RESPIRATION DERIVED FROM THE ELECTROCARDIOGRAM: A QUANTITATIVE COMPARISON OF THREE DIFFERENT METHODS

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ABSTRACT

Three methods were developed to derive the respiration from the Electrocardiogram (ECG). The basis for deriving the respiration from the ECG relies on the fact that during respiration, the heart's position in the thoracic cavity changes. Consequently, the angle of the mean cardiac vector also changes during respiration. Two orthogonal leads of ECG and a measure of respiration were taken from 9 healthy subjects during rest, paced breathing, and exercise. To determine the optimum method, the ECG derived respiration was compared to the measured respiration using cross-correlation and coherence. The results indicate that one method provides more accurate results than the other two.

INTRODUCTION

Power spectral analysis of heart rate variability is a powerful tool to measure autonomic function non-invasively[1]. To determine the power which corresponds to parasympathetic activity, the frequency of respiration must be known. However, during ambulatory studies, two leads of ECG are acquired, but the respiration waveform is not. Therefore, by deriving the respiration from the ECG, this problem would be alleviated.

The basis for deriving the respiration from the ECG relies on the fact that the ECG is modulated by the frequency of respiration. This modulation is due to the change in position of the heart in the thoracic cavity during breathing, as well as the movement of the electrodes with respect to the heart[2]. More specifically, the change in amplitude is due to the change of the vector projection of the instantaneous heart vector on each lead.

During each cardiac cycle, the time path of the instantaneous heart vector produces three distinct loops, namely the P, QRS, and T loop. For each loop, a mean vector can be calculated. All three methods developed measure the angle of the mean cardiac vector during each QRS loop in the frontal plane (the plane defined by leads I and III), relative to one of the leads. The interpolated values, which represents the change in angle of the mean cardiac vector over time, is the derived respiration waveform.

METHODS

The first step in all three methods is to detrend the ECG to get rid of any DC offset and any frequencies below 0.05 Hz. Next, the minimum of each lead is found. Then, each lead is shifted vertically by 110% of the absolute value of the minimum. This results in an ECG that contains all positive samples.

Fixed QRS Window, Independent Leads Method

To calculate the area under the ECG during the QRS complex, this method uses a fixed QRS window. The window width for lead I is independent of the window width for lead III. However, the fixed window width in each lead is the same for each QRS complex in that lead. More specifically, for each lead, this method detects the R-wave and Q-wave, and then the average Q-wave to R-wave length is calculated. Twice this average value is the width of the fixed window. Once the average window width is calculated for each lead, the area within the window under each QRS complex is calculated. The local baseline area is subtracted from the area. To calculate the baseline area, the minimum within the window is multiplied by the width of the window. The calculated area is then placed in time to correspond to the time of the peak in the R-wave. The areas for each lead are then interpolated using cubic spline interpolation, and the arctangent is taken between the division of the two interpolated signals.

Variable QRS Window, Independent Leads Method

The difference between this method and the previous method is that the QRS complex is not assumed to be symmetrical. In other words, the Q, R, and S-waves are detected for each QRS complex. The detection of the Q, R, and S- waves for lead I are independent for those detections in lead III.

Variable QRS Window, Dependent Leads Method

This method is different from the previous method because the leads are not independent. In this method, one lead is chosen to detect the Q, R, and S-waves. The Q, R, and S-waves for the one lead are then referred to as the Q, R, and S-waves of the other lead.

The reason this method was done is to use the same samples in time of the QRS loop in the area calculation for each lead. In the two other methods, the samples of importance were detected independent of one another. Because these samples can occur at slightly different periods in time, the points used in the area calculation might not be synchronous between the leads.

Subjects and Experimental Protocol

Two leads of ECG (leads I and III which were forced to be orthogonal) were collected on 9 healthy subjects during 2 minutes each of rest, paced breathing at 8, 12, and 16 breaths/min, exercise on the treadmill at 3.5 mph, and at 3.5 mph with a 5% incline. To have a basis for comparison for the ECG derived respiration signals, the subject's respiration waveform was acquired simultaneously by impedance pneumography (RESPI, UFI, Morrow Bay, CA) which was sampled at 200 Hz. The ECG was collected using a Holter monitor (Del Mar Avionics, Irvine, CA). During playback the two channels of ECG were amplified to reduce quantization error and were sampled at 500 Hz each.

