Reduction of Motion Artifacts from Photoplethysmographic Recordings Using a Wavelet Denoising Approach

C. M. Lee and Y. T. Zhang
Joint Research Center for Biomedical Engineering
The Chinese University of Hong Kong, Shatin, N.T. Hong Kong

Abstract-**In this work, the effects of motion artifacts on photoplethysmographic signals obtained at fingertip was evaluated. A wavelet-based method was proposed to reduce the influence of motion artifacts on heart rate (HR) and heart rate variability (HRV) estimation. Two kinds of motions were investigated – vertical and circular motions. During the motion, reference signals were acquired at other hand as a standard. Results show that the HR and HRV estimation error can be reduced significantly.**
Keywords - **Photoplethysmography (PPG), wavelet transform, motion artifact.**

I. INTRODUCTION

Photoplethysmography (PPG) is a noninvasive technique for measuring volume changes in a specific body segment conducted by optical means [1] and can be used to estimate heart rate (HR) and heart rate variability (HRV) conveniently. HR and HRV estimations are based on the time interval between consecutive PPG peaks, so the accuracy of the estimation relies on the peak detection. However, PPG is very sensitive to motion artifact (MA) which may lead to wrong estimations if fault peaks are detected. In this study, MA was reduced by discrete wavelet transform method and HR and HRV were estimated from the denoised PPG signals.

II. METHODOLOGY

The algorithm for MA reduction was based on stationary wavelet transform (SWT) and the wavelet transform modulus maxima (WTMM).

By applying pairs of low-pass and high-pass filters with downsampling at each decomposition level, discrete wavelet transform (DWT) of a sequence is obtained.

For stationary wavelet transform (SWT), no downsampling is performed, so the length of the sequences at each level is same as that of the original sequence. It is a redundant representation of a signal showing great potential in signal processing and statistical analysis [2].

Let $W(2^j,\tau)$ be the wavelet coefficients at level j. Modulus maxima of the wavelet transform (WTMM) is defined as any point $(2^j,\tau_0)$ such that $|W(2^j,\tau)| < |W(2^j,\tau)|$ if τ belongs to either the right or left neighborhood of τ_0, and $|W(2^j,\tau)| \leq |W(2j,\tau_0)|$ if τ belongs to the other side of the neighborhood of τ_0 [3]. WTMM corresponds to the singularity or shape edge in the signal and their applications include signal denoising [3], feature extraction [4] and so on.

A. Experiment

There were two identical PPG circuits used in the experiment. One was on the subject's left index finger which was held in a stable position to obtain a reference signal as a standard because the PPG signals acquired from two hands are assumed to be identical if both of them are stable. Meanwhile, the right index finger moved vertically or circularly to create signal with MA. Signals were acquired from 15 subjects and sampled at the frequency of 200Hz. For each subject, one set of data was collected for each motion.

B. Algorithm

The contaminated PPG signals were decomposed by 7-level SWT. All the coefficients at level 7 (the lowest frequency range) were set to zero to remove the noise at the very low frequency. SWT coefficients of contaminated and reference signals were compared in order to find a threshold for the noise removal at levels 1 to 6. By observing the SWT coefficients, the values of positive coefficients for contaminated signal were larger than those for reference signal. This difference should be due to MA. Based on this, at levels 1 to 6, the coefficients larger than the threshold were set to the value of the threshold and the threshold at each level was equal to the average coefficients at that level. Signal was reconstructed by inverse of SWT. For circular motion, this was the last step for denoising.

If the motion was vertical, WTMM were found for the signal reconstructed by the inverse of SWT at the previous step. At each scale, if the absolute value of the WTMM was smaller than a threshold, it was set to zero. This is because the WTMM of small values should be due to MA. The signal was reconstructed by inverse of WTMM.

Peaks were detected for the reconstructed, contaminated and reference signals (Figs. 1 and 2) respectively.

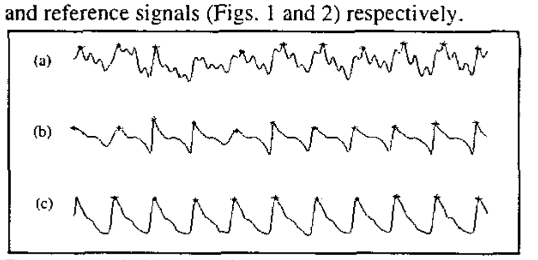

Fig. 1. For vertical motion, (a) contaminated; (b) reconstructed; and (c) reference signal. The symbol * indicates the location of the detected peak.

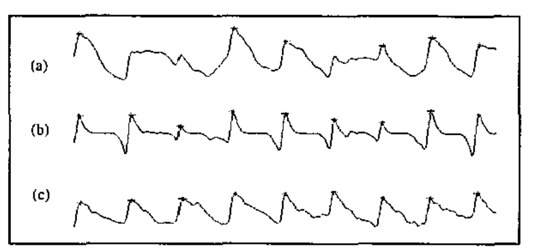

Fig.2. For circular motion, (a) contaminated; (b) reconstructed; and (c) reference signal. The symbol * indicates the location of the detected peak.

