# ECG-Derived Respiration: Comparison and New Measures for Respiratory Variability

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## Abstract

*During ECG recording, several methods can be applied to derive a respiratory signal from the ECG (EDR signal). In this paper 4 EDR methods, including ECG filtering, R and RS amplitude based techniques and QRS areas, are examined. Comparison of these methods with a simultaneously recorded respiratory signal lead to the conclusion that the R and RS amplitude based techniques generate the best respiratory signals (respectively MSE = 0.63 and MSE = 0.72) and have the advantage over ECG filtering (MSE = 1.53) and QRS areas (MSE = 2.15) that even sighs can be detected. Based on the respiratory signal, new measures (rMSSD, SDSD, pBB1 and pBB2) that reflect the respiratory variability (RV) are defined. Those RV measures have proven their use by the ability to distinguish between periods of rest and stress during mental stress testing (5 alternating periods of rest and mental stress). Moreover, most RV measures are able to differentiate between the first resting period and the periods following mental stress.*

## 1. Introduction

Methods to obtain a respiratory signal include impedance sensors, pressure sensors and a thermistor in the nose. However, respiration can also be extracted from the ECG signal having the advantage that, during ECG recording, no extra equipment is needed. These respiratory signals are called ECG-derived respiration or EDR signals and arise from the movement of electrodes with respect to the heart during respiration. This causes changes in the electrical impedance, which modifies the ECG. This study first examines which EDR method is the most accurate during mental stress testing.

Starting from the best EDR signal breath-to-breath (BB) intervals are defined, representing the duration of respiratory cycles. Using those BB intervals, the variability of respiration (RV) is characterized in a similar way as RR intervals are used to measure heart rate variability (HRV).

Vlemincx *et al.* showed that stress influences RV [1]. Therefore, it is meaningful to validate the new measures for RV by investigating the ability to differentiate between periods of rest and mental stress.

## 2. Methods

### 2.1. Data acquisition

The data for this study are part of a larger project that investigates the influence of stress and anxiety during pregnancy. For this project 140 women, aged 18–40, are recruited from 10 to 12 weeks gestation onwards. Inclusion criteria are: no current substance abuse problems, no severe psychiatric problems and no pregnancy-associated medical problems such as diabetes or hypertension.

The participants are subjected to a stress test, during which the ECG is recorded at 1000 Hz by the Vrije Universiteit - Ambulatory Monitory System [2]. The stress test consists of 5 periods of 5 minutes, in which alternating periods of rest and mental stress, by solving arithmetic tasks, occur.

Due to artefacts in the ECG and no precise indication of the beginning of the stress test, ECG data of only 86 subjects are selected for the analysis of RV.

### 2.2. ECG-derived respiration methods

Bailón *et al.* provided an interesting summary of EDR methods [3]. Based on advantageous results as described in literature [3–9], 4 methods are implemented to extract a respiratory signal from the ECG.

### 2.2.1. ECG$_{filt}$

The first EDR signal arises from bandpass filtering of the ECG signal in the respiratory frequency band (normally 0.2–0.4 Hz). Although Boyle *et al.* [4] conclude that a bandpass filter of 0.2–0.8 Hz provides a more accurate respiratory signal than a bandpass filter of 0.2–0.4 Hz,

visual control of the 2 EDR signals leads to the preference of the 0.2–0.4 Hz bandpass.

### 2.2.2. $R_{ampl}$

During respiration the recording of the ECG is influenced by the movement of electrodes with respect to the heart. This effect generates slow amplitude changes in the ECG [5]. These changes are used to extract a respiratory signal by interpolating between the amplitudes of successive R peaks with respect to the baseline. Removal of the baseline wander is performed by the application of 2 median filters of $200\ ms$ and $600\ ms$ respectively. The former filter removes QRS complexes and P waves from the ECG signal, while the latter eliminates T waves. The resulting signal is the baseline [5].

### 2.2.3. $RS_{ampl}$

Instead of removing the baseline wander, as in $R_{ampl}$, it is also possible to use the S points of the QRS complexes as a reference. $RS_{ampl}$ consists of the amplitude differences between the R peaks and the S points of the corresponding QRS complexes.

### 2.2.4. $A_{QRS}$

The last EDR signal is composed of the baseline-corrected ECG and comprises the area of the QRS complexes. Usually this area is determined by the integration over a fixed window, starting from the Q point of the QRS complex [5, 6]. Ambiguity about the length of the fixed window leads to the decision of defining $A_{QRS}$ literally as the area within the QRS complex, as described in [8].

In order to obtain evenly sampled and smooth respiratory signals, like $ECG_{filt}$, the other EDR signals are resampled by linear interpolation (10 Hz) and smoothed by a FIR filter with a cut-off frequency of 0.4 Hz.

