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ESTIMATION OF RESPIRATORY FREQUENCY AND HEART RATE VARIABILITY PARAMETERS IN THE CASE OF RESPIRATORY EXERCISES

BY

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Abstract. In this paper, we presented how breathing influences the electrocardiographic and photoplethysmographic signal as well as heart rate variability. In the first part, we analyzed the effects that four breathing exercises had on the values of electrocardiographic and photoplethysmographic signals. It was observed that deep inhale/exhale cycles influence the amplitude of the QRS complex of the ECG signal and also the amplitude of the pulse wave of the PPG signal. From the analysis of these changes in ECG and PPG signals, we could estimate the respiratory rate and compare the results with those of the respiratory signal. We noticed that the results obtained from the analysis of the ECG signal are more relevant in contrast to those obtained from the PPG signal. In the second part of the paper, we studied the effect of these breathing exercises on HRV parameters. We studied the time domain parameters and the frequency domain parameters. For the time domain parameters, we noticed that the results have higher values during the breathing exercises, except for the mean RR, compared to those obtained before and after performing them. In the case of HRV parameters in the frequency domain, the low-frequency spectrum (0.04 Hz - 0.15 Hz) had a proportion of over 65% during breathing exercises. We also

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noticed a change in the parameters before and after practising the breathing exercises.

Keywords: heart rate variability; electrocardiography; photoplethysmography; respiratory rate; wearable device.

1. Introduction

Heart rate and respiratory rate are two vital parameters used in assessing patients' health. Long-term monitoring of these parameters can lead to a qualitative medical evaluation, given that some pathological episodes do not continually occur in ambulatory monitoring regimens. The results obtained from long-term recordings can lead to indications for a healthier lifestyle. Also, thanks to currently available technologies, new methods of health assessment can be studied or verified.

From previous studies, we determined that from synchronous recordings of two or more biomedical signals, we can estimate several parameters of interest, such as HRV and blood pressure parameters from synchronous recordings of ECG and PPG signals (Podaru, 2018; Podaru, 2020).

To monitor the respiratory rate indirect methods are used. Some techniques for determining the respiratory rate use solutions such as: monitoring the temperature on inhalation/expiration; measuring the change in thoracic/abdominal volume during the respiratory cycle; other researchers have used systems or methods that estimate respiratory rate from other physiological signals as shown in studies (Berset, 2012; Lázaro *et al*., 2018; Lázaro *et al*., 2020; Sweeney, 2013). They processed the ECG signal and determined the respiratory rate using the usual methods.

Another study, (Babaeizadeh, 2015), compared three known methods of estimating respiratory rate in the ECG signal, namely: amplitude analysis for each QRS complex from derivation I or derivation II, analysis of the ratio of measurements performed in the amplitude of the QRS complex in the first and second derivatives and analysis of the time variation between two cardiac cycles. They concluded that respiratory rate may be more accurate by analyzing changes in the ECG waves amplitude, from one lead, rather than the changes in heart rate.

Since methods such as time analysis between two heartbeats are used in estimating respiratory rate, it means that respiration is a factor that could influence HRV parameters. In the study (Zhang Kai, 2017), results of the influences of three respiratory rates on HRV parameters for a group of athletes were presented. They concluded that depending on the frequencies and the breathing exercises, there are differences in some parameters. The influences of three respiratory rates, respectively 16, 8 and 5 breaths per minute, were studied.

In this paper, we estimated the respiratory rate using the amplitude of the R-wave peaks of the ECG signal, respectively P-wave of the PPG signal. In the second part, we also analysed the HRV parameters for the four types of respiratory exercises and compared the parameters from before, during and after practices.

2. Determination of Respiratory Rate from the Analysis of the R-Wave Peaks of the ECG Signal and P-Wave Peaks of the PPG Signal

In this part of the paper, we performed a set of simultaneous recordings of the ECG, PPG signals and the respiratory wave to determine the respiratory rate and the effect of respiration on HRV parameters.

To record the ECG, PPG and respiration signals, we realised a wearable device able to monitor these parameters simultaneously. For the ECG signal, we have used the Heart Rate Monitor AD8232, and for the PPG signal, the PulseSensor module for Arduino. To record the breath, we used a NTC thermistor that was integrated into a breathing mask. The thermistor measured the temperature difference during inspiration and expiration. The signals monitored with this system have been saved afterwards on an SD card. In Fig. 1, is presented the diagram of the portable system used by us.

