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Full Length Research Paper

Contact-free measurement of cardiopulmonary signatures via a microwave Doppler radar using adaptive filter

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It has been proven that the respiration and heartbeat signals can be contact-free detected via a microwave Doppler radar. However, the heartbeat signal cannot be identified from the body-movement signal when the human subject breathes freely. To resolve the problem, the adaptive filter is used to simultaneously measure the heartbeat and the respiration signal. Firstly, the respiration and the body-movement signal are filtered by finite impulse response (FIR) band-pass digital filter with the cutoff frequency of 0.03 and 3.3 Hz. Then, the respiration signal is regarded as reference input of adaptive noise canceller (ANC) and the body-movement signal is regarded as the primary input. Finally, the heartbeat signal is extracted from the body-movement signal using the recursive-least square (RLS) algorithm. Experimental results showed that the adaptive filter cannot only effectively remove the respiration signal, but also the heart rate derived from the filtered heartbeat signal was strongly correlated with that from the electrocardiogram (ECG) recordings ($\gamma^2 = 0.95$, $p<0.0001$, $n=16$).

Key words: Contact-free, microwave Doppler radar, adaptive noise canceller, recursive-least square, heart rate.

INTRODUCTION

Since the 1970s, the microwave Doppler radar has received more attention as a remote sensing system on human healthcare monitoring, such as physiologic movement and volume change sensing (Matthews et al., 2000), life detection for finding human subjects trapped in earthquake rubbles (Chen et al., 2000) or detecting human subjects behind a barrier (Wu and Huang, 2008), cardiopulmonary monitoring for sleep apnea syndrome detection (Brink et al., 2006), human vital signs (Li et al., 2009; Uenoyama et al., 2006), as well hearing rate variability measurement (Nagae and Mase, 2010). But in the studies above, the heartbeats could not be measured when the subject breathed freely, because the heartbeat and respiration signals were superimposed on each other and the random body-movement produced some noise.

To separate the small heartbeat signal from the much larger respiration signal, new radar transceivers were developed that incorporated analog and digital signal processing. The quadrature transceiver combined analogy amplification and filtering was used for separation of heart beat and respiration signatures (Bakhtiari et al., 2011). The multiple-input, multiple-output (MIMO) technique was used to solve the problem of motion artefacts (Li and Lin, 2008). However, the structure of the radar was complex and expensive, and the random movement of human body still could not be removed.

In our preliminary study (Wang et al., 2007), the digital finite impulse response (FIR) filter with a cutoff frequency of 0.7 Hz combined with symmlets wavelet was used to measure the heartbeat signal, the experimental results

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showed that this method did not work well, because the FIR digital filter could not remove the harmonic components overlapped with heartbeat signals, and the wavelet de-noising method could not reject the body motion artefacts without any prior knowledge. With the pioneering work of Wiener and later Kalman, adaptive noise cancellation was developed to estimate signal components optimally without requiring explicit a priori knowledge of statistical properties and assumption of the stationary of the signal or noise. Based on some algorithms, the adaptive filter trains itself using the initial statistical properties of the input and adapts to track the changes in the signals or noise and extracts desired signal. In this paper, the adaptive noise canceller (ANC) based on the recursive least square (RLS) algorithm was used to extract the heartbeat signal by removing the respiration noise and body random artefacts.

MATERIALS AND METHODS

Signal recording

Sixteen volunteers (16 males; 23.0 ± 4.0 years (mean±S.D.)) participated in this study. Ethic Committee of the Fourth Military Medical University approved the study. All subjects were healthy and informed consent was obtained prior to their participation.

For recording the respiration and body-movement signals, the custom-developed contact-free cardiopulmonary signatures monitor was used. The monitor is composed of a low-power microwave Doppler radar, a pre-processor and the power supply sets. The Doppler radar operates at 35 GHz and the transmission power is 1 mW. The microwave beams are radiated by the Doppler radar through a two-way antenna with the gain of 17 dB. When the microwave beams arrive at the chest of the human subject, the echo signal is reflected by the chest wall motion introduced from the breathing activity. The output of the radar is conditioned by a pre-processor consisting of an amplifier with the gain of 60 dB, two low pass filters with cutoff frequency of 0.5 and 3.3 Hz. Two-channel signals are output from the pre-processor, one is called respiration signal, the other one is called body-movement signals, including the respiration, heartbeat signal and other tiny body movement noise. The power supply sets provide the voltage, the radar and the pre-processor required, which can make the monitor continuously work for 10 h.