RESULTS

The derived respiration signals were compared to the measured respiration in the time domain and the frequency domain using cross-correlation and coherence, respectively. During the data analysis, the measured respiration waveform was low-pass filtered and then decimated to downsample the waveform to 20 Hz. Likewise, the derived respiration methods downsample the splined waveforms to a frequency equivalent to 20 Hz. For the coherence calculation, the coherence was

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Table 1 Average Cross-Correlation Coefficient Between the Derived Respiration and the Measured Respiration

Method	Rest	Paced at 8 bpm	Paced at 12 bpm	Paced at 16 bpm	3.5 mph	3.5 mph, 5% incline
Fixed QRS Window Independent Leads	0.468	0.717	0.685	0.608	0.410	0.426
Variable QRS Window Independent Leads	0.521	0.671	0.706	0.587	0.399	0.422
Variable QRS Window Dependent Leads	0.522	0.756	0.730	0.626	0.434	0.433

Table 2 Average Coherence at the Frequency of Respiration Between the Derived Respiration and the Measured Respiration

Method	Rest	Paced at 8 bpm	Paced at 12 bpm	Paced at 16 bpm	3.5 mph	3.5 mph, 5% incline
Fixed QRS Window Independent Leads	0.595	0.942	0.931	0.872	0.532	0.618
Variable QRS Window Independent Leads	0.592	0.934	0.923	0.858	0.508	0.599
Variable QRS Window Dependent Leads	0.593	0.937	0.925	0.833	0.469	0.599
Difference of Range	0.032	0.017	0.008	0.039	0.103	0.025

computed using a Hanning window, 700 points long, with a 350 point overlap. To tabulate the results of coherence, the maximum coherence near the main frequency of respiration was recorded.

The average of the cross-correlation coefficients for each method, for each section of the experimental protocol are shown in Table 1. Notice that in Table 1, the respiration waveform derived with the variable QRS window, dependent leads method has a higher cross-correlation coefficient than the other two methods for every section of the experimental protocol.

The average values for the coherence between the derived respiration and the measured respiration are shown in Table 2. Notice that there is no one method that has the highest coherence for all six sections of the experimental protocol. In addition, also note that in the last row of the table, the difference of the maximum coherence and the minimum coherence for each section of the experimental protocol is calculated. The difference of the range for each section of the protocol is between 0.008 and 0.103. In fact, the second highest difference is 0.032. Therefore, the spectrum of each of the three methods contains the same content regarding the main frequency of respiration.

The significance of the variable QRS window, dependent leads method having the highest cross-correlation than the other two methods, but similar coherence at the main frequency of respiration indicates that the other two methods have some higher frequency content than the variable QRS window, depenedent leads method. Figure 1 illustrates this point. The coherence at the frequency of respiration between the measured respiration and the derived respiration for the fixed QRS window, independent leads method and the variable QRS window, dependent leads method was 0.950 and 0.943, respectively. Therefore, by coherence alone, the fixed QRS window, independent leads method appears to be more accurate. However, the cross-correlation coefficient between the respiration derived with the fixed QRS window, independent leads method and the measured respiration was 0.686, opposed to 0.840 for the respiration derived with the variable QRS window, dependent leads method. This is because the fixed QRS window, independent leads method contained some higher frequencies that were not present in the original respiration as is apparent in Figure 1.

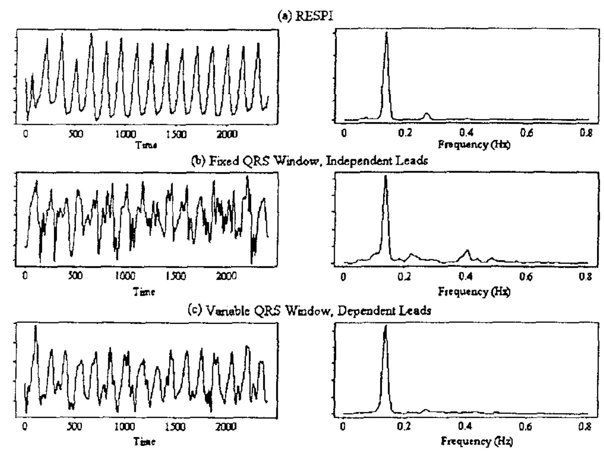

Figure 1 (a) Measured Respiration waveform (b) Respiration Derived with the Fixed QRS Window, Independent Leads Method (c) Respiration Derived with the Variable QRS Window, Dependent Leads Method

CONCLUSION

Based on the cross-correlation and coherence results, the variable QRS window, dependent leads method was consistently more accurate than the other three methods. This implies that the best way to estimate the mean cardiac vector should utilize the same samples in time from the same lead.

REFERENCES

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