Evaluation of Methods for Estimation of Respiratory Frequency from the ECG

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Abstract

A comparative study of methods for estimating respiratory frequency through electrocardiogram was carried out. Methods were based on beat morphology (QRS area or amplitude) and heart rate variability. In addition a combination of methods was also investigated. For each method, time and frequency correlation between the ECG derived respiration and the real respiration recorded by chest plethysmography were computed as well as the relative error in the respiration rate. Results indicate that combining the spectra of different methods gives overall the best estimation of the respiration rate. This technique obtained a median relative error of 1.07% (mad=22.13) in free breathing signals. Methods based on Area, Amplitude and AMEA had relative errors around 1.10% (17/18). HRV however, had high relative errors in free breathing signals (42.70% (24.26)).

1. Introduction

Breathing is one of the main body functions and its alterations have been proved to be a risk factor in different patient population [1]. The measurement and monitoring of respiration is important in order to check the respiration rate and breathing health.

Direct recording of respiratory signals presents practical relevant problems. Equipments strongly interfere with the patient and are often not suitable for long duration recordings, stress testing or ambulatory monitoring [2, 3]. In addition, these methods interfere with natural breathing, and many subjects seem to modify their respiratory pattern unconsciously once they become aware their respiration is monitored [4].

Obtaining the respiration rate from ECG measurement could be a better alternative. Respiratory activity influences electrocardiographic measurements in various ways, and can be separate in two types: those which affect beat morphology and those affecting heart rate variability. During the respiratory cycle, heart movements within the chest cause a rotation of the electrical axis of the heart which affects beat morphology. The apex of the heart is stretched towards the abdomen during inspiration and compressed towards the breast during expiration; therefore the mean electrical axis direction is affected [5]. The movement of the chest also affects beat morphology. The position of the electrodes relative to the heart changes during respiration resulting in R-wave modulation. Changes in thorax impedance due to filling and empting of the lungs also contribute to the electrical rotation [3, 6]. Heart Rate Variability (HRV) is influenced by an effect called Respiratory Sinus Arrhythmia (RSA). The heart rate increases during inhalation and decreases during exhalation. This effect results in oscillations of RR interval series corresponding to breathing activity. It has been observed that the effect of RSA is stronger in young population and it decreases with age [5].

There are several applications for the ECG Derived Respiration (EDR), for instance certain cardiac arrhythmias can be understood only with reference to respiration. One of the most known breathing disorders, apnea, may be associated with tachycardia, increased ventricular ectopy, or asystole. Furthermore, stress, heart failure, and chronic lung disease may result in both tachypnea and tachyarrhythmia [4, 7].

Several techniques to estimate respiratory information from the ECG are available in literature. Some techniques are based on respiration-induced variations in beat-to-beat morphology, while others attempt to extract from HRV [3]. In this paper we investigate the performance of those techniques under different conditions: paced and free breathing signals; and noisy signals recorded with motion of the patient. Also, some other factors such as the influence of electrodes position or the age of the patient are studied.

2. Methods

2.1. Experimental protocol

In order to evaluate and compare different methods for deriving EDR signals, data was collected from 20 subjects. The subject characteristics were: five female and fifteen male, with ages in the range 22-45 (mean 30.2, standard deviation 7.49). 15 channel ECG signals were recorded, 12 standard leads plus 3 non standard precordial leads: V5R (V5 in the right side) and two extra leads above V1 and V2, X1 and X2 (Figure 1).

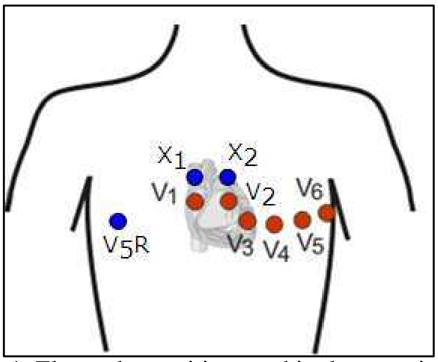

Figure 1. Electrodes position used in the experiment.