If t_n is defined as time interval between two successive peaks with $n = 1, \ldots, N$, instantaneous HR is given by $60/t_n$. HR defined as the mean of the instantaneous HR and HRV defined as the standard derivation of t_n [5] were estimated from the reconstructed and contaminated signals for each

0-7803-7944-6/03/$17.00©2003 IEEE.

subject. The estimated HR and HRV were compared with those estimated from the reference signal to find the estimation error. Meanwhile, the mean of the instantaneous heart rate error between the contaminated or reconstructed and reference PPG was also computed.

III. Results

In vertical motion, for the HR estimation and instantaneous HR error, out of 15 subjects, there was clear improvement in 14 subjects. In contrast, the results of 13 subjects showed improvement in the HRV estimation. The overall results for all subjects demonstrated that there were 87% reductions in HR estimation error, 76% in HRV estimation error and 66% in instantaneous HR error.

In circular motion, for the HR estimation and instantaneous HR error, out of 15 subjects, there was improvement in 12 subjects. For HRV estimation, the results of 11 subjects showed improvement in it. There were 61% reductions in HR estimation error, 70% in HRV estimation error and 46% in instantaneous HR error in the overall results.

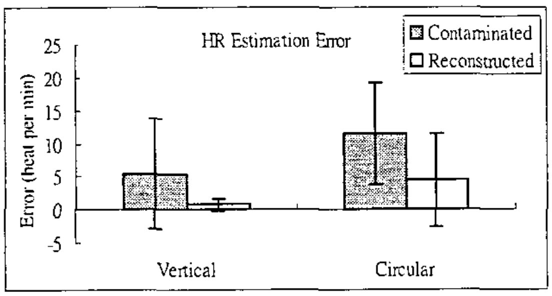

Fig.3. Averaged HR estimation error with the standard derivation for all subjects.

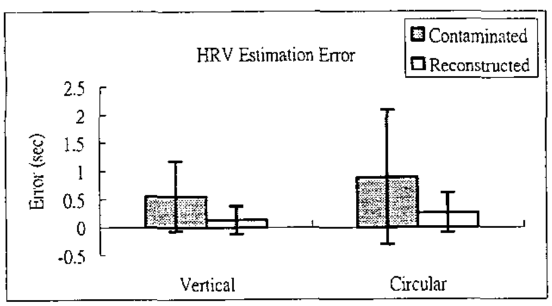

Fig.4. Averaged HRV estimation error with the standard derivation for all subjects.

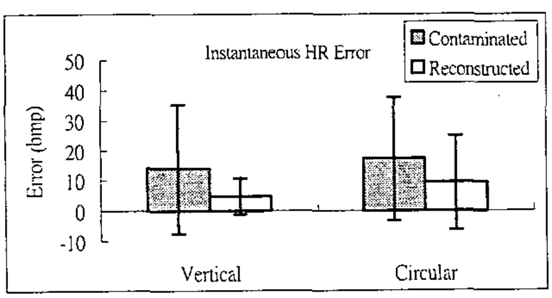

Fig.5. Averaged instantaneous HR error with the standard derivation for all subjects.

IV. Discussion

In this study, it was assumed the PPG signals obtained at two hands were the same and the PPG signal obtained at the left hand simultaneously was considered as a reference signal when right hand was moving. However, it may not always be true as the force acting on the sensors by different fingers may not be the same. Hence, even if the HR and HRV estimated by the reconstructed signal were the same as the clean signal at the right hand, there may be still error between these parameters and those estimated from the reference signal obtained at left hand.

The value of the threshold in the denoising algorithm was based on a series of trials, so it may not be the optimal for all subjects. Obviously, the waveform of the reconstructed signal relied on this threshold and hence the result also may not be optimal for every subject.

The motion created by subjects was difficult to control. In some cases, the signals acquired were not similar to those by other subjects although the similar motion was created. For this kind of cases, the results were poor.

The results of our present study suggested that the wavelet transform based denoising method on PPG signal could improve the performance in estimation of the HR and HRV. For further improvement, adaptive threshold across the time-axis should be considered. Investigation on the possible signal difference between two hands is needed and this difference should be taken into account to improve the estimation.

Acknowledgment

This work is supported by Hong Kong Innovation and Technology Fund (ITS/114/01) and co-sponsored by Standard Telecommunications Ltd. and IDT Technology Ltd.

References

[1] Robert B. Northrop, *Noninvasive instrumentation and measurement in medical diagnosis*, Boca Raton: CRC Press, pp. 241 – 252, 2002.

[2] G. P. Nason and B. W. Silverman, "The stationary wavelet transform and some statistic application," *Lecture Notes in Statistics*, 103, pp. 281-299, 1995.

[3] S. Mallat and W. L. Hwang, "Singularity dectection and processing with wavelets," *IEEE Trans Inform. Theory*, vol. 38, pp.617 – 643, Mar. 1992.

[4] J. S. Sahambi, S. N. Tandon and R. K. P. Bhatt, "Using wavelet transforms for ECG characterization. An on-line digital signal processing system," *IEEE Eng. Med. and Bio.*, vol. 16, pp. 77 – 83, Jan/ Feb. 1997.

[5] M. Brennam, M. Palaniswami and P. Kamen, "New insights into the relationship between Poincaré plot geometry and linear measures of heart rate variability," *23rd IEEE Annual EMBS International Conference of proceedings*, pp. 526 – 529, 2001.