ABSTRACT

For ubiquitous healthcare, interests for unconstrained method for ECG measurement have increased in the biomedical engineering field. Recently, capacitive-coupled method was introduced as the unconstrained method. However, the ECGs obtained from this method have many motion artefact noises, so heart rate data becomes intermittent finally. In this paper, spectral analysis methods of heart rate variability (HRV) for intermittent heart rate (HR) data are compared through simulation of artificial and real intermittent HR data. As the index of comparison, LF/HF ratio is used, which is a parameter reflecting the sympatho-vagal balance. In conclusion, the Burg’s algorithm of parametric method has the lowest error, and the Lomb-Scargle (LS) periodogram of uneven method has the worst result. But, in low intermittent number, LS periodogram is the best.

KEY WORDS

capacitive-coupled ECG measurement, heart rate variability (HRV), intermittent, spectral analysis

1. Introduction

Recently, many unconstrained methods for electrocardiogram (ECG) measurement have been introducing in ubiquitous healthcare field. One of the methods for unconstrained ECG measurement is capacitive-coupled method. This method was reported by a team from University of Sussex in England for the first time [1]. In this method, the ECG is measured by the capacitive electrodes remotely, not by direct skin contact. Lim, Kim, and Park applied this technology to a chair and a bed [2], [3]. On a chair, the ECG can be measured even with clothes on the body by this method in daily life, and on a bed, ECG can be also measured even through the mattress cover during sleep.

However, the capacitive-coupled ECGs include more motion artefact noises than direct skin contact methods. These noises disturb characteristic point (usually, R-peak) detection which is necessary to obtain heart rate (HR) data, after all the HR data can be intermittent. This intermittent data can affect heart rate variability (HRV) analysis.

In this study, HRV analysis methods, especially spectral methods, are compared to find the optimal method for intermittent HR data obtained from ECG measured as unconstrained method. Artificial intermittent HR data are simulated and then real data from the capacitive-coupled ECG during sleep on a bed are used for the evaluation for optimal method.

2. Methods

2.1 Capacitive-Coupled ECG Measurement

The capacitive-coupled ECG measurement system has active electrodes and a capacitive ground basically. The active electrodes are shielded and have their own pre-amplifier that transfers the displacement current through the insulation, such as cloth or mattress cover, into the voltage.

In the system on a chair, two active electrodes are used, and the signals from these electrodes are differentiated by a differential amplifier and the differential signal is filtered with bandwidth of 10 to 45 Hz. The capacitive ground is used for the reference electrode that is conductive sheet within the seat cushion as Figure 1 [2].
2.2 Spectral analysis of HRV

In spectral analysis of HRV, two main frequency components, which are the power in the relevant frequency range, are used for 5-min heart rate data: LF in low frequency range (0.04 ~ 0.15 Hz) caused by baroreflex activities and HF in high frequency range (0.15 ~ 0.4 Hz) which comes from the respiration [4]. The ratio of LF to HF (LF/HF) reveals sympatho-vagal balance and is usually used as the important parameter of ANS activities.

Power spectral density (PSD) from spectral analysis is estimated usually by the non-parametric method and parametric method. In the non-parametric method, the PSD is calculated directly from the signal itself. The common such method is the periodogram that based on the Fourier transform. In the modified periodogram method, the non-rectangular window is applied in the signal for the PSD. In this study, the periodogram and modified periodogram applied hanning window are used as the non-parametric method for the PSD calculation of the 4 Hz re-sampled RR-interval tachogram.

For parametric methods, the AR model estimated from a signal that is assumed to be output of a linear system driven by white noise is used, and the frequency response of transfer function of the model is calculated to the PSD. To estimate the AR model, Yule-Walker method and Burg method is generally used. Yule-Walker method utilizes the autocorrelation function of a signal in which this process is complex because of calculation of the inverse matrix. Burg algorithm that is based on minimizing the forward and backward prediction errors while satisfying the Levinson-Durbin recursion is computationally efficient and more accurate than Yule-Walker method [5], [6]. As the advanced method, covariance method based on minimizing the forward prediction error might be used. The order of AR model influences the estimation accuracy. In a previous study about the parametric model order for HRV spectral analysis, it is reported that the optimum order is around p = 16 for the 4 Hz re-sampled RR-interval data [7]. In this study, the Burg method and covariance method are used as the parametric method in the experiments, having the model order of 16 and the re-sampling frequency of RR-interval data of 4 Hz.