Respiration waveforms were recorded simultaneously using inductance plethysmography in both chest and abdomen. In order to investigate the effect of different body positions and respiration patterns, 10 different conditions were considered. Three different respiration patterns were used: paced breathing with 9 or 12 breaths per minute and no paced, free breathing. Each of the measurements were recorded with three different corporal positions: supine, standing and seated. An additional recording was also done standing while the subject was doing a bit of movement (jogging on the spot). All signals had a duration of 2 minutes and were recorded at a sampling frequency of 4800 Hz. ECG recordings were filtered with a 50 Hz notch filter and a 0.05 Hz high pass filter in order to remove power interference and baseline wander. Then, the data was annotated using an automatic beat detector algorithm [8]. Beat annotations were verified by visual inspection.

In addition to our in-house dataset, the Fantasia database was also used. This database is widely known and is freely available in the Physionet website [9]. It consists of 40 subjects divided in two groups of 20 people each: young people (ages from 21 to 34) and elderly people (ages from 68 to 85). The subjects underwent 120 minutes of continuous supine resting while they were watching the film Fantasia (Disney, 1940) to help maintain wakefulness. During the 2 hours an ECG and a respiration signal were recorded. Signals were sampled at 250 Hz.

2.2. ECG derived respiration methods

Four different methods to obtain the EDR signal were selected: HRV (based on RSA), Amplitude, Area and AMEA (based on beat morphology).

HRV method uses the beat-to-beat intervals for the construction of the EDR signal [4].

Amplitude method calculates the EDR from the change in the amplitude of each QRS complex. The amplitude is computed as the difference between the maximum and minimum value within a time window of 100ms around the R peak within each beat [10] (Figure 2).

Area method is a variation of the previous method. The area of the QRS complex is computed against its baseline. The baseline is defined as the mean value around each beat. The baseline is subtracted to the ECG and the area is calculated within a 100 ms time window around the R peak [1].

Angle of Mean Electrical Axis (AMEA) method estimates the EDR as the variations of the heart axis. The area of two ECG leads is calculated. The angle of the mean electrical axis is obtained as arctangent of the ratio of these areas [5, 7].

The EDR signals are interpolated and resampled to 50 Hz. Then, the FFT is computed with 4 times zero padding in order to obtain the spectrum. The frequency resolution was of 0.0033Hz. The frequency corresponding to the maximum of the spectrum within a bandwidth of 0.1 to 0.5 Hz was considered as the main respiration frequency [4].

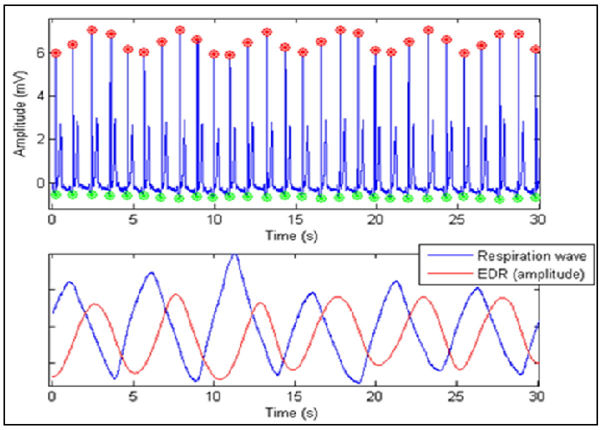

Figure 2. Top, ECG with maxima and minima values around the QRS complex marked. Bottom, respiration signal together with EDR based on QRS amplitude variability.

A combination of the spectra calculated by each method independently was also considered as an additional method. *Combination method* is computed as the average of the spectra of the rest of methods. In this way, the main frequencies are enhanced while minimizing the energy of the spurious frequencies.

