ECG-Derived Respirations Based on Phase-Space Reconstruction of Single-Lead ECG: Validations over Various Physical Activities Based on Parallel Recordings of ECG, Respiration, and Body Accelerations

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***Abstract*—ECG derived respiration (EDR) provides a comfortable measurement of respiration and is recently applied to sleep studies. Nevertheless, the mechanic disturbances due to postural changes or other physical activity during long-term recording is less investigated. In the present study, ECG, impedance-based respiration, and body accelerations were parallel recorded during a series of scheduled postures in 8 healthy subjects and during 24 hours in one subject. In addition, a novel EDR method based on phase space reconstruction of single-lead ECG is also proposed. The area under major portrait radius (MPR) curve is employed to quantify the deviation of phase-space loop which is related to respiration. Coherence analysis between the EDR and the impedance-based respiration demonstrated that the MPR-based EDR had better performance than using R peak or QRS area as the EDR feature in the scheduled postures.**

I. INTRODUCTION

Electrocardiogram (ECG) is a low-cost, noninvasive measure of the heart's electrical activity. ECG analysis has become a standard diagnostic tool for detecting cardiac arrhythmia. A typical ECG waveform consists of three features, labeled P, QRS, and T waves. The QRS complex (containing the Q, R, and S peaks) is generated from the sequential depolarizations of bundle branches, Purkinje fibers, and ventricular muscles. QRS complex is the most apparent feature in the ECG. The variation of QRS amplitude can be used to estimate respiratory activity, also named as ECG-derived respiration (EDR) [1]. The advantage of using ECG to measure respiration is that it is more comfortable than the measurement by the ribcage respiratory effort belt. Although thoracic impedance can also be used to derive respiration without such uncomfortableness as the ribcage belt, the commonly used cadiac Holter does not have this measurement. The EDR parallel with heart rate variability has been applied to detect obstructive sleep apnea [2, 3], sleep staging [4], or to investigate cardiopulmonary coupling characteristic [5], and so on.

The principle of EDR is the distance between electrodes and the heart is changed during respiration. During the inspiration, the distance increases and causes the decrease of QRS amplitude; vice versa. However, the mechanic disturbances from physical activity, particularly during long-term, free-moving recording, will affect the accuracy of the respiration estimation by EDR and depends on the level of physical activity, static or dynamic, and the type of the posture.

In the present study, ECG, impedance-based respiration, and body accelerations were parallel recorded during a series of scheduled postures and during 24 hours. A novel EDR based on phase-space reconstruction of ECG which covers temporal characteristic is proposed. The relation of the EDR and the impedance-based-respiration during different postures or physical activities were investigated by coherence analysis.

II. METHODS

A. Subjects and Data Collection

Eight healthy male subjects performed a series of static physical activities, stand, supine, left-lateral lying, and right-lateral lying, each lasted for 3 minutes. One subject also continued a 24-hour recording. The protocol of this study was approved by the local Research Ethics Committee. The participants gave their informed consent.

Three-lead ECG (leads I, II and precordial) and thoracic impedance (ADS 1294R, Texas Instruments, TX) and 3-axial accelerometer (ADXL-330, Analog Devices, MA) were parallel recorded with a sampling rate of 250 Hz in a portable device (Kangyi Electronics, Taiwan).

B. EDR analysis

Lead II ECG was used. QRS was detected and verified. The normal heartbeats were included for EDR analysis. Three QRS features were employed to estimate respiration. The first feature is the peak amplitude of R wave (peak-based EDR). The second feature is the area under QRS waveshape (area-based EDR). The third feature is the major portrait radius (MPR) that is derived from the phase space of ECG.

Phase space reconstruction expands a time series $x(t)$, $t = 0\ldots T$ into a series of vectors $\mathbf{x}(t)$, $t = 0\ldots T-(d_m-1)\,\tau$:

$$\mathbf{x}(t) = [x(t)\ \ x(t+\tau)\ \cdots\ x(t+(d_m-1)\tau] \tag{1}$$

where τ is a constant time delay and d_m is the embedding dimension. Plotting $\mathbf{x}(t)$ in multiple dimensions depicts the phase space trajectory of the time series. The present study

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uses a two-dimensional phase space diagram (d_m=2) to reconstruct the phase space of the QRS complex instead of a higher embedding dimension, and the time delay is set to 8 ms. The two-dimensional reconstruction displays a clear phase space trajectory, and lends itself more readily to feature extraction. Before phase space reconstruction, every QRS complex was resampled at a higher resolution (ten points per datum) by cubic interpolation.