To select the best EDR method for this data set, each EDR signal is compared with a real respiratory signal. These validation data originate from a previous study by Vlemincx *et al.* [1] and consist of an ECG signal with a simultaneously recorded respiratory signal during a stress test, which is comparable to the stress test in this study. Selection of the most accurate EDR method is based on the similarity of BB intervals, quantified by the mean-squared error (MSE).

### 2.3. Processing of BB intervals

From each respiratory signal, the peaks and valleys are detected because they indicate the beginning of an expiration and an inspiration respectively. BB intervals contain the durations of respiratory cycles, defined from val-
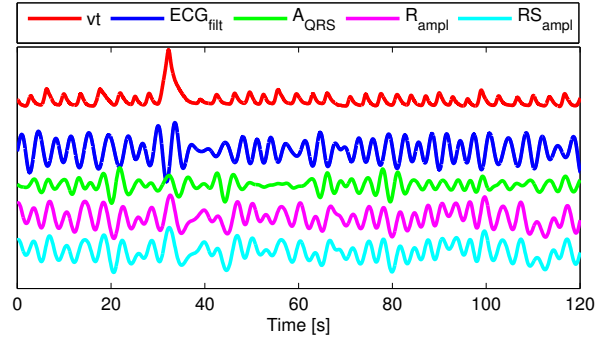


Figure 1. Overview of the EDR signals, compared to the reference respiratory signal $vt$.

ley to valley. However, the detection of peaks and valleys also includes the detection of local optima. In order to remove these false inspirations and expirations a preprocessing method is applied to the respiratory signals. The preprocessing method is based on the duration and amplitude difference of successive peaks and valleys and is similar to the method used by Mazzanti *et al.* [7]:

• *duration*: the minimum duration of a respiratory cycle is set at $1500\ ms$ in order to be accepted as a correct BB interval. Shorter respiratory cycles are eliminated by the removal of a peak and a valley in such way that the amplitude difference between the remaining successive peaks and valleys is maximal.

• *amplitude*: the amplitude difference between a peak and a valley should be at least 15% of the previous and the following amplitude difference. Otherwise, the removal of a peak and a valley is performed in order that a maximal amplitude difference between 2 optima is obtained.

### 2.4. Measures for respiratory variability

BB intervals are used to characterize RV. The measures used for RV are based on the HRV measures. Some simple measures include the mean BB interval (*meanBB*), the standard deviation of the BB intervals (*SDBB*) and the difference between the largest and smallest BB interval (*diffBB*). Other RV measures are defined as follows:

• *rMSSD*: square root of the mean squared differences of successive BB intervals;

• *SDSD*: standard deviation of the differences between successive BB intervals;

• *pBB1 (and pBB2)*: number of consecutive BB intervals that differ more than $1s$ (and $2s$) relative to each other, divided by the total number of BB intervals.

### 2.5. Statistical analysis

In order to demonstrate the use of the RV measures and to investigate the effect of stress, a pairwise comparison of
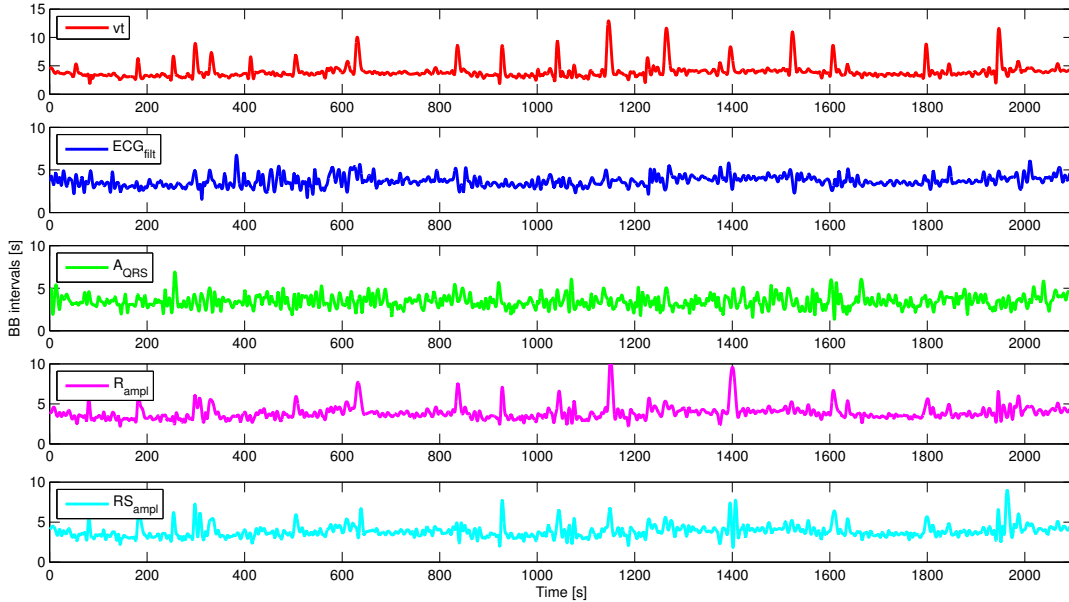
Figure 2. BB intervals of the reference respiratory signal $vt$ and the EDR signals.

the periods of the stress test is performed, using the non-parametric Wilcoxon signed rank test. $P < 0.05$ is considered statistically significant.