2.3. Evaluation parameters

All recordings within the datasets were analyzed in segments of 1 minute length.

In order to evaluate the performance of the selected methods, three parameters were computed: first the correlation between the real respiration and the EDR signal; second the correlation of the spectra of both the real respiration and the EDR signal in the range of interest

(0.1-0.5Hz) [4]; and finally the relative error (in percentage) of the main respiration frequency obtained from both the real and the estimated respiration.

3. Results

Although two respiration signals were recorded (chest and abdomen), it was found that, both signals gave a similar performance (median correlation indexes above 0.90 and median relative errors of 0% for both free and paced breathing measurements).

3.1. ECG lead position

We investigated the performance of different electrode position in estimating the respiratory rate. With this aim, fifteen different leads were recorded. Figure 3 shows the median values of correlation between EDR (obtained by computing the amplitude) and respiration signals in both time and frequency domains and relative error of respiratory frequency during free breathing.

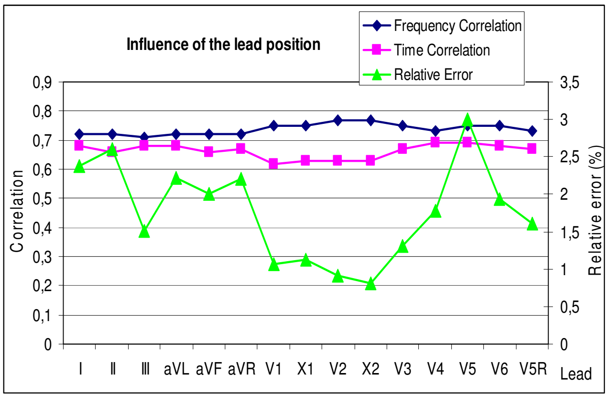

Figure 3. Median values of time and frequency correlation between respiratory signal and EDR obtained by amplitude method in free breathing.

The best performance was obtained with the electrode positions corresponding to leads V1, V2, X1 and X2. This was more obvious when looking at the relative error with a minimum value in lead X2 with 0.81% (14.93) in free breathing signals and 0.66% (4.22) in paced breathing.

3.2. Method comparison

Signals recorded with paced respiration and while free breathing were investigated separately.

In paced breathing the methods gave a similar performance in respect to time correlation with median (mad) values of 0.61 (0.09) for Area, 0.59 (0.09) for Amplitude, 0.71 (0.07) for HRV and 0.61 (0.08) for AMEA. When evaluated with frequency correlation, the performance was also similar (Area: 0.89 (0.08), Amplitude: 0.89 (0.07), HRV: 0.86 (0.08), AMEA: 0.88 (0.08) and 0.87 (0.07) when combining the spectra).

In free breathing signals, the difference between methods was also small by compared with the correlation in time: 0.63 (0.08) for Area, 0.62 (0.08) for Amplitude, 0.69 (0.06) for HRV and 0.64 (0.08) for AMEA while the correlation of spectra yielded in a slight higher difference between methods: 0.73 (0.09) for Area, 0.75 (0.09) for Amplitude, 0.62 (0.12) for HRV and 0.76 (0.09) for AMEA and 0.71 (0.12) for Spectral Combination (Figure 4)

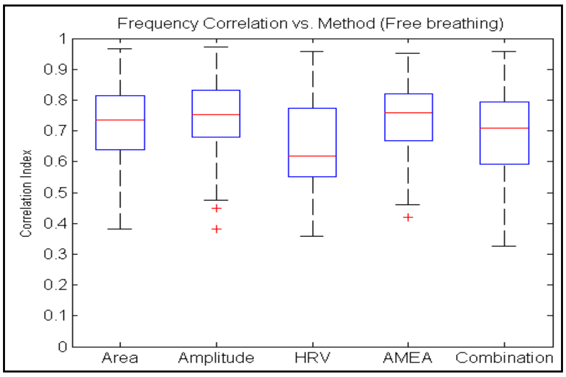

Figure 4. Boxplots of the correlation coefficients between respiration and EDR spectra.

