Remote Photoplethysmography for the Neuro-electrostimulation Procedures Monitoring

The Possibilities of Remote Photoplethysmography Application for the Analysis of High Frequency Parameters of Heart Rate Variability

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Abstract: The paper presents assessments of the remote photoplethysmography (rPPG) capabilities for evaluation of heart rate variability (HRV) for monitoring the neuro-electrostimulation procedures. In our experiment, 20 minute long videos of 20 people in office lighting conditions were analyzed. We checked the accuracy of well-known methods and some modern methods of rPPG. In this work, we evaluated the accuracy of rPPG methods in high frequency (HF) band (0.4 - 0.15 Hz), and sub-bands (0.4 - 0.3 Hz), (0.3 - 0.15 Hz). For the sub-band (0.3-0.15 Hz) HRV signals obtained with rPPG are better correlated with HRV signals obtained with electrocardiography (ECG). The results have shown that POS method provides the best HRV parameter evaluation.

1 INTRODUCTION

Due to increased mortality from cardiovascular diseases devices for continuous monitoring of human physiological parameters were actively developed in the past decade. Nowadays the size of holter monitors has been significantly reduced. Fitness tracker and other devices for everyday use have appeared. The main disadvantage of such devices is their influence on the organism caused by the contact with the body. Thus, the remote monitoring methods are more promising.

The cardiovascular system is one of the most important element of the human body. The heart rate (HR) and heart rate variability (HRV) are the main parameters that allow to investigate the cardiovascular system functioning.

In recent years researchers have presented a number of new methods for non-contact physiological monitoring by using the remote photoplethysmography technology (rPPG). There are already more than 300 articles about the development of this technology. In these studies, the possibilities of applying rPPG technology as an alternative channel for monitoring the human state were actively investigated. In particular, there were approaches that use rPPG for monitoring premature babies (N. Blanik and Leonhardt, 2016) and patients under anesthesia (U. Rubins and Miscuks, 2013).Lots of articles have shown that rPPG can reliably measure the HR in comparison with the contact photoplethysmography. It was shown that it is possible to determine the parameters of pulse rate variability, blood oxygen saturation, respiratory rate and other parameters in controlled experiments.

In many studies the video records shorter than 5 minutes were used. For example, in (M.Z.Poh and Picard, 2011), (Y. Sun and Hu, 2012) the investigation of pulse rate variability parameters in HF (0.4 - 0.15 Hz), LF (0.15 - 0.04 Hz) bands was conducted. In such short periods of time subject is able to sit still. So the influence of movements was minimal. Such conditions impose significant limitations on the applicability of rPPG technology.

In other studies (Y. Sun and Greenwald, 2013), (A.A Kamshilin and Giniatullin, 2013), specialized light sources were used to enhance the rPPG signals. In (M.Z.Poh and Picard, 2011), (A. Moco and de Haan, 2015), sources of ambient light, such as the sun or a lamp "Philips HF-3319 EnergyLight White" in front of the skin were used. These sources provide a uniform level of illumination. Such sources illuminate the face almost regardless of the position of

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the head. However, light sources are usually located above the head. Due to that, there is some reflection and regions with different luminance.

The studies (M.Z.Poh and Picard, 2011), (Y. Sun and Greenwald, 2013) evaluate the HRV parameters in comparison with the contact photoplethysmography (PPG). However, the most examined and reliable way to determine the changes of the autonomic nervous system by means of the HRV evaluation is based on electrocardiography (ECG).

Earlier, we have presented the possibilities of assessing the VLF and LF parameters assessment by using the PCA-based rPPG (Kublanov and Purtov, 2015). However, it was shown that this method does not give a correct estimation of the HF band.

The main idea of this work is to evaluate the possibilities of rPPG for detecting changes of HRV in the HF band. To do this, we evaluate the accuracy of the rPPG methods compared with the parameters of HRV obtained by ECG.

Besides, we measure the respiratory rate (RR) by using the motion tracking techniques with preprocessing by Eulerian Video Magnification method. Such techniques now are very popular, but they work only if the person has relatively stable position in time.