To test the errors between heart rates derived from the contact-free cardiopulmonary signatures monitor and electrocardiograph, the electrocardiogram was recorded. The disposable Ag/AgCl resting electrocardiogram (ECG) electrodes (Red Dot™ -2352; 3M Company; Minnesota, USA) were attached to the right leg (‘Ground’), right wrist (‘Negative’) and left wrist (‘Positive’). Wires from the electrodes were attached to an ECG amplifier (ECG100C; BIOPAC Systems Inc., Goleta, California, USA).

The outputs of ECG amplifier and cardiopulmonary signatures monitor were connected to a 16-channel A/D converter (MP150; BIOPAC Systems Inc., Goleta, California; USA), which was in turn directly connected to a desktop computer. All the signals were sampled at a frequency of 1000 Hz simultaneously recorded for 7 min using the AcqKnowledge software package (v 3.8.1; BIOPAC Systems Inc., Goleta, California; USA). The digitalized respiration, body-movement and ECG signals were digitally processed performed in Matlab (v6.5; Math Works Inc, Natick, MA, USA). Subjects remained still throughout the recording period and were instructed to minimize their movement. The distance between the antenna and the human subject ranges from 0.1 to 2.5 m.

Extraction of the heartbeat signal and heart rate

Extraction of heartbeat signals from the body-movement was performed using the signal processing techniques. The procedure is illustrated in Figure 1. A 2 min segment of body-movement signals and respiration signals were selected from each subject. Both signals were pre-processed using a high-pass filter at 0.03 Hz to remove the DC component of the radar outputs and a low pass filter at 2.0 Hz to remove other high-frequency body motion noises. The filtered signals were then filtered with an ANC utilizing the RLS algorithm. The recorded body-movement signals composed of desired heartbeat signals and respiration noise is defined as d (n). The signal (u’ (n)) is then estimated by the reference respiration signal (u (n)) recorded from a separate channel via a finite impulse response (FIR) digital filter. The desired heartbeat signal(e(n)) is defined as the difference between d(n) and u’(n). The RLS algorithm adaptively adjusted and updated the coefficients of the FIR filter to minimize the weighted least-square errors between u(n) and u’(n).

For extraction of the heart rates derived from the ECG and the filtered heartbeat signals, power spectra of both signals were obtained by Welch’s method, with the 2-min signals segmented into 50% overlapping sections. A Hamming window of 1024 data points was used to reduce the variance of the resulting spectra estimate. The heart rate was calculated by the frequency occurrence of the peak of the spectra times sixty.

Statistical analysis

To assess whether the heart rates derived from heartbeat was related to those derived from the ECG, linear regression analysis and Pearson correlation were performed. Before analyses, heart rates were examined for deviations from normality by the Kolmogorov-Smirnov test. The level for significance was set at $p<0.05$. Statistical analyses were performed in SPSS (v13, SPSS Inc., Chicago, IL, USA). Graph was plotted using Origin (v7.5776, Northampton, MA, USA).

RESULTS

20s segment of one of the human subjects’ respiration (ResP), body-movement (BodyM) and ECG signals are shown in Figure 2. The respiration signal, the body-movement signals and the ECG signals were displayed from top to bottom, respectively. In Figure 2b, the body-movement signals were composed of the respiration and other physiological activities, from which the heartbeat might be extracted by the method described in the paper.