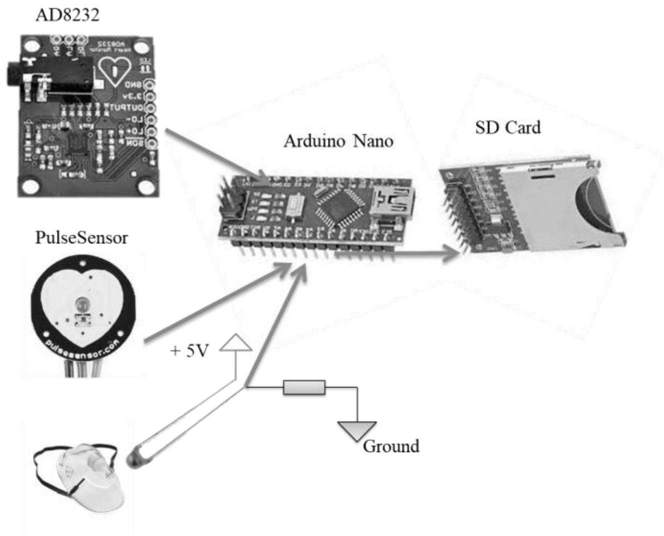

Fig. 1 – The bloc diagram of the wearable system.

To put in evidence how these signals were affected by breathing, we followed four breathing exercises. These breathing exercises have certain times of inspiration, expiration and pause, and the duration of each exercise is seven-minute. The models of the respiratory practices used in this study are presented in Fig. 2.

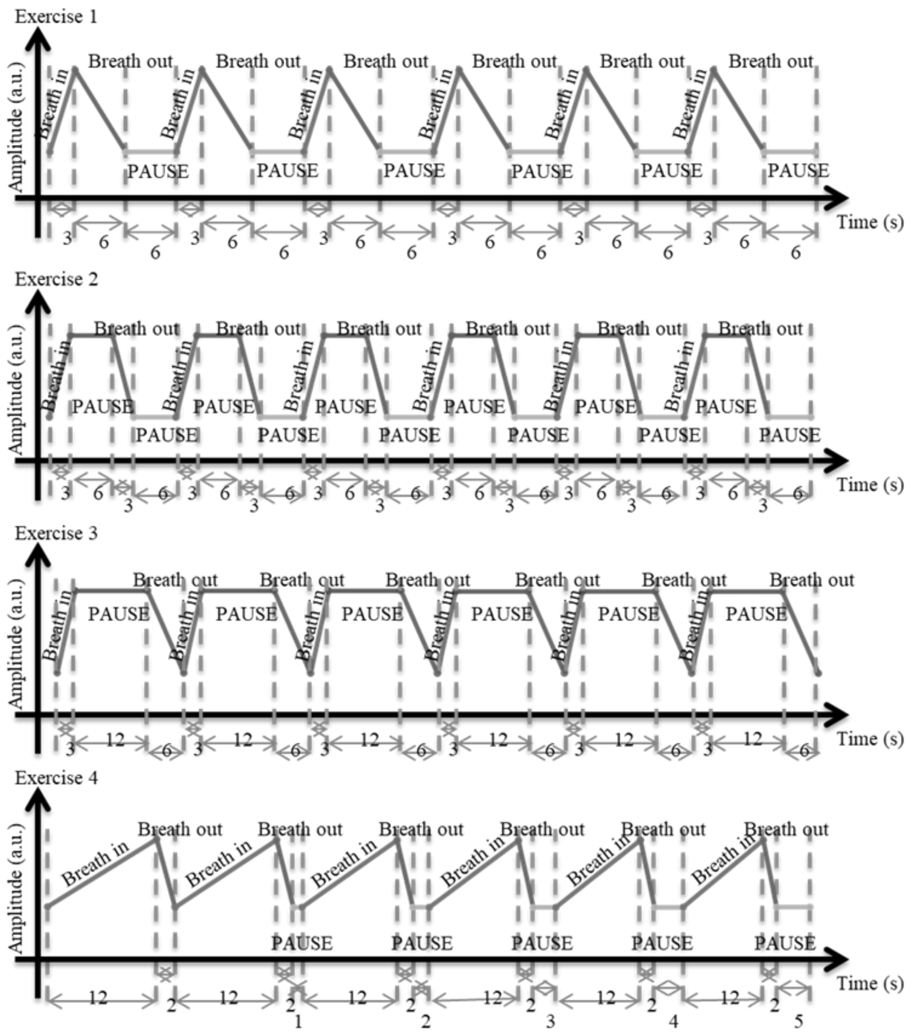

Fig. 2 – The four models of breathing exercises used in the study.

The recordings have been made on a single subject at different day times. For each breathing exercise, we have recorded the signals 7 minutes before, 7 minutes during exercise and 7 minutes after. The recorded respiratory waveform has a similar shape to the type of exercise shown in Fig. 2, as can be seen in Fig. 3.