2 MATERIALS AND METHODS

2.1 Methods

In recent years researchers have presented a number of new methods for recovering rPPG signals. Their full comparison with all the components and conditions is not possible in a single article. Therefore, in this paper we consider the methods, which:

1. Allow to process a signals in real-time;
2. Work with only one digital RGB camera;
3. Have varying physiological models of signals.

Thus, we choose the following methods: RoverG, XoverY, CHROM, ICA, PCA, 2SR, POS. These methods were proposed in the works (M.Z.Poh and Picard, 2011),(D. McDuff and Picard, 2014), (M. Lewandowska and Kocejko, 2011), (de Haan and Jeanne, 2013), (W. Wang and de Haan, 2015), (W. Wang and de Haan, 2016).

The settings for each of the rPPG method were used in accordance with recommendations of the authors. For example, the ICA method was implemented in accordance with the specifications: we split the signals to the 30 seconds overlap-add windows, and use the JADE ICA algorithm. The pulse component selection was based on the FFT analysis After the selection, the signals were inverted according to the rule: $\mu_{peakamp} < \mu_{troughamp}$,
where $\mu_{peakamp}$ is the mean absolute peak value, $\mu_{troughamp}$ is the mean absolute trough value

Each rPPG method was used on the same skin areas (pixels) to ensure the correctness of comparison. For each subject, the choice of skin boundaries was made in HSV and YC_bC_r color formats. Before the processing, the color boundaries were determined manually to get the maximum skin area on the face without areas with glare, because reflectance has great influence on the parameters of rPPG signal.

In the first image of the video, the face area was detected by using the Viola-Jones method (Viola and Jones, 2001). In other images, it was tracked by using implementation of KCF method (F. Henriques and Batista, 2015) which allows to work in real-time.

The method presented in a master thesis (Balakrishnan, 2014) was used to RR detection. It allows to estimate the RR signals by tracking the chest movements with motion preprocessing by Eulerian video magnification.

2.1.1 Evaluation Metrics

For comparison of different rPPG methods, we evaluate their performance by the following metrics.

- The Pearson correlation coefficient was used to evaluate the accuracy of different rPPG methods. It allow to compare HR and HRV signals measured by rPPG with reference to PPG and ECG signals.
- The signal to noise ratio (SNR) was used to assess the quality of measured rPPG signals. It is derived by the ratio between the energy around the first HR harmonic and the remaining parts in the 4 - 0.5 Hz frequency band. The location of the first harmonic is determined by the contact PPG-signal. It is was measured as follows:

$$SNR = 10 \cdot lg\left(\frac{(U_{signal})^2}{(U_{noise})^2}\right), \quad (1)$$

where U_{signal} is the intensity of the first heart rate harmonic, U_{noise} is the intensity of the remaining parts in the (4 - 0.5 Hz) frequency band.

2.2 Experiment

This work is performed at the Research and Development Medical and Biological Engineering Center of High Technologies, Ural Federal University (Russian Federation) with partisipation of employees of the Psychiatry Department, Ural State Medical University (Russian Federation). Ethical committee approved of this study. Informed consent was obtained from each subject. Twenty healthy volunteers (males and females) aged from 20 to 25 took part in this investigation. Records were made after using the ”SYMPATHOCOR-01” neuro-electrostimulation device (Kublanov, 2008).

Neuro-electrostimulation process with using the SYMPATHOCOR-01 device is the procedure when the device generates the field of spatially distributed current pulses at the subject neck. The neuro-electrostimulation effect can be measured by different techniques, such as the ECG. It was decided to check the accuracy of rPPG methods after the stimulation procedure.

The experiment is conventionally divided into 3 parts. The first and the third parts are the 5 minute rest periods when the subject does not do anything. In the second part of the experiment the subjects performed the ”Bourdon test” which took 10 minutes duration. The test task is not considered in this study.