## 3.    Results and discussion

### 3.1.    Selection of the EDR method

Figure 1 shows the different EDR signals, compared to the reference respiratory signal $vt$. Visual inspection of these respiratory signals does not allow us to choose an optimal EDR method. Since analysis of RV is based on BB intervals, another way to select the best EDR signal involves the composition and comparison of the duration of those BB intervals. The signals in Figure 2 comprise the BB intervals of the respiratory signals. Notable are the large BB intervals in $vt$. Those peaks represent sighs, one of which is also shown in Figure 1 as the largest peak of $vt$. Vlemincx *et al.* proved that the sigh frequency is related to the presence of stress [1]. Therefore, the chosen EDR method should have the ability to even extract sighs from the ECG signal. In order to investigate which EDR method approximates $vt$ the most and deals the best with sighs, the BB intervals are compared. The MSE quantifies the difference between corresponding BB intervals of the EDR signals and the reference respiratory signal, including and excluding sighs. The results of these comparisons are found in Table 1 and show that all EDR methods have difficulties dealing with sighs. However, Figure 2 shows that $R_{ampl}$ and $RS_{ampl}$ are often able to detect sighs. This is

Table 1. MSE of EDR signals compared to $vt$

|  | incl. sighs | excl. sighs |
|---|---|---|
| $ECG_{filt}$ | 1.5268 | 0.5567 |
| $A_{QRS}$ | 2.1531 | 1.4133 |
| $R_{ampl}$ | 0.6296 | 0.2176 |
| $RS_{ampl}$ | 0.7244 | 0.2693 |

also reflected in the results of Table 1 as those 2 EDR methods give the most accurate approximations of the respiratory signal. Taking all the results into account, the EDR method of choice is $R_{ampl}$, which will be used to analyze RV.

### 3.2.    Respiratory variability during mental stress testing

Based on the RV measures, composed of the BB intervals, periods of rest and mental stress are compared. Table 2 provides the numerical results of all the comparisons between the various periods of the stress test. All RV measures, except for *diffBB* and *SDSD*, are able to distinguish periods of rest and stress ($p_{1,2}$, $p_{2,3}$, $p_{3,4}$ and $p_{4,5}$). An increased RV is observed during stress.

The RV measures can also differentiate between the first resting period and the resting periods following the mental tasks, in which RV is increased due to the recent mental stress ($p_{1,3}$ and $p_{1,5}$). However, no significant difference between the 2 resting periods following the stress periods is found ($p_{3,5}$).

Table 2. Pairwise comparisons ($p$-values) between RV measures of periods of the stress test (mean $\pm$ standard deviation).

| | period 1 (rest) | period 2 (stress) | period 3 (rest) | period 4 (stress) | period 5 (rest) |
|---|---|---|---|---|---|
| meanBB | 3636.94 $\pm$ 493.56 | 4057.56 $\pm$ 645.84 | 3851.90 $\pm$ 535.09 | 4037.66 $\pm$ 612.82 | 3864.59 $\pm$ 529.65 |
| diffBB | 5130.26 $\pm$ 1438.33 | 6357.89 $\pm$ 1829.77 | 5950.00 $\pm$ 1967.23 | 6022.37 $\pm$ 1451.12 | 5850.00 $\pm$ 1555.51 |
| SDBB | 886.81 $\pm$ 310.68 | 1239.83 $\pm$ 413.20 | 1078.40 $\pm$ 346.55 | 1190.64 $\pm$ 379.16 | 1060.26 $\pm$ 336.31 |
| rMSSD | 1147.95 $\pm$ 415.46 | 1644.96 $\pm$ 562.98 | 1410.71 $\pm$ 480.80 | 1583.36 $\pm$ 558.47 | 1389.74 $\pm$ 465.40 |
| pBB1 | 22.34 $\pm$ 12.21 | 39.08 $\pm$ 16.72 | 29.51 $\pm$ 14.74 | 39.67 $\pm$ 16.77 | 29.85 $\pm$ 16.15 |
| pBB2 | 9.21 $\pm$ 7.02 | 18.50 $\pm$ 11.60 | 13.39 $\pm$ 8.79 | 18.88 $\pm$ 12.80 | 13.72 $\pm$ 8.93 |
| SDSD | 856.76 $\pm$ 303.92 | 1122.44 $\pm$ 348.82 | 1034.30 $\pm$ 358.72 | 1051.25 $\pm$ 313.81 | 1002.69 $\pm$ 305.83 |