The Lomb-Scargle (LS) periodogram for PSD estimation is a more appropriate method to an unevenly sampled signal such as the RR-interval data [8], [9], [10]. Lomb supposed that an unevenly sampled signal model is

\[ x(t_n) + \varepsilon_n = a \cos(2\pi f_0 t_n) + b \sin(2\pi f_0 t_n), \]

where \( \varepsilon_n \) is the mean squared error that minimized with the proper \( a \) and \( b \) parameters, and \( t_n \) is the unevenly sampled time. So, the expression for the normalized LS periodogram is

\[ P_x(f) = \frac{1}{2\pi^2} \left[ \frac{\sum_n (x(t_n) - \bar{x})(\cos(2\pi f(t_n - \tau)))}{\sum_n \cos^2(2\pi f(t_n - \tau))} \right] \left[ \frac{\sum_n (x(t_n) - \bar{x})(\sin(2\pi f(t_n - \tau)))}{\sum_n \sin^2(2\pi f(t_n - \tau))} \right], \]

where \( \bar{x} \) and \( \sigma^2 \) are the mean and variance of the data and \( \tau \) is

\[ \tau = \frac{1}{4\pi^2} \tan^{-1} \left( \frac{\sum_n \sin(4\pi f \tau)}{\sum_n \cos(4\pi f \tau)} \right). \]

Clifford reported that while the FFT-based periodogram overestimates the LF/HF ratio in HRV spectral analysis since the re-sampling process adds the LF component and reduces the HF content, the LS periodogram estimates the LF/HF ratio more accurately [11]. This LS periodogram are used as the uneven method for the comparison experiments in this study.

3. Experiments

3.1 Artificial intermittent HR data

Artificial HR data is generated by the McSharry’s method for the simulation [12]. McSharry’s HR model is expressed as

\[ HR(t) = HR_0 + A_l \sin(2\pi f_l t) + A_h \sin(2\pi f_h t + \phi) \]

where \( HR_0 = 60 \) bpm, dominant LF \( f_l = 0.1 \) Hz, dominant HF \( f_h = 0.25 \) Hz, LF amplitude \( A_l = 2 \), HF amplitude \( A_h = 2.5 \), the HF phase \( \phi = 0 \). The LF component \( f_l \) and HF component \( f_h \) are varied by the time \( t \) in Gaussian distribution having the mean value of dominant LF and HF and the variance of (LF range = 0.15 ~ 0.04) / 15 and (HF range = 0.4 ~ 0.15) / 15, respectively, so this artificial
HR data will be non-stationary. The LF/HF ratio of this artificial HR data is theoretically \((A_l / A_h)^2 = (2/2.5)^2 = 0.64\). The artificial RR-interval tachogram \(RR(t)\) and sampling time \(t_n\) can be calculated by this HR data \((RR(t) = 60 / HR(t), t_n = n / f_s)\) where sampling frequency \(f_s\) = 128 Hz and \(n = 1, 2, \ldots, N\). The total length of the synthesized RR-interval data was 5 minutes. Figure 3(a) and 3(c) shows the histogram of LF and HF component and the PSD of the artificial RR-interval tachogram by periodogram, respectively.

For the simulation of HRV spectral analysis of the HR data from the ECG including motion artefacts, the artificial intermittent RR-interval data could be used. For this, the continuous RR-interval beats are removed randomly. The number of removal was increased from 0 to 150 beats with 5-beat interval. The 150 heart beats corresponds about 150 seconds, half of the total length of simulated RR-interval data. Each removed RR-interval tachogram was interpolated by cubic spline mode in which better result was obtained between linear and cubic spline mode in the previous study [11], and re-sampled by 4 Hz. This re-sampled RR-interval data was analyzed by the non-parametric and parametric spectral analysis methods. For the uneven method, LS periodogram, removed and no re-sampled RR-interval tachogram was used. In Figure 3(b), the removed and re-sampled RR-tachogram for the non-parametric and parametric methods is plotted with the removed and no re-sampled RR-tachogram for the uneven method. The LF/HF ratio in different spectral analysis methods was observed with different continuous intermittent numbers (0 ~ 150 beats with 5-beat interval) in a 5-min artificial RR-interval tachogram with theoretical LF/HF ratio of 0.64. In each number, 1000 Monte Carlo simulations for the HRV spectral analysis in various methods were performed, and the continuous removal data were selected randomly.

3.2 Real intermittent HR data

Capacitive-coupled (CC) ECG used in this experiment was measured for about six hours during sleep on a bed in the method of Figure 2 [2]. CC-ECG measurement was progressed with Ag/AgCl ECG measurement as the reference, simultaneously. The Ag/AgCl ECG was measured by LEAD II mode and with isolated amplifier to eliminate the influence of ground to CC-ECG measurement. The posture change during sleep makes to change the electrode channel of detecting the ECG. So the best channel for R-peak detection was selected by self-developed algorithm in which the power in frequency range related to motion is used.