An example of QRS transformation to a two-dimensional phase space portrait can be seen in Fig. 1. The large trajectory (middle) that is attributed to the main part of the QRS complex is seen. The phase space portrait is subsequently projected onto a one-dimensional major portrait radius (MPR) (right). The MPR is composed of radiuses of major portraits at phases from 0 to 2π (partitioned by M=25). If there is more than one radius at some phases, the largest one is chosen.

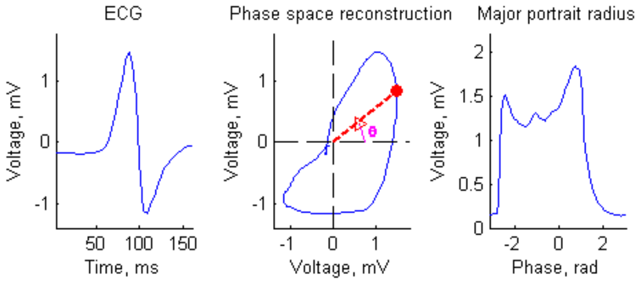

Fig 1. Phase space reconstruction of a QRS complex and the descriptive feature

Fig. 2 shows an example of a subject who underwent normal breathing, breath holding, normal breathing, and deep breathing. Both the detected QRS of Leads I and II ECGs show variation of waveform due to respiration. The phase space portraits and the derived MPR of the detected QRS also present respiratory-related variation. The area under MPR curve shows oscillatory component during different states of respiration (the third row) as well as the respiration derived from the thoracic impedance (the second row).

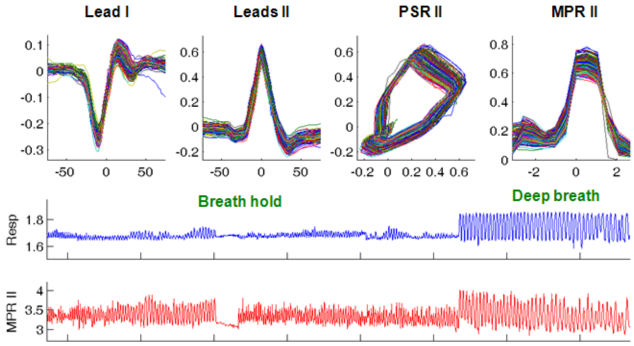

Fig 2. The variation of ECG waveform and their phase-space reconstruction (PSR) and major portrait radius (MPR) in a subject who performed normal breathing, breath holding, normal breathing, and deep breathing.

C. *Coherence Analysis between Impedance-Based Respiration and EDR*

To test the reliability of EDR, coherence analysis is used to quantify the consistency of EDR with impedance-based respiration. Given two respiration signals $x(t)$ and $y(t)$, the magnitude squared coherence reflects a linear association between these two signals at each frequency, defined as the normalized cross spectrum:

$$c_{xy}(f)=\frac{|X(f)Y^{*}(f)|^{2}}{|X(f)|^{2}|Y(f)|^{2}} \tag{2}$$

where $X(f)Y^{*}(f)$ denotes a cross-spectrum and $|X(f)|$ and $|Y(f)|$ refer to auto-spectra. The coherence theoretically varies from 0 to 1 over frequencies. The cross-spectrum and auto-spectra were computed using multiple nonoverlapping 20-sec segments. A high coherence can be linked to a high consistency between the EDR and the impedance-based respiration.

III. RESULTS

Fig. 3 shows the spectra of the impedance-based respiration in a subject during standing, supine, left-lateral lying, and right-lateral lying. Apparent spectral peaks are observed. The peak frequency is related to the breathing frequency.

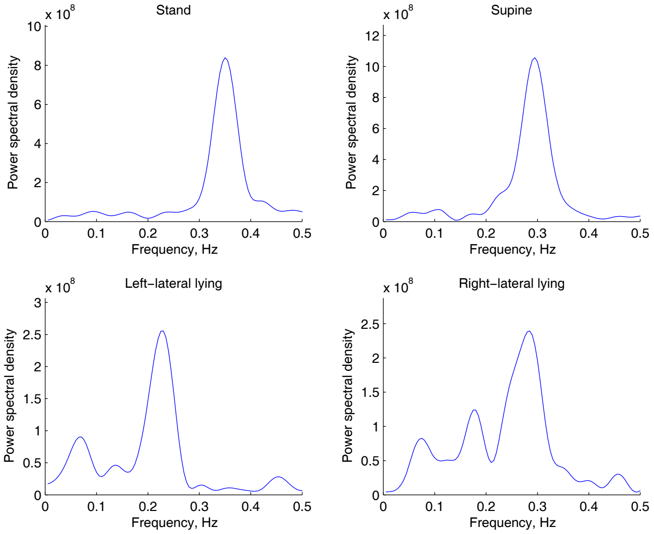

Fig 3. The spectra of the impedance-based respiration in a subject.

