Analysis of High Frequency Components of the QRS Complex in 3-D MCG Using Wavelet Packets

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(Received; October 6, 2000 Accepted; January 24, 2001)

Wavelet packets (WPs) was applied to detect the high frequency components of the QRS complex in magnetocardiogram (MCG) signals recorded by a 3-D second-order gradiometer connected to three rf-SQUIDS. By using a quadrature mirror filter (QMF) bank in the WPs implementation, we performed the MCG waveform analysis for a normal subject and a patient with myocardial infarction (MI). The high frequency components of the QRS complex related to the ventricular late potential (LP) were observable from a patient with MI at different scale. By computing its root-mean-square (RMS), the ventricular LP extended a mean of about 40 ms after termination of the QRS complex. The amplitude had about 0.33 pT, 0.46 pT, 0.49 pT respectively for B_x , B_y , B_z components, the bandwidth was about from 62.5 to 125 Hz. It is useful to use the WPs for signal processing to 3-D MCG signals.

Key words: wavelet packet, quadrature mirror filter bank, 3-D MCG, high frequency component, late potential, root-mean-square

1. Introduction

As a non-invasive measurement, high-resolution magnetocardiogram (MCG) has been paid attention to analyze the high frequency components of the QRS complex, especially, relating to the ventricular late potential (LP) that is at risk of ventricular arrhythmias and sudden cardiac death. The first study of the ventricular LP in MCG to myocardial infarction was reported in 1983¹⁾. It is thought that the ventricular LP is practically much smaller than the QRS complex and exists in the range of about 40 to 200 Hz²⁾. Therefore, it is very important to develop a method to analyze the high frequency low amplitude signals in clinical diagnosis. In most reports, the signals were recorded in high gain with wide band pass filters. In this study, we presented wavelet packets (WPs) to analyze the signals recorded from a normal subject and a patient with myocardial infarction (MI) by a 3-D second-order gradiometer connected to three rf-SQUIDS³⁾. Being different from general multiresolution wavelet transform (WT), both a finer detail and a coarse form are decomposed at each scale in the WPs implementation⁴⁾. And the WPs also has better tracking for a time varying signal or a signal of transient change in a

shorter time domain. A purpose of this study is to analyze the high frequency components related to the ventricular LP existing behind the offset of the QRS complex.

2. Wavelet Packets

A WPs is defined by taking linear combinations of ordinary wavelet⁴⁾. The wavelet $\phi(t)=W_0(t)$ and $\psi(t)=W_1(t)$ are the functions generated by a quadrature mirror filter (QMF) bank. The WPs is implemented as a QMF bank. The QMF bank consists of a lowpass filter $H(w)$ and a highpass filter $G(w)$ that split the signal's bandwidth in half. The signal $f(n)$ is decomposed into approximation and detail signals at each scale by the $H(w)$ and the $G(w)$ respectively and then downsampled as shown in Fig. 1. The QMF bank defines two orthonormal projection operators. The WPs generates a binary tree by successively applying the orthonormal projections operators. The nodes correspond to the output from the QMF bank at each scale as illustrated in Fig. 2. Where, for the original signal $f(n)$, N presents the samples, f_s presents the sampling frequency. The full tree contains the $j=\log_2 N$ resolution scales. At the resolution scale j , the signal's bandwidth is divided 2^j equal sections. The output from the node $(j,1)$ covers the bandwidth of $f_s/2^{j+1}$ to $2f_s/2^{j+1}$. Daubechies wavelet functions with the compact support are used in the WPs implementation. The WPs can construct a time-frequency plane that is divided information cells by the orthonormal projection operators. In the plane, the estimation of energy distribution for a information cell is given by the squared magnitude of the node output at each scale.

Fig. 1 Basic block diagram for decomposition of signal using wavelet packets.

Fig. 2 Basic tree for decomposition of signal using wavelet packets.