The adaptive filter was used to extract the heartbeat signals from another subject. Recordings of ResP, BodyM, ECG signals filtered heartbeat signals (HeartB) and their power spectra are shown in Figure 3. Left panel of Figure 3a to d display the waveforms of respiration, body-movement, heartbeat and ECG, right column from Figure 3e to g was their power spectrum, respectively. In Figure 3e, the peak frequency in the spectrum was 0.26 Hz. In Figure 3f, there were two peak frequencies in the spectrum, one was 0.26 Hz and the other one was 1.28 Hz, and the power of the first peak was 14 times than that of the second peak. Figure 3g displayed the spectrum of the heartbeat signal extracted after adaptive filter. After processing, the peak frequency of 0.26 Hz was removed

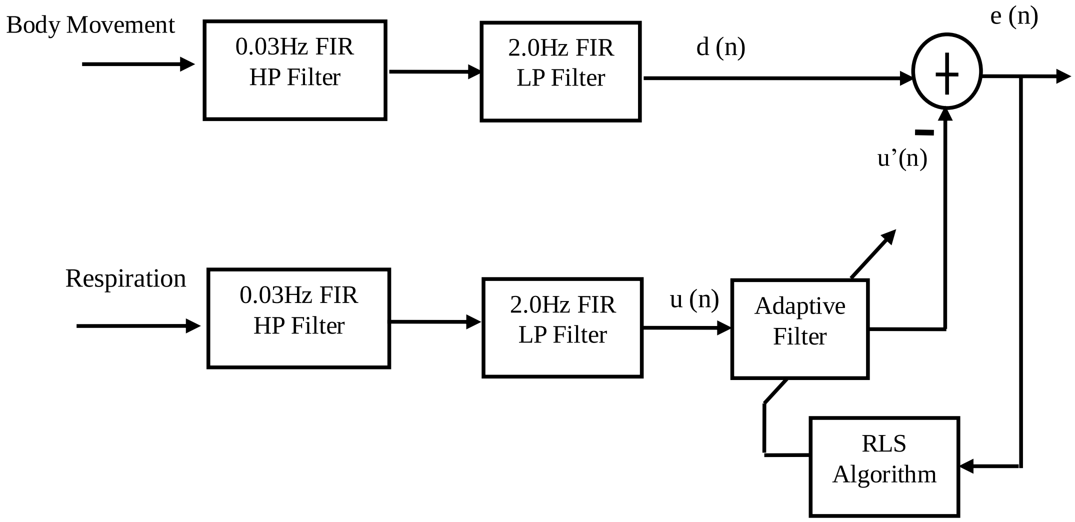

Figure 1. The basic flow chart of adaptive noise canceller.

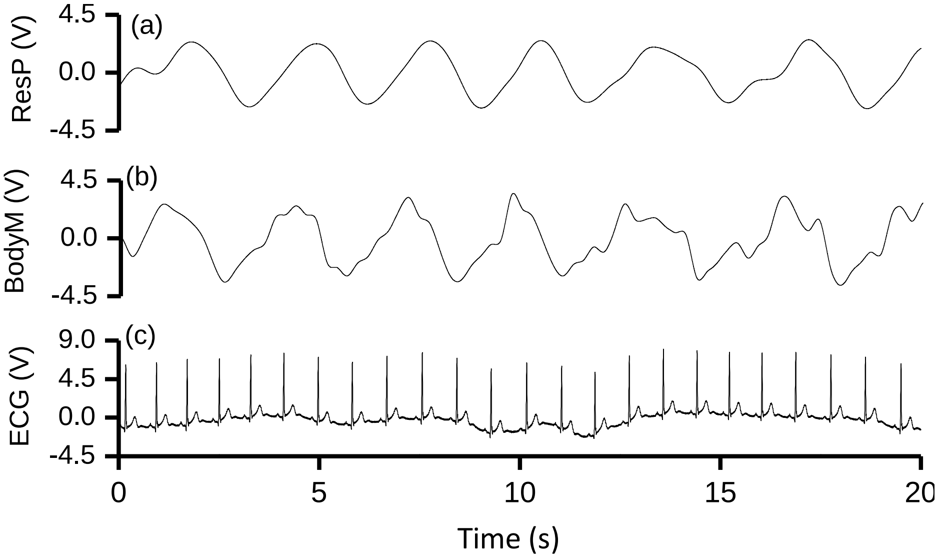

Figure 2. Waveforms recorded from the contact-free cardiopulmonary signatures monitor and ECG system. (a) 20 s-segment of respiration signals. (b) 20 s-segment of body-movement signals. (c) 20 s-segment of ECG signals.

and the peak frequency of 1.28 Hz remained, which denoted that the heart rate was 77 per minute. Figure 3h showed the spectrum of ECG, the peak frequency was 1.28 Hz, and the heart rate was 77 beats per minute. From Figure 3, it can be seen that the respiration noise was been effectively removed from the body-movement signal using adaptive filtering method proposed in this paper.