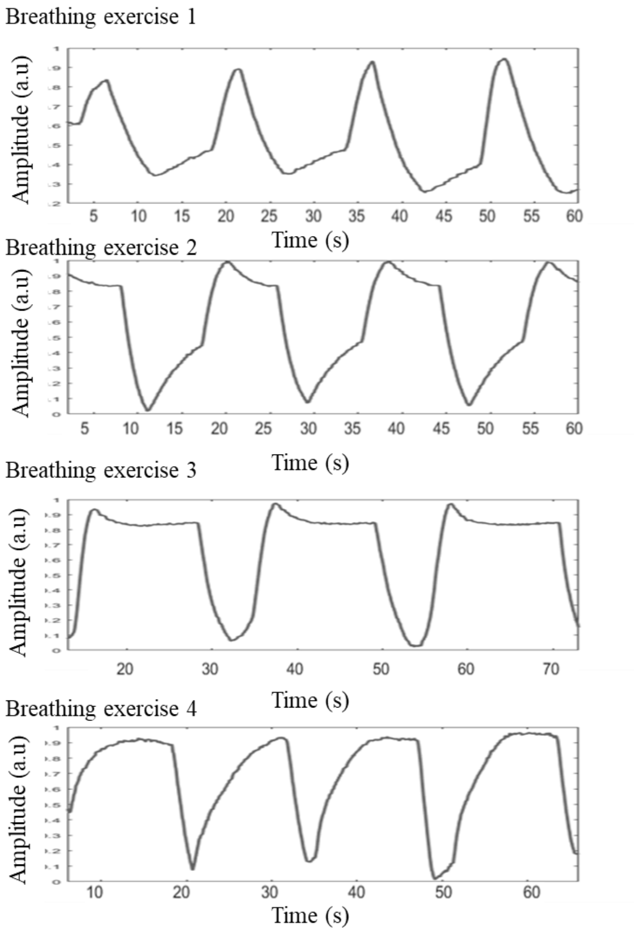

Fig. 3 – Waveforms of the recorded respiratory signals.

Fig. 3 shows that during pauses in breathing exercises, a linear waveform cannot be obtained due to the stabilization of the sensor temperature. The pause zones are distinguished by a slightly ascending or descending slope and the inspiratory-expiratory zones by a sudden increase, respectively a decrease.

The changes in both the PPG signal and the ECG signal are visible on the amplitude changes of both the QRS complex and the pulse wave. For these recordings, the R peaks of the ECG signal and the P peaks of the PPG signal were determined. A simple graphical representation of them shows a similarity between the shape of the respiratory signal and the graph of the amplitude modulation of the detected peaks. In Fig. 4 are presented the amplitude modulations of these peaks for the first respiratory exercise, for one minute.

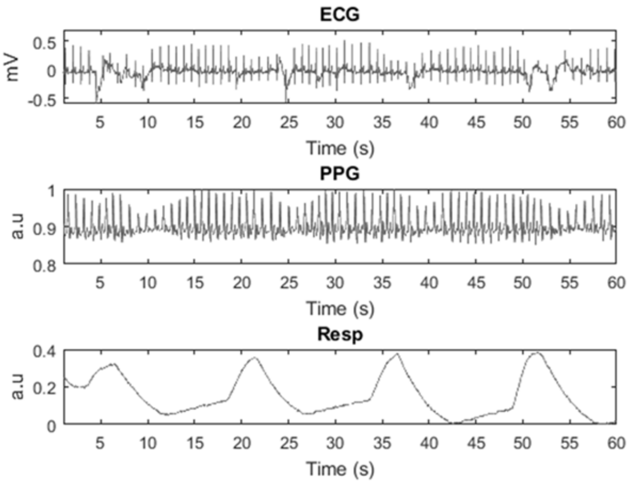

Fig. 4 – The tendency of amplitude modulation of the QRS complex and the P wave with respiration signal.

We observed that the lowest values of the QRS complex are visible when the inspiration is at maximum, and referring to the PPG signal, the lowest values of P peaks appears with a delay due to the distance that the blood flow has to follow.

From Fig. 5, where the respiratory rates from ECG and PPG signals are represented it is visible that a better estimation of the respiratory rate can be obtained from ECG signal analysis. The results obtained in the case of exercise 2, 3 and 4 are shown in Fig. 6, Fig. 7, respectively Fig. 8.

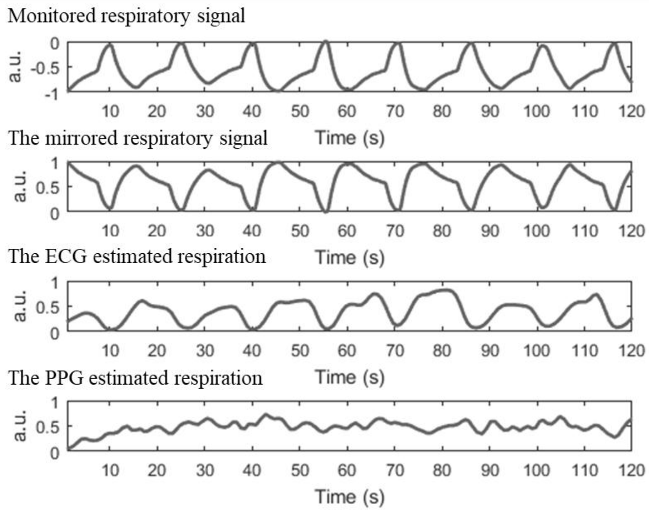

Fig. 5 – Estimation of respiratory waves from ECG and PPG signals for the first exercise.