3. MCG Measurement

We carried out MCG measurement for a normal subject and a patient with MI in a magnetically shielded room by use of a 3-D second-order gradiometer connected to three rf-SQUIDS³⁾, which is made of superconducting wire (Nb-Ti-Cu) and is orthogonally wound on a rectangular solid $3 \times 3 \times 6$ cm. A 12-bit A/D converter is used with 1 kHz sampling frequency. The output of MCG signals was monitored on a computer display, and recorded on a tape recorder. ECG signals in lead II were also recorded on the tape recorder simultaneously as a timing reference for averaging MCG signals. Fig. 3 shows the measurement grids ($X=4$ cm, $Y=4$ cm) of MCG signals. Measurement positions of 42 points on the anterior chest wall were set up according to the Sarrien's method⁵⁾. For 3-D MCG measurement, B_x component is tangential to the anterior chest wall and from the right to the left. B_y component is also tangential to the anterior chest wall and from the head to the foot. B_z component is perpendicular to the anterior chest wall and from the back to the front.

Fig. 3 MCG measurement grids according to the Sarrien's method.

4. Results

As an example, the 3-D MCG signals at the position C5 of measurement grids were analyzed for a patient with MI. To enhance the signal-to-noise ratio (SNR) of the 3-D MCG signals, first an average of 200 original data (0.5-300 Hz) was maintained from the record. Fig. 4(a) represented the averaged 3-D MCG signals containing $N=1024$ data points. The WPs transform of the averaged signals was computed using Daubechies wavelet function with an order of 6 and produced $j=10$ resolution scales consisting of $N=512, 256, 128, \dots, 2$ data points for each node. Fig. 4(b) represented the high frequency region with 256 data points at node (2,1) (The bandwidth is 125-250 Hz). Fig. 4(c) represented the high frequency region with 128 data points at node (3,1) (The bandwidth is 62.5-125 Hz). The high frequency components separated from the averaged signals have been observed by the WPs from Fig. 4(b) and Fig. 4(c). The 3-D MCG signals at the position B3 of measurement grids were also analyzed for a normal subject as shown in Fig. 5. Comparing Fig. 4 with Fig. 5, it is clear that the high frequency components related to the LP is visible for a patient with MI, especially in B_y, B_z components. In order to make the high frequency components quantitatively, the root-mean-square (RMS) values are calculated in various QRS complex intervals by

$$RMS = \left[\frac{1}{n} \sum_{j=1}^n B^2(t_j) \right]^{1/2} \quad (1)$$

Where, t_j is j^{th} sample point, $B(t_j)$ is the signal amplitude at j^{th} sample point, and t_1 is the beginning of the high frequency component. The QRS intervals and the LP interval were determined from the averaged MCG signals. Table 1 represented the RMS values of 0-50 ms, 0-100 ms and 50-100 ms of the QRS intervals, and 100-140 ms of the LP interval. Where, 0 ms and 100 ms are the onset and the offset time of the QRS complex respectively. The RMS values of the high frequency component of the QRS complex are listed in Table 1 for a normal subject and a patient with MI respectively. From the Table 1, it has been seen that a patient with MI had the higher RMS values than a normal subject behind the offset of the QRS complex, especially in B_y, B_z components. The RMS values of B_y, B_z components were significantly higher in a patient with MI than a normal subject at node (2,1) (0.247 vs 0.150 pT, 0.128 vs 0.012 pT). Similarly, the RMS values of B_y, B_z components in a patient with MI were also significantly greater at node (3,1) (0.468 vs 0.181 pT, 0.496 vs 0.064 pT). The RMS value of B_x component is almost the same at node (2,1) and node (3,1) (0.188 vs 0.183 pT, 0.338 vs 0.312 pT), this is probably because noises had certain influence for B_x component. The

Fig. 4 3-D MCG waveforms decomposition of a patient with MI by wavelet packets: (a) averaged MCG; (b) MCG at node (2,1); (c) MCG at node (3,1).