In order to compare correlation ship between the heart rate extracted from ECG and adaptively filtered heart beat signals, the linear regression analysis was used and the result is shown in Figure 4. The result demonstrated that the heart rates from the filtered heartbeat signals strongly correlate to those from the ECG recordings ($\gamma^2 = 0.95$, $p<0.0001$, $n = 16$), which means that the adaptive filter could effectively extract the heartbeat.

DISCUSSION

In contact-free cardiopulmonary signatures monitor via a microwave Doppler radar, one of the key problems is how to separately measure the respiration and heartbeat, which will provide important health information of subjects in the clinic. In good conditions while the subject keeps motionless during the recording, heartbeat signal can be

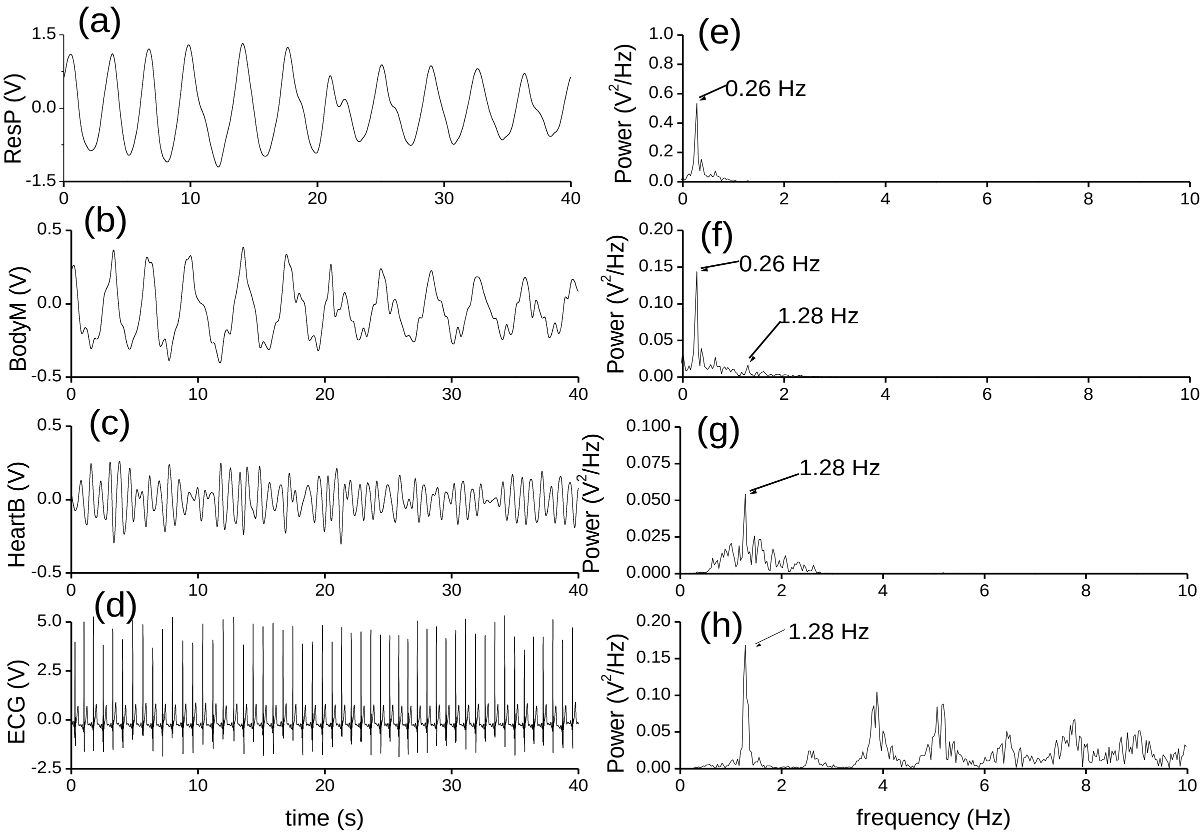

Figure 3. Outputs of the contact-free cardiopulmonary signatures monitor and ECG with their power spectral analysis. Left column from a to d is waveform of respiration, body movement, filtered heartbeat and ECG respectively. Right column from e to h is power spectrum analysis of the four signals aforementioned.