| | $p_{1,2}$ | $p_{2,3}$ | $p_{3,4}$ | $p_{4,5}$ | $p_{1,3}$ | $p_{3,5}$ | $p_{1,5}$ | $p_{2,4}$ |
|---|---|---|---|---|---|---|---|---|
| meanBB | 1.01 e-08 | 5.07 e-04 | 1.18 e-03 | 4.11 e-03 | 2.19 e-09 | 8.01 e-01 | 4.00 e-09 | 7.52 e-01 |
| diffBB | 7.12 e-07 | 9.47 e-02 | 5.34 e-01 | 9.84 e-01 | 2.33 e-03 | 9.47 e-01 | 4.07 e-04 | 4.12 e-02 |
| SDBB | 1.07 e-10 | 1.78 e-03 | 1.66 e-02 | 1.84 e-02 | 5.32 e-07 | 7.68 e-01 | 5.95 e-07 | 8.46 e-02 |
| rMSSD | 1.20 e-10 | 7.07 e-04 | 9.96 e-03 | 6.37 e-03 | 1.01 e-06 | 8.89 e-01 | 9.68 e-07 | 1.57 e-01 |
| pBB1 | 1.77 e-11 | 7.15 e-06 | 1.30 e-06 | 2.47 e-05 | 8.48 e-07 | 9.11 e-01 | 3.03 e-06 | 8.21 e-01 |
| pBB2 | 1.46 e-10 | 4.18 e-04 | 1.30 e-04 | 3.58 e-04 | 1.03 e-05 | 7.44 e-01 | 3.52 e-06 | 7.26 e-01 |
| SDSD | 1.09 e-07 | 2.04 e-02 | 4.05 e-01 | 5.14 e-01 | 2.20 e-05 | 8.41 e-01 | 3.67 e-05 | 9.84 e-03 |

The first period during which the pregnant women are subjected to mental stress testing, shows a significantly higher *SDSD* than the second period of stress ($p_{2,4}$). No other RV measure makes a distinction between those 2 stress periods.

The influence of stress on the respiratory system is clearly reflected in the new RV measures, which proves the use of those measures.

## 4. Conclusions

In this paper a comparison of 4 EDR methods lead to the conclusion that $R_{ampl}$ generates the best approximation of the respiratory signal. An important feature of this EDR method comprises the ability to extract sighs from the ECG signal.

Based on BB intervals, composed of the respiratory signal, RV measures were defined and have proven their use by the capacity to distinguish periods of rest and mental stress. Research on the physiological meaning of the new RV measures may contribute to the knowledge about the respiratory system.

## References

[1] Vlemincx E, Taelman J, De Peuter S, Van Diest I, Van den Bergh O. Sigh rate and respiratory variability during mental load and sustained attention. Psychophysiology 2010; doi:10.1111/j.1469–8986.2010.01043.x.

[2] Vrijkotte T, van Doornen L, de Geus E. Effects of work stress on ambulatory blood pressure, heart rate, and heart rate variability. Hypertension 2000;35(4):880.

[3] Bailón R, Sörnmo L, Laguna P. ECG-derived respiratory frequency estimation. Advanced methods and tools for ECG data analysis Artech House Inc 2006;215–244.

[4] Boyle J, Bidargaddi N, Sarela A, Karunanithi M. Automatic detection of respiration rate from ambulatory single-lead ECG. IEEE Transactions on Information Technology in Biomedicine 2009;13(6):890–896.

[5] De Chazal P, Heneghan C, Sheridan E, Reilly R, Nolan P, O'Malley M. Automated processing of the single-lead electrocardiogram for the detection of obstructive sleep apnoea. IEEE Transactions on Biomedical Engineering 2003; 50(6):686–696.

[6] Furman G, Shinar Z, Baharav A, Akselrod S. Electrocardiogram derived respiration during sleep. Computers in Cardiology 2005;32:351–354.

[7] Mazzanti B, Lamberti C, de Bie J. Validation of an ECG-derived respiration monitoring method. Computers in Cardiology 2003;30:613–616.

[8] Mendez M, Corthout J, Van Huffel S, Matteucci M, Penzel T, Cerutti S, Bianchi A. Automatic screening of obstructive sleep apnea from the ECG based on empirical mode decomposition and wavelet analysis. Physiological Measurement 2010;31:273–289.

[9] O'Brien C, Heneghan C. A comparison of algorithms for estimation of a respiratory signal from the surface electrocardiogram. Computers in Biology and Medicine 2007; 37(3):305–314.

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