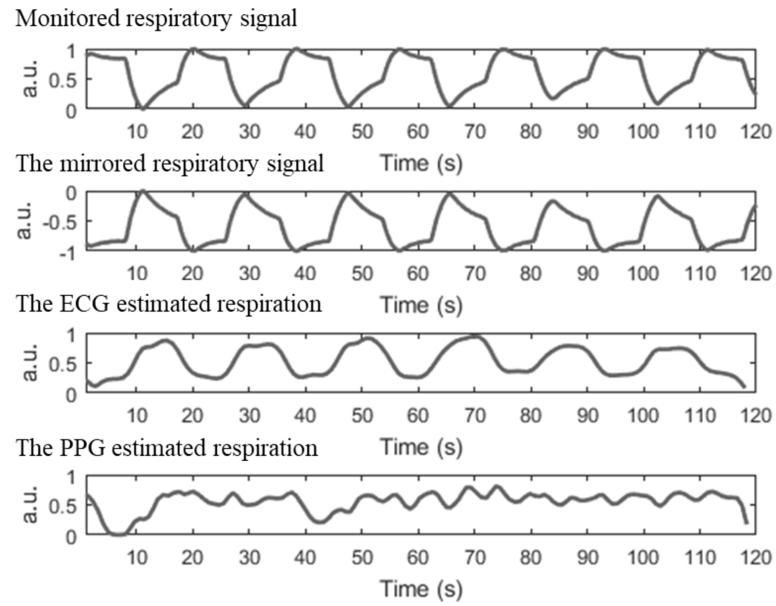

Fig. 6 – Estimation of respiratory waves from ECG and PPG signals for the second exercise.

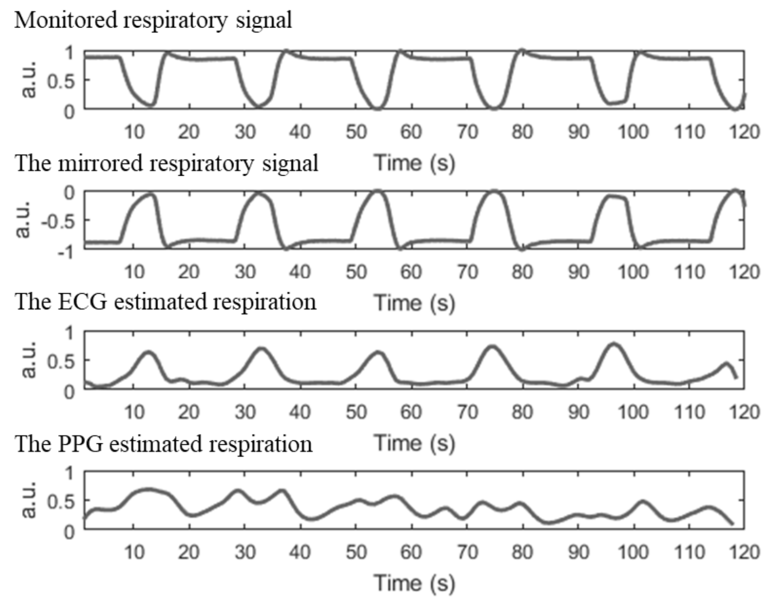

Fig. 7 – Estimation of respiratory waves from ECG and PPG signals for the third exercise.

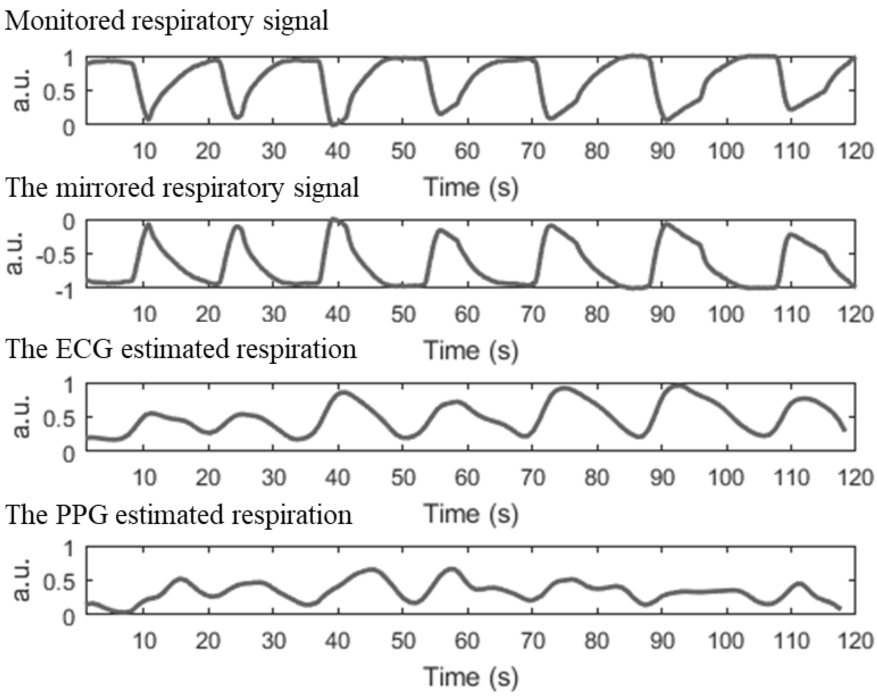

Fig. 8 – Estimation of respiratory waves from ECG and PPG signals for the fourth exercise.