Fig. 5 3-D MCG waveforms decomposition of a normal subject by wavelet packets: (a) averaged MCG; (b) MCG at node (2,1); (c) MCG at node (3,1).

Table 1 Root-mean-square values of the high frequency components of the QRS complex: (A) a patient with MI; (B) a normal subject. Unit of B (B_x, B_y, B_z) is picotesla (pT).

Intervals(ms)		0-50	0-100	50-100	100-140
node (2,1)	B_x	0.328	0.290	0.252	0.188
	B_y	0.254	0.255	0.255	0.247
	B_z	0.137	0.134	0.130	0.128
node (3,1)	B_x	0.554	0.474	0.395	0.338
	B_y	0.599	0.647	0.696	0.468
	B_z	0.301	0.294	0.285	0.496

(A)

Intervals(ms)		0-50	0-100	50-100	100-140
node (2,1)	B_x	0.212	0.249	0.286	0.183
	B_y	0.226	0.265	0.304	0.150
	B_z	0.842	0.541	0.239	0.012
node (3,1)	B_x	0.488	0.501	0.513	0.312
	B_y	0.180	0.651	1.122	0.181
	B_z	1.855	1.261	0.668	0.064

(B)

RMS values of B_y , B_z components at node (2,1) were lower than one at node (3,1). This means that a weak signal related to the ventricular LP mainly existed behind the offset of the QRS complex, and distributed in the bandwidth of about 62.5 to 125 Hz. For B_z components, the RMS values of a normal subject were much higher than those of a patient with MI in 0-50 ms, 0-100 ms and 50-100 ms of the QRS complex intervals. In particular, The RMS values of 0-50 ms of the QRS complex interval were significantly greater at node (2,1) and (3,1) in a normal subject than in a patient with MI (0.842 vs 0.137 pT, 1.855 vs 0.301 pT). Fig. 6 showed the time-level energy distribution using the WPs method at the position C5 of measurement grids for a patient with MI, where, level relates to frequency and the lower level corresponds to the lower frequency. The time-level plots were normalized with respect to the highest energy in any cells. The white color shows the highest energy. All cells with normalized energy less than 3% are black. From the Fig. 6, it can be seen that the energy distribution was mainly in the low level, which corresponds to the range of about 0.5 to 62.5 Hz. The duration was about from 400 to 800 ms. The weak signals of the QRS complex existing in the range of about 62.5 to 125 Hz have also been recognized. The duration was about from 420 to 560 ms.

5. Discussion

- 1) In the multiresolution WT, at each scale, the detail signal is stored and the decomposition continues by filtering the approximate signal as the input signal for the next scale⁶⁾. However, being different from general multiresolution WT, the both detail and approximation signals are decomposed at each scale in the WPs transform. For the WPs, The best basis can be selected using criteria. The most widely used criterion is based on the entropy⁷⁾.
- 2) By the WPs, the weak magnetic signals have been found after termination of the QRS complex in 3-D MCG for a patient with MI. They are related to the ventricular LP. By

computing the RMS value, it has been proved that there existed the weak magnetic signals after the offset of the QRS complex. They would be transient signals generated by the fragmented activity of myocardial tissues. This activity is caused by small areas of ischaemic or other damaged tissue⁸⁾.

6. Conclusion

In this study, we have used the WPs transform to analyze the high frequency components of the QRS complex related to the ventricular LP in 3-D MCG. The weak magnetic signals have been detected by using a QMF bank and quantified by computing RMS value. Our results also represent the ventricular LP existing after termination of the QRS complex. In order to predict arrhythmic events in 3-D MCG, we are considering to quantify the signals by some new methods such as signal source estimation based on mapping of the filtered QRS complex.

Acknowledgments

This study was support in part by a grant from the Center for Research of Tokyo Denki University and the Ministry of Education, Science and Culture in Japan.

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Fig. 6 Time-level energy distribution for a patient with MI by wavelet packets in 3-D MCG.