2.2.1 Description

Simultaneous recording of the video and human physiological parameters (ECG, PPG, respiratory rate) was carried out during the experiment. The studies were all conducted indoors without sunlight. Each subject sat in front of a monitor of a personal computer (PC). The webcam was placed on the right from the monitor at a distance of 0.5 meters from a subjects face. The experiment room was illuminated by two usual fluorescent light sources placed on the ceiling. Each experiment was recorded and took 20 minutes. Subjects were asked to sit in front of the camera and perform a computer test.

All methods were implemented as a real-time application in the Python 2.7. The application uses the popular open-source packages OpenCV 2.4.11, numpy, PyQt. The implementation runs on a common personal computer with computatonal unit Intel Core i7 4770, 3,4 GHz, and 8 Gb DDR4 RAM.

2.2.2 Video Recording

Each experiment were recorded by using the low-cost webcam Logitech C920, which allows to capture RGB frames approximately at 30 frames per second (fps) in color (24 bits, 8 bit per color channel). The camera resolution was 640×480 pixels. Each image frame was saved in raw png format to the local database with a filename which contains the time of the frame capture. The template of a filename format is ”image[%d] yyyy-MM-dd hh-mm-ss.msec.png”, where %d means the sequential number of the image. Such a filename format allows to accurately determine capture moments.

2.2.3 Contact Measurements

The referenced HR, HRV and RR signals were obtained by the rehabilitation complex ”REACOR” (MEDICOM MTD, Russian Federation). It provides a real-time registration of respiratory monitoring, ECG and PPG with 250 Hz sampling rate and stores the signals in the PC. To analyse and compare the signals, all data were saved as comma-separated text files in the local database. To ensure good electrical contact of the electrodes with the body, gel ”Uniagel” (Geltek-Medica, Russian Federation) was used. The changes in finger blood flow are measured by contact photoplethysmography from left forefinger. RR signal was measured by using the respiration transducer belt.

3 RESULTS

In this section, the results of measuring HR, HRV and RR obtained by different rPPG methods are presented. For convenience, we show the evaluation only for 7 subjects, but their data are comparable with other subjects.

3.1 Heart Rate

Figure 1 shows the spectrograms of measured signals. First column contains spectrograms of PPG signals. The other columns present the spectrograms of rPPG signals obtained by the following methods: PCA, ICA, 2SR, POS, CHROM, XoverY and RoverG. All spectrograms were calculated for 10-second time windows with 5-second overlap.

The HR was determined as the maximum power spectrum in the (4 - 0.5 Hz) frequency band, which corresponds to the range of 30 to 240 heart beats per minute. In this case the error of determining HR was less a 0.1 Hz.

Tables 1 and 2 represent the accuracy of the HR for these rPPG methods. Table 1 contains the average value of the absolute difference between rPPG HR and PPG HR. Table 2 contains the values of standard deviation for the difference between rPPG HR and PPG HR.

Currently, ICA and PCA methods are the most common ways to measure rPPG signals and estimate the HR. According to the data presented in Table 1,