From these figures, we observed that the shape of the estimated respiratory signal, from the ECG signal, respectively the PPG signal, is mirror image of the measured respiratory signal.

3. Influence of Breathing on HRV Parameters

In this part of the paper, we determined the HRV parameters for each record as follows: case 1 (C1) for the entire recording of a breathing exercise, case 2 (C2) for 7 minutes before exercise, case 3 (C3) during respiratory exercise and case 4 (C4) for 7 minutes after exercise, as can be seen in Fig. 9. We had chosen the same time window as the time of the breathing exercise. To determine HRV parameters, we used Kubios HRV Standard (Tarvainen, 2020).

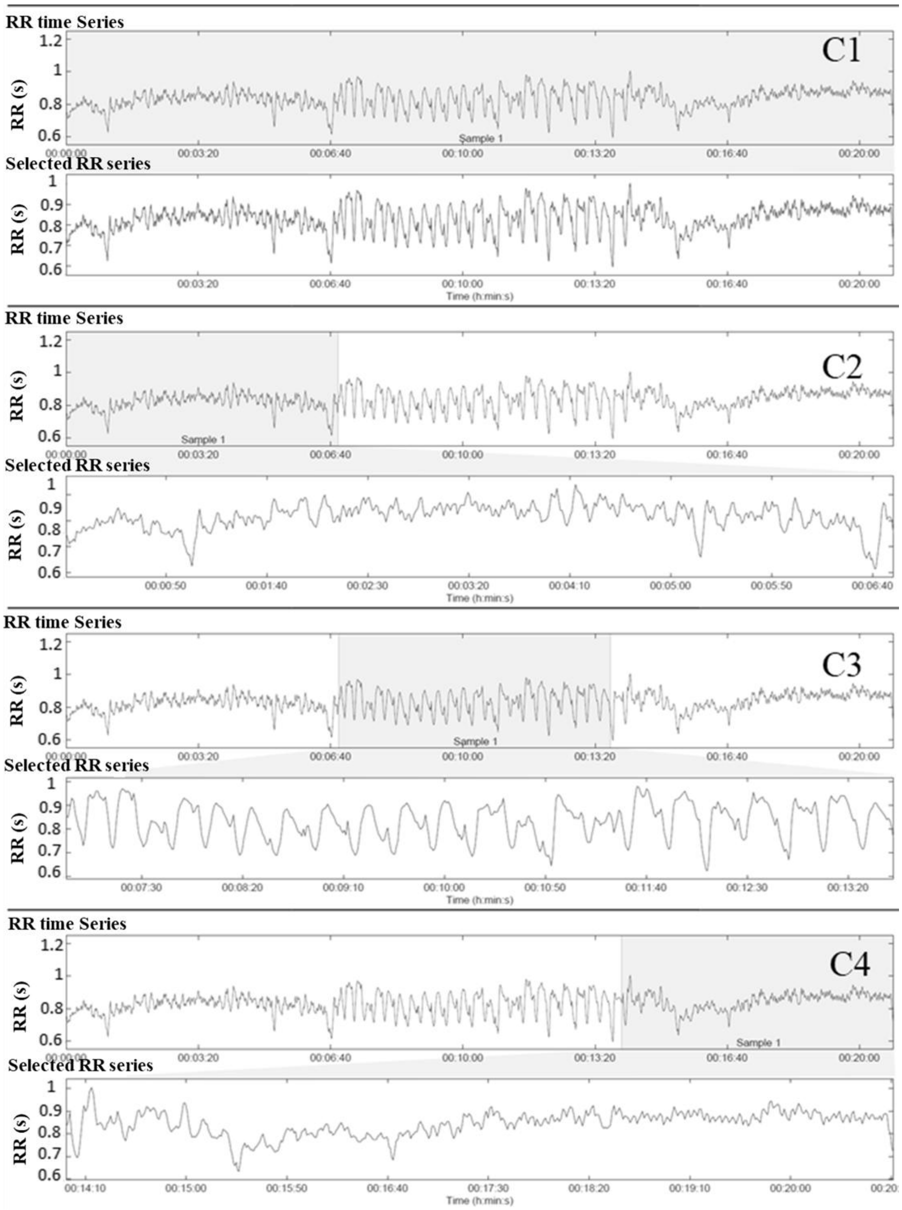

Fig. 9 – Analysis of HRV parameters in Kubios HRV Standard for the first breathing exercise.

From this figure, it is observed that we used the same time interval for cases C2, C3 and C4, to have a better understanding of the HRV parameters before, during and after the breathing exercises. The same analysis was made for all recordings, namely exercises 2, 3 and 4, and the results of the HRV parameters are shown in Table 1 and Table 2.