Table 1 shows the relative error obtained for all the methods and paced-free breathing. During paced breathing all methods had a similar and low median error (lower for Combination, 0.63%; higher for HRV, 0.89%) while for free breathing HRV had a significant higher median error (42.7%) than the remaining methods.

Table 1. Relative error vs. Method

Method	Respiration	Error: median (mad)
Area	Paced	0.69% (9.00)
Area	Free	1.32% (18.81)
Amplitude	Paced	0.70% (7.34)
Amplitude	Free	1.07% (16.81)
HRV	Paced	0.89% (5.80)
HRV	Free	42.70% (24.26)
AMEA	Paced	0.70% (7.95)
AMEA	Free	1.03% (17.45)
Combination	Paced	0.63% (2.88)
Combination	Free	1.07% (22.13)

3.3. Robustness to noise

When the noise increased (due to the movement of the subjects) the relative errors obtained were in general much higher (minimum of 39.16% by Area method and maximum of 52.36% by HRV method). Correlation values also decreased for both time (minimum of 0.65 for Amplitude method, maximum of 0.68 for Amea method) and frequency (minimum of 0.59 for Combination method, maximum of 0.65 for Amplitude method).

Alternatively to Fourier analysis, the breathing rate was obtained by counting the duration of the respiration cycles in time signals [4]. Once the duration of each cycle is measured, the mean of these lengths is calculated. The inverse of the mean duration is considered as the main frequency of the signal. Using this method the obtained relative errors ranged from 14.78% (HRV method) to 18.90% (Amplitude method).

3.4. Age and body position

The effect of age in the RSA [5] was also studied using the Fantasia database. The relative error obtained with the HRV method for both groups (young and elderly) was significantly different (t-test, p=3.43e-6). However, the relative error obtained by the rest of methods did not yield to significant differences between both populations.

Different body positions were also investigated. It was observed slightly higher relative errors in seated signals. For instance, Area method and paced breathing, gave a relative error of 0.80% (mad=1.13) while seating, 0.54% (4.76) for stand signals and 0.66% (0.55) for supine signals.

4. Conclusion

We evaluated different methods for estimation of respiratory frequency from the ECG signal. A dataset of ECG and respiration signals was collected. In addition, the Fantasia database was also used. Four different methods were selected for evaluation: Area, Amplitude, AMEA and HRV. Finally a combination (spectral average) between the methods was also implemented.

When the respiration rate was constant (paced breathing) all methods had high performance obtaining a good estimation of the respiration signal (0.70% (mad=7.34) relative error, 0.89 (0.07) frequency correlation and 0.61 (0.09) time correlation). In the case of free breathing tests, the similarity between EDR and real respiration was lower (1.07% (16.81) relative error, 0.75 (0.09) frequency correlation and 0.62 (0.08) time correlation).

We observed that the optimal lead position for estimating the respiration was in the middle of the chest, leads V1, V2, X1 and X2 (0.81% (14.93) relative error in free breathing signals and 0.66% (4.22) in paced breathing signals, both for X2 lead).

The spectral combination method gets better results in paced breathing tests (0.63% (3.51) relative error and 0.87 (0.07) frequency correlation), however, it requires computing all the remaining methods, so it may not be the most appropriated when computing power is limited. Number of leads should be also considered as AMEA method requires at least two ECG leads. During free breathing, Amplitude method achieved the best performance (1.07% (mad=16.81) relative error, 0.75 (0.09) frequency correlation and 0.62 (0.08) time correlation).

Heart Rate Variability (HRV) method showed a good performance in paced breathing tests. This method is the most simple of the selected and therefore the fastest. However, for free breathing recording it gave the highest error (42.70% (24.26)). In addition, this method gives a higher error (23.03% (30.05)) when estimating the respiration in elderly population.

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