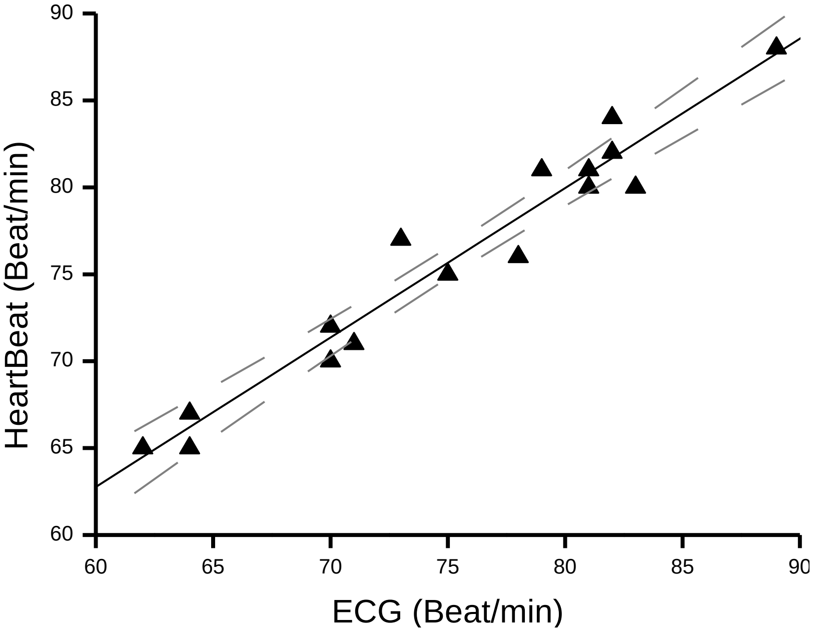

Figure 4. Correlation between the heart rate derived from ECG recordings and filtered heartbeat signals. Solid line = linear regression, outer dashed line = upper and lower 95% confidence intervals ($\gamma 2 = 0.95$, $p<0.0001$, $n = 16$).

easily identified from the body movement recordings by simple analog and digital filters using a band pass filter with the lower cut-off frequency of 0.8 Hz and the upper cut-off frequency of 2.5 Hz (Wang et al., 2007). However, the extraction of the heartbeat signal became very difficult while the effects of breathing and involuntary body-surface movements of subjects occurred. There are two reasons, one is the minute chest movement caused by the respiration is much stronger than that caused by the heartbeat, the other one is that the high order of the harmonics component of respiration is overlapped with that of the heartbeat, thus, it is difficult to separate the heartbeat signal from the overlapped signals using complex Doppler radar transceivers combined with analogy filters (Bakhtiari et al., 2011; Kim et al., 2007; Li and Lin, 2008). Some advanced digital signal processing methods such as wavelet transformation (Tateishi et al., 2007) and maximum likelihood estimator (Host-Madsen et al., 2008) were used to remove the respiration noise and body motion artefacts in heartbeat signals,these method required the prior knowledge of respiration noise and body motion artefacts. Adaptive filter used in the paper can perform well in our experiments, which could produce the ideal results by automatically adjusting the parameters of the filter according to the changes of the inputs to the ANC.

Several factors may influence the performance of an adaptive filter, for instance the filter structure, rate of convergence, robustness, etc. The RLS algorithm iteratively computes the updated estimate of the filter coefficients upon the arrival of new data. Adjusting the forgetting factor permits control over the convergence rate, decreasing the forgetting factor results in faster convergence but with an associated increase in fluctuations of filter coefficients. The RLS algorithm naturally provides a fast convergence rate so as to render tuning by the forgetting factors redundant in the specific case of de-noising heartbeat signals. When the recorded body-movement signal have relatively more heartbeat components, a forgetting factor very close to one proves sufficient.

Respiration and heartbeat can be remotely monitored by the microwave Doppler radar without any electrodes and sensors touching the subject at a distance less than 2.5 m, which will make the human subject feel relaxed and comfortable. Health-care monitor made from this technology can be widely used in clinic, such as ambulatory monitoring the seriously burned patients, infectious disease patients, and can be used in the field of psychophysiology study.

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