Table 1
HRV Parameters Calculated for the First and Second Exercises

Parameter	Breathing exercise 1					Breathing exercise 2				
	C1	C2	C3	C4	Δ = |C2-C4|	C1	C2	C3	C4	Δ = |C2-C4|
Mean RR (ms)	891	891	882	905	14	937	948	917	944	4
SDNN (ms)	47.6	32.3	61.4	37.1	4.8	72.4	48.6	94	63	14.4
RMSSD (ms)	34.4	25.7	46.7	25.4	0.3	49.3	42	62.7	39.6	2.4
NN50 (beats)	100	10	76	8	2	329	83	163	78	5
pNN50 (%)	7.13	2.17	16.31	1.86	0.31	24.16	18.86	35.67	17.61	1.25
HRV triangular index	8.36	6.51	12.29	7.17	0.66	13.23	9.59	20.82	9.65	0.06

Table 2
HRV Parameters Calculated for the Third and Fourth Exercise

Parameter	Breathing exercise 3					Breathing exercise 4				
	C1	C2	C3	C4	Δ = |C2-C4|	C1	C2	C3	C4	Δ = |C2-C4|
Mean RR (ms)	808	806	772	846	40	826	814	826	841	27
SDNN (ms)	71.6	43.5	84.7	61.9	18.4	64.4	52.1	76.8	55.8	3.7
RMSSD (ms)	33.1	23.1	41.8	32.5	9.4	26.8	22.7	32.4	22.8	0.1
NN50 (beats)	154	13	88	54	41	79	13	46	16	3
pNN50 (%)	9.34	2.5	15.47	10.91	8.41	5.22	2.58	9.27	3.28	0.7
HRV triangular index	16.49	7.78	11.18	10.55	2.77	14.99	10.5	17.75	11.11	0.61

We performed correlations as follows: for C2 and C3 cases, for C2 and C4 cases, and C3 and C4 cases and the Pearson correlation coefficient had values of over 0.98. Although the results of the Pearson correlation coefficients show a strong connection between these values, when we calculate the differences between C2 and C4 cases, small values were observed before and after breathing exercises 1, 2 and 4, and higher differences were determined for C2 and C4 cases, for the third breathing exercise.

The results of HRV parameters obtained for cases C3 have greater values, compared to those for C2 and C4 cases, for all four breathing exercises, excepting the mean RR. The changes that appear at SDNN, RMSSD and pNN50, are caused by the increase of the respiration effect on heart rate.

The next step was the analysis of the frequency domain of HRV parameters. Fig. 10 presents the differences between the four cases chosen by us for the first breathing exercise. We can see that the differences are visible on the RR spectrum. It can easily be observed that the breathing exercise is reflected in the frequency spectrum: very low frequencies (VLF = 0.00 - 0.04 Hz), low frequencies (LF = 0.04 - 0.15 Hz) and high frequencies (HF = 0.15 - 0.5 Hz). Before the exercise, it was observed that the very low frequencies dominated, in a proportion of 41.25%, low frequencies 34.75%, the rest being high frequencies, having an LF / HF ratio of 1.45. After exercising, there are changes in these proportions, the very low and low frequencies have a lower proportion than before, and the LF / HF ratio is 0.83, which indicates that the high frequencies have a higher proportion than low frequencies.

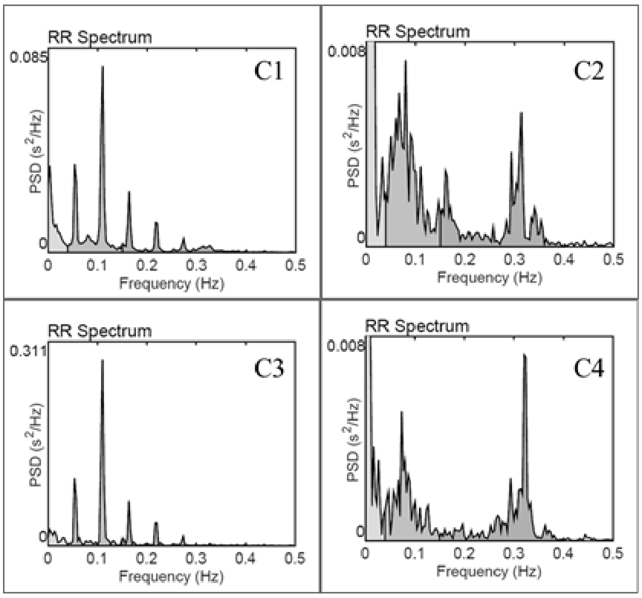

Fig. 10 – Frequency representation of HRV parameters for the first exercise.

A change in the proportions of the frequency ranges has been noted for all breathing exercises. Unlike the first exercise, for the second one, there is an increase in the proportion of VLF frequencies, while the rest decrease in the same proportion, given that the LF / HF ratio has a similar value for case 2 and case 4, Fig. 11.