The R-peak was detected by the adaptive threshold method in CC-ECG and Ag/AgCl ECG. In CC-ECG, R-peak detection was not performed in the region of motion artefact by posture change and so the RR-interval data was intermittent as Figure 4. In CC-ECG and Ag/AgCl ECG, RR-interval data in the following rule, this rule means the ectopic beat, were rejected: \(RR(k) > 0.7 * (RR(k+1) + RR(k-1))\).

Intermittent RR-interval data of removal of beats including motion artefacts or ectopy were applied to spectral analysis by uneven method, and cubic spline re-sampled of that RR-interval data was done to the analysis by non-parametric and parametric methods. LFs, HFs, and LF/HF ratios in Ag/AgCl ECG and CC-ECG were obtained in each 5-min frames at 30-sec intervals, and the mean squared errors (MSEs) of LF, HF, LF/HF ratio between in Ag/AgCl ECG and in CC-ECG were compared by various spectral analysis methods.
Figure 5. Error bars (indicating mean and standard deviation) of LF/HF ratio estimated by non-parametric (periodogram and modified periodogram), parametric (Burg and covariance method), and uneven (LS periodogram) spectral analysis of artificial intermittent RR-interval tachogram of 5-min on the 1000 Monte Carlo simulations. Theoretical LF/HF ratio of this tachogram is 0.64. The results of non-parametric and parametric method, and of uneven method over the number of continuous undetected RR-interval of about 125 is overestimated

4. Results

4.1 Artificial intermittent HR data

Theoretical LF/HF ratio of artificial intermittent RR-interval generated by McSharry’s method was 0.64. However, the results obtained with non-parametric and parametric spectral analysis were overestimated around 0.85, whilst LS periodogram calculated the ratio more correctly as similar to the results in the previous research [11]. Figure 5 shows that the more number of removals of continuous RR-interval data increased, the more variance of the LF/HF in 1000 Monte Carlo runs also increased. In this figure, it is also observed that the ratio from LS periodogram increased suddenly in case the intermittent number is over about 100.

4.2 Real intermittent HR data

Figure 6 shows LF/HF results for four spectral analyses of RR-interval variation in Ag/AgCl ECG and CC-ECG during sleep. In Figure 6(a), the numbers of removed beats by motion artefact or ectopy in CC-ECG are plotted. First, looking around about the results in Ag/AgCl ECG (blue), it is appeared that Burg’s, covariance, and LS method estimates the ratio having a lower variance, and in modified periodogram, the variance is biggest. However, comparing with the results in CC-ECG (red), LS periodogram has the biggest error, and Burg and covariance method have the lowest error. These errors (mean squared error) are showed in Figure 7.

5. Discussion

Figure 6. Numbers of removed beats including motion artifact and ectopy in RR-interval data of CC-ECG (top), and LF/HF ratios obtained from four spectral analysis methods in Ag/AgCl ECG as reference (blue) and CC-ECG (red); FFT-based periodogram (2nd), modified periodogram with hanning window (3rd), Burg method with AR model order p = 16 (4th), and LS periodogram (bottom)

Figure 7. Mean squared error of LF/HF ratio, LF, and HF between RR-interval data in Ag/AgCl ECG and CC-ECG for four spectral HRV analysis methods. In LS periodogram, the errors are biggest, and Burg and covariance method have the lowest error.

In the experiment for artificial intermittent HR data, LS periodogram derived good performance about LF/HF ratio under the number of omitted RR-interval of 100 as Figure 5. These values have small variances and mean values near theoretical LF/HF ratio of 0.64. The results of non-parametric and parametric methods were overestimated and the variances increased with the number of undetected beats. However, when the intermittent number is over about 125, the results of LS periodogram diverged. In this region, the Burg’s method or covariance method will give a low error. The divergence of LF/HF ratio estimated by LS periodogram is considered as an underestimation of HF by decreasing of the data number. The frequency component is determined with the data number in LS periodogram, so when the data number is reduced, the frequency information in HF can be eliminated. Figure 6 shows the intermittent numbers and LF/HF ratios in real RR-interval tachogram from CC-ECG during sleep.
Although the intermittent numbers are not over 125, LS periodogram estimated the LF/HF values having large errors. In Figure 7, the results of LS method are also worst, and HF has more MSE value. From this experiment, it is thought that Burg’s algorithm or covariance method is optimal for HRV spectral analysis of intermittent HR data.

Burg algorithm has been improving. Waele (2000) proposed the Burg method for segment data [13], and Bos (2002) reported that Burg algorithm can be applied to irregularly sampled data [14]. If these methods is used for the intermittent HR in future study, the performance of HRV spectral analysis will be able to be advanced.

Acknowledgement

This study was supported from a grant in Advanced Biometric Research Center in Seoul National University in Republic of Korea.

References