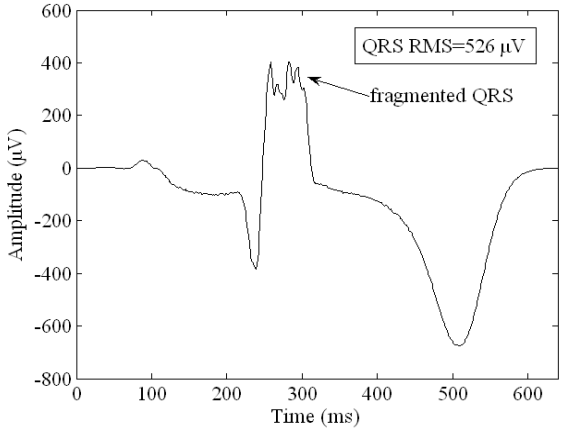


(a)

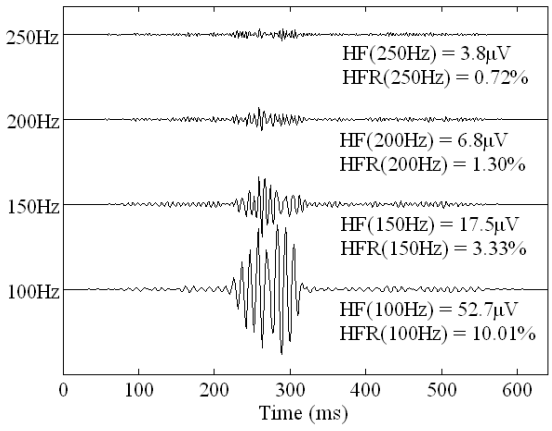


(b)

Fig.1 Illustrations of (a) a non-fQRS waveform and (b) the corresponding wavelet coefficients with center frequencies of 100Hz, 150Hz, 200Hz and 250Hz for a normal subject.



(a)



(b)

Fig.2 Illustrations of (a) an fQRS waveform and (b) the corresponding wavelet coefficients with center frequencies of 100Hz, 150Hz, 200Hz and 250Hz for an MI patient.

4. Discussion and conclusions

This study proposes the high-frequency analysis of the fQRS complexes using a continuous wavelet transform-based approach for the evaluation of MI patients. The wavelet coefficients with a predetermined central frequency can be used to extract the high-frequency components of the QRS complex. Because of the linearity of the wavelet transform, the extracted high-frequency components are proportional to the amplitude of the input QRS complexes. For example, if the RMS value of the non-fQRS complex in Fig. 1(a) is amplified 2 times to 2,212 V, the HF(100Hz) is also amplified 2 times to 166.6 V. Hence the study further defined a high-frequency ratio in Eq. (6) to normalize the high-frequency parameter.

Although the study results show that the mean high-frequency ratios of fQRS were larger than those of non-fQRS, the main limitation of the high-frequency analysis for the detection of the fQRS complexes is its low sensitivity, only about 60% in the 12-lead ECGs and 65% in the Frank-lead ECGs. The possible reason for this low sensitivity may be that the high-frequency fragmentations were covered by the sharp and high-frequency R wave. The study results also show that the fQRS complexes not only present in the MI patients but also in the normal subjects. The occurrences of fQRS are 20.1% and 5.9% for MI patients and 11.8% and 1.7% for normal subjects in the 12-lead and the Frank-lead ECGs, respectively.

In conclusion, the mean high-frequency ratios of the fQRS complexes were significantly larger than those of the non-fQRS complexes.

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Table 1. Summary results of high-frequency ratios of fQRS and non-fQRS for MI patients and normal subjects in 12-lead ECGs.

	MI Patients (N = 76)	
12-lead ECG	fQRS	non-fQRS
Number	191	721
HFR(100Hz) (%)	19.7 ± 13.4	9.8 ± 6.0***
HFR(150Hz) (%)	7.9 ± 5.2	4.3 ± 2.6***
HFR(200Hz) (%)	4.2 ± 2.7	2.3 ± 1.4***
HFR(250Hz) (%)	2.6 ± 1.6	1.4 ± 0.8***
	Normal subjects (N = 43)	
12-lead ECG	fQRS	non-fQRS
Number	61	455
HFR(100Hz) (%)	24.1 ± 13.3	9.9 ± 6.3***
HFR(150Hz) (%)	10.3 ± 6.7	4.4 ± 2.7***
HFR(200Hz) (%)	5.8 ± 4.0	2.2 ± 1.3***
HFR(250Hz) (%)	3.4 ± 2.2	1.4 ± 0.8***

*** denotes $p < 0.001$.

Table 2. Summary results of high-frequency ratios of fQRS and non-fQRS for MI patients and normal subjects in Frank-lead ECGs.

	MI Patients (N = 76)	
Frank-lead ECG	fQRS	non-fQRS
Number	54	174
HFR(100Hz) (%)	21.4 ± 11.5	9.0 ± 5.6***
HFR(150Hz) (%)	8.6 ± 5.5	3.9 ± 2.4***
HFR(200Hz) (%)	4.6 ± 2.7	2.1 ± 1.2***
HFR(250Hz) (%)	2.7 ± 1.7	1.3 ± 0.7***
	Normal subjects (N = 43)	
Frank-lead ECG	fQRS	non-fQRS
Number	9	120
HFR(100Hz) (%)	24.1 ± 11.0	8.6 ± 4.8**
HFR(150Hz) (%)	9.5 ± 4.4	3.8 ± 2.1**
HFR(200Hz) (%)	5.3 ± 2.3	2.0 ± 1.2**
HFR(250Hz) (%)	3.4 ± 1.5	1.2 ± 0.7**

** and *** denote $p < 0.01$ and $p < 0.001$, respectively.

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Address for correspondence.

Chun-Cheng Lin
Department of Electrical Engineering, National Chin-Yi University of Technology
No.57, Sec 2, Jhongshan Rd., Taiping Dist., Taichung 41170, Taiwan
cclin@ncut.edu.tw