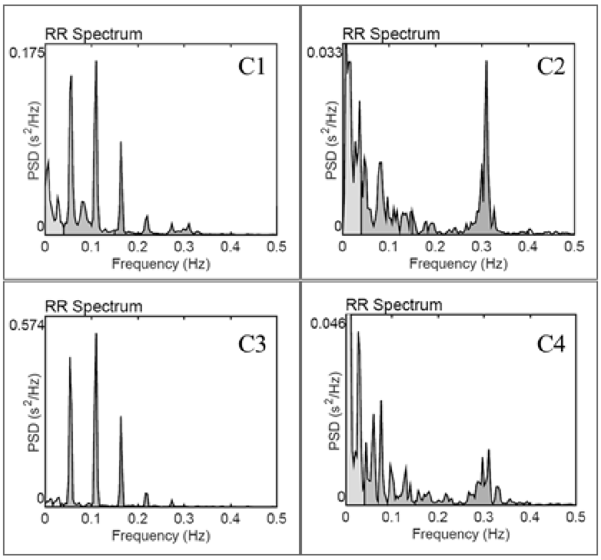

Fig. 11 – Frequency representation of HRV parameters for the second exercise.

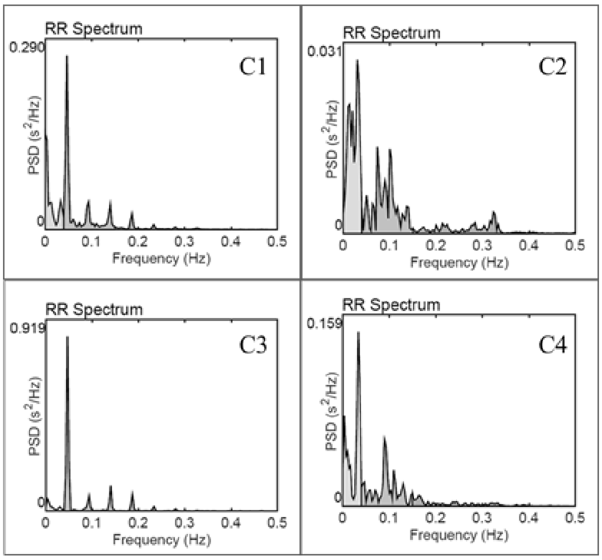

Fig. 12 – Frequency representation of HRV parameters for the third exercise.

In Fig. 12 and Fig. 13, it was noticed that after the breathing exercise, the very low and low-frequency spectra dominate. By comparing with the start moment of the exercise, the high-frequency spectrum changes its amplitude.

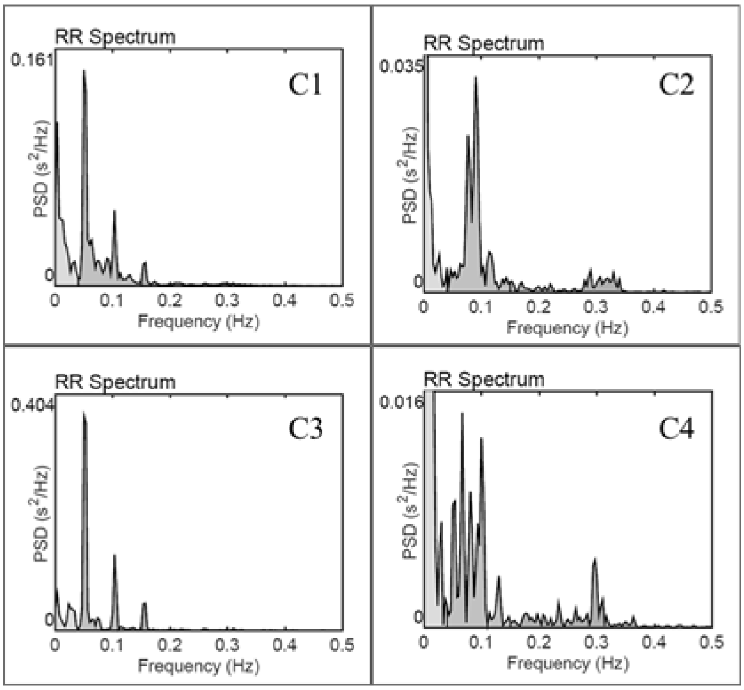

Fig. 13 – Frequency representation of HRV parameters for the fourth exercise.

By analysing the influence of respiration on HRV parameters, we did not observe significant differences for the parameters in the time domain, except when exercising takes place. For the parameters in the frequency domain, differences can be observed even from their graphical representation. These influences are observed both before and after the respiratory exercise.

4. Results and Discussions

From the analysis of the four recordings, we observed that breathing influences the ECG and also the PPG signals in amplitude. That is why an estimation of the respiratory rate can be obtained from the R-wave amplitude analysis of the ECG signal. Also, by analysing the PPG signal amplitude modulation, we see that an estimation of the respiratory rate can result from it.

For the four recordings, all breathing cycles were counted, and the results were compared to the estimated numbers obtained from the ECG and the PPG signal, as shown in Table 3.