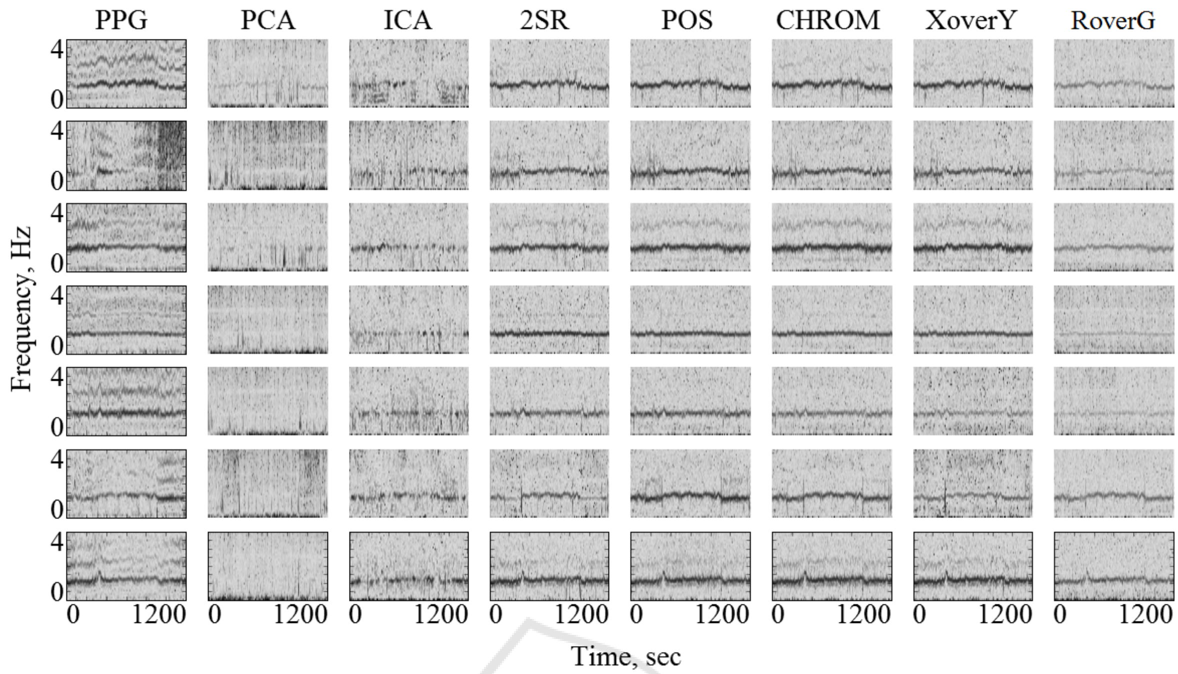

Figure 1: The spectrograms of PPG and rPPG signals; rows denote the unique subjects.

Table 1: Mean values of absolute difference between HR rPPG and HR PPG, msec.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	133	302	11	8	8	8	11
2	184	154	74	75	74	76	84
3	372	145	8	8	9	9	16
4	189	181	3	4	4	3	6
5	414	207	23	30	31	18	45
6	301	88	18	9	14	19	13
7	168	77	10	12	10	11	14

Table 2: Standart deviation of absolute difference between HR rPPG and HR PPG, msec.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	236	292	64	46	45	47	32
2	226	230	184	185	185	187	186
3	414	273	32	33	34	34	46
4	339	265	16	19	19	15	22
5	401	281	74	102	102	47	115
6	255	204	78	36	60	73	49
7	264	160	35	39	34	36	42

HR accuracy obtained by these methods is significantly worse than HR accuracy obtained by other methods.

Table 3: Mean value of SNR rPPG signals with 10 sec overlap-add window, dB.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	7.30	6.85	10.15	10.70	10.65	10.60	8.85
2	7.15	7.05	9.35	9.75	9.80	9.60	8.40
3	6.50	6.85	9.65	10.00	10.05	9.90	8.95
4	6.30	6.25	10.95	11.40	11.30	11.35	8.95
5	5.80	5.95	8.95	9.45	9.15	8.95	7.60
6	6.05	7.35	9.25	10.10	10.15	9.75	9.45
7	6.35	7.10	9.85	9.90	10.3	10.30	9.25

The HR estimates obtained by 2SR, POS, CHROM, XoverY are highly reliable and slightly different from each other. The RoverG method is one of the first rPPG method. So, it is more inaccurate than others, but much better than PCA or ICA.

The quality of rPPG signals was evaluated by SNR metric, which was described in the previous section. Table 3 presents the results of the average SNR, where each score was obtained as the average value of SNR calculated for 10 second intervals with a 5 second overlap.

According to Table 3, it is evident that CHROM and POS methods show the largest SNR values. In our tests for 20 people, the difference between these methods does not exceed 1 dB. ICA and PCA methods showed the lowest SNR results. This may be due to the large time intervals (30 seconds) required for the correct calculation of these methods.

3.2 Heart Rate Variability

HRV signals are of great interest in the evaluation of parameters of cardiovascular system. According to the international standard of research (HRV, 1993), HRV signal can be determined as the distance between the peaks of the PPG signal.