Fig. 4 shows the corresponding coherence spectra between the EDR and the impedance-based respiration in the same subject. The MPR-based EDR has higher coherence at the frequency corresponding to the spectral peak of the impedance-based respiration.

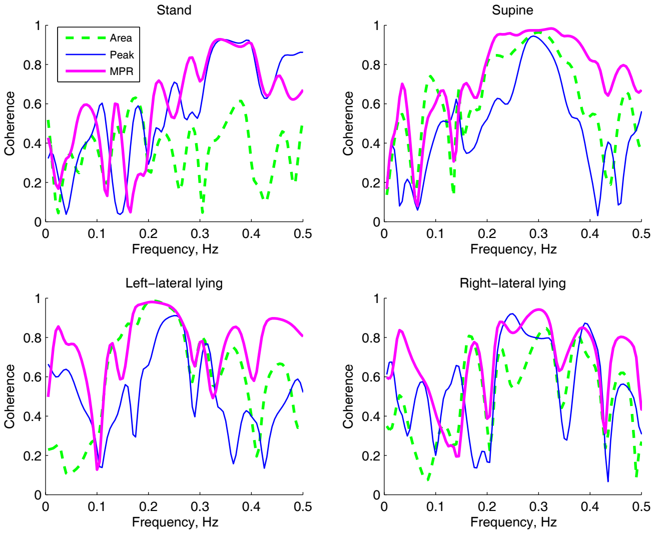

Fig 4. The coherence spectra between the EDR and the impedance-based respiration in a subject.

Using the frequency of the spectral peak in the impedance-based respiration, the coherences which are related to the peak-based EDR, the area-based EDR, and the MPR-based EDR were extracted, respectively. Fig. 5 shows the statistical result of these coherences in different postures. The MPR-based EDR had better coherences than the area-based EDR in each posture and better coherence than the peak-based EDR during supine. During standing, the area-based EDR had the least coherence. The averaged coherence during supine was largest during supine but not significant.

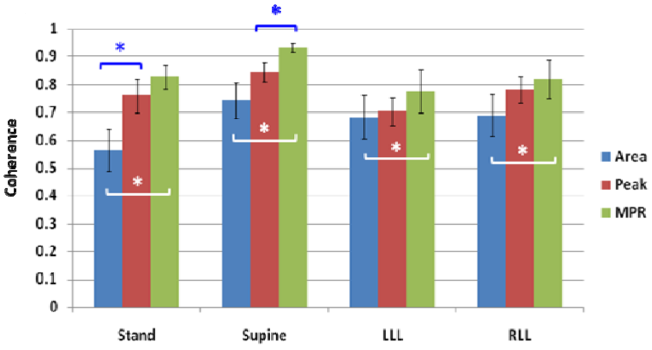

Fig 5. Coherence between the EDR and the impedance-based respiration. LLL, left-lateral lying; RLL, right-lateral lying. * indicating significant difference ($p<0.05$).

IV. DISCUSSION

Since the impedance-based respiration and body accelerations were parallel recorded with ECG in the present study, the reliability of the EDR during different postures and during long-term recording can be investigated. Based on the coherence analysis, the proposed MPR-based EDR performed better than the peak-based EDR and the area-based EDR in the scheduled postures. The area-based EDR had the worst performance. The possible reason for the worst performance in the area-based EDR is that the summation of the amplitude of the QRS samples smears the most essential information from the R peak. Nevertheless, the QRS complex is expanded in a two-dimensional phase space and the most striking loop comes from the R wave. The MPR provides a good way to cover this striking loop not only its amplitude but also the temporal relationship which is expected to better than using only R peak to derive respiration.

In previous researches, phase-space reconstruction is also applied to derive respiration from ECG. However, these methods are based on two leads [1] or vector leads [6, 7]. Our method uses only single-lead ECG to expand the phase space based on the time-delay technique. In addition, phase space reconstruction does not use absolute time relationships, lending itself to an alignment-free advantage on classification of neuronal action potentials [8], personal identification by electrocardiogram [9], and ventricular extrasystole recognition [10]. That means the phase space-based method does not need an accurate detection of R peak. As long as the complete waveform of a QRS complex is included, the MPR can cover the essential information of the QRS complex.

Although correlation analysis can quantify temporal relationship between the EDR and the impedance-based respiration, the EDR usually contains other contents that are not related to the respiration which will disturb the quantification. Coherence analysis that gives signals' relationship at various frequencies provides a better way for this assessment. Continued from this work, the estimation of frequency and amplitude of respiration from the EDR is also important, particularly in noisy environment [7].

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