Table 3
Estimated Number of Breaths Compared to a Measured Number of Breaths

Breathing exercise	Recording duration (min: sec)	Respiratory rate from:		
		Respiration	ECG signal	PPG signal
1	25:58	270	280	288
2	23:02	217	238	278
3	23:50	223	215	289
4	26:01	252	246	283

Following the analysis of HRV parameters, we did not observe significant differences for the time domain, except for exercise 3, where the most significant differences were obtained between cases C2 and C4.

For the frequency domain, the differences are found both in the graphical representations and from Table 4 and Table 5. We observed that when the proportions of the frequency intervals do not change, the total power changes. When the total power does not change, the frequency proportions appear to be changing.

Table 4
HRV Parameters in the Frequency Domain

Parameter	Breathing exercise 1				Breathing exercise 2			
	C1	C2	C3	C4	C1	C2	C3	C4
Power VLF (%)	22.75	41.25	12.22	37.01	21.31	42.03	7.08	62.01
Power LF (%)	52.91	34.75	65.46	28.62	58	29.31	70.46	21.36
Power HF (%)	24.33	24	22.3	34.35	20.68	28.61	22.45	16.63
Total power (ms^2)	2075	872	4168	529	5282	1820	8831	3065
LF/HF ratio	2.175	1.448	2.936	0.833	2.804	1.024	3.138	1.285

Table 5
HRV Parameters in the Frequency Domain

Parameter	Breathing exercise 3				Breathing exercise 4			
	C1	C2	C3	C4	C1	C2	C3	C4
Power VLF (%)	34.88	48.8	10.88	50.17	34.05	48.33	19.52	74.44
Power LF (%)	55.83	38.45	78.81	38.64	58.46	41.72	72.1	18.85
Power HF (%)	9.29	12.74	10.31	11.46	7.49	9.95	8.38	6.71
Total power (ms^2)	4767	1292	6824	3882	3926	1710	5423	2247
LF/HF ratio	6.009	3.019	7.648	3.451	7.805	4.194	8.609	2.81

A common element for the HRV parameters in the frequency domain for all exercises appears during the breathing exercise, case C3, where we observed that the low-frequency spectrum dominates.

5. Conclusions

To determine and verify the same biomedical parameters, we made simultaneous recordings of the ECG, PPG and respiratory signals. We estimated the respiratory rate by analysing the changes that appear in amplitude in both the QRS complex of the ECG signal and the P wave of the PPG signal. A better estimation of respiratory rate results from ECG signal analysis. Comparing the total respiratory cycles, estimated from the ECG signal with the number of respiratory cycles from the recorded respiration signal we see that the differences between these values are 5% -10% for all recordings.

We analyzed the influence of breathing exercises on HRV parameters, and we observed that the results obtained indicate the presence of these influences on the HRV values. Changes have been found both for the time domain parameters and for the frequency domain. For the time domain parameters, it was noticed that during the respiratory exercise, the SDNN, RMSSD, NN50, pNN50 and HRV triangular index have higher values compared to the ones determined for the same period before and after the exercise. When comparing the values obtained for case C2 and case C4, we did not find any significant differences, except for exercise 3.

For HRV parameters in the frequency domain, during the four exercises, it has been observed that the dominant power is found in the low-frequency spectrum (0.04 - 0.15 Hz), having a proportion of over 65% in all cases. Also, it can be noticed that the total power increased after the respiratory exercise, compared to the values determined before, except for the values obtained for the first exercise.

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ESTIMAREA FRECVENȚEI RESPIRATORII ȘI AI PARAMETRILOR VARIABILITĂȚII FRECVENȚEI CARDIACE ÎN CAZUL UNOR EXERCIȚII RESPIRATORII

(Rezumat)

În această lucrare este prezentat modul în care respirația influențează semnalul electrocardiografic, fotopletismografic și variabilitatea ritmului cardiac. În prima parte, se analizează efectele pe care patru exerciții de respirație le au asupra semnalelor electrocardiografic și fotopletismografic. S-a observat că ciclurile de inspir / expir profunde influențează amplitudinea complexului QRS al semnalului ECG și, de asemenea, amplitudinea undei de impuls a semnalului PPG. Din analiza acestor modificări ale semnalelor ECG și PPG, se estimează frecvența respiratorie și se compară rezultatele cu cele din semnalul respirator. Se observă că rezultatele obținute din analiza semnalului ECG sunt mai apropiate de frecvența respiratorie măsurată, în comparaţie cu cele obținute din semnalul PPG. În a doua parte a lucrării se analizează efectul acestor exerciții de respirație asupra parametrilor HRV în domeniul timp și în domeniul frecvență. Din analiza în domeniul timp se observă ca toți parametrii, cu excepţia mediei RR, au valori mai mari în timpul exercițiilor de respirație comparativ cu cele obținute înainte și după efectuarea acestora. Pentru parametrii HRV din domeniul frecvență, spectrul de frecvență joasă (0.04 Hz – 0.15 Hz) este evidențiat în timpul exercițiilor și, de asemenea, se observă o modificare a parametrilor după efectuarea lor, comparativ cu starea lor înainte de exerciții.