To increase the accuracy of peaks localization, each rPPG signal was interpolated to 250 Hz sampling rate by using a cubic spline interpolation. It was selected to correspond the accuracy of contact methods.

After that, all signals were filtered by the 5 order Butterworth bandpass filter with 1 Hz bandwidth and central frequency selected according to the current HR. To calculate the pulse to pulse intervals, the common PPG peak detection algorithm was used.

All extrasystoles in the HRV ECG signals were removed in accordance with the article (T. Briiggemann and Schroder, 1996).

Tables 4, 5, 6 present the results of a comparative analysis of the ECG HRV and rPPG HRV signals in VLF (0.04 - 0.003 Hz), LF (0.15-0.04 Hz) and HF (0.4 - 0.15 Hz) bands. The Pearson correlation coefficient was used as the similarity criterion.

According to Tables 4, 5, 6, PCA, ICA methods show significantly poorer scores than other methods. It can be explained by the fact that the subjects were working with the PC, and, thus, did not control their behavior during the video recording.

According to Table 4, in the VLF band the HRV rPPG signals were determined with high accuracy by methods POS, CHROM, XoverY and 2SR. The Pearson correlation coefficient for these methods in all studies is higher than 0.9. The most accurate estimates were obtained by POS method.

Table 5 shows that in the LF band the most accurate methods are POS, CHROM, XoverY and 2SR. The Pearson correlation coefficient in this case varies from 0.7 to 1.

In the HF band, the maximum values of the Pearson correlation coefficient match to POS, CHROM, XoverY and 2SR. However, these values were changed in the range from 0 to 0.9. This suggests a weak correlation between rPPG HRV and ECG HRV signals in the HF band.

3.3 Respiration Rate

The Pearson correlation coefficients obtained in HF band were low. Therefore, it was decided to determine the accuracy of various subbands of HF. First of all the accuracy of RR selection was checked. The respiration is the main component in HF band. Usually it has the biggest values in HRV HF spectrogram.

Figure 2 presents the spectrograms of RR signals measured by different methods. Each row contains the spectrograms of signals for a single subject. The contact RR (cRR) signal was obtained by using respiration transducer belt placed on the subject chest. Video RR (vRR) was obtained by using the method based on Eulerian video magnification with tracking points on the subject chest by Lucas-Kanade algorithm. The other columns in the figure present the HRV signals that were obtained by ECG and rPPG techniques in HF band.

Table 4: Pearson correlation coefficient between ECG HRV and rPPG HRV VLF (0.04 - 0.003 Hz) band.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	0.48	0.42	0.95	0.97	0.98	0.98	0.92
2	0.38	0.59	0.89	0.87	0.93	0.87	0.87
3	0.12	0.06	0.97	0.99	0.98	0.96	0.94
4	0.41	0.25	1.00	1.00	0.94	1.00	0.89
5	0.06	0.03	0.93	0.95	0.90	0.93	0.67
6	0.10	0.32	0.93	0.97	0.94	0.94	0.96
7	0.32	0.73	0.95	0.99	0.99	0.98	0.97

Table 5: Pearson correlation coefficient between ECG HRV and rPPG HRV LF (0.15 - 0.04 Hz) band.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	0.02	0.09	0.76	0.81	0.85	0.81	0.49
2	0.09	0.30	0.69	0.73	0.72	0.69	0.60
3	0.04	0.27	0.86	0.92	0.90	0.84	0.75
4	0.12	0.01	0.95	0.95	0.84	0.97	0.63
5	0.02	0.17	0.72	0.79	0.62	0.70	0.47
6	0.03	0.25	0.67	0.81	0.68	0.78	0.75
7	0.05	0.19	0.68	0.87	0.88	0.83	0.72

Table 6: Pearson correlation coefficient between ECG HRV and rPPG HRV in HF (0.4 - 0.15 Hz) band.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	0.04	0.03	0.44	0.48	0.50	0.41	0.30
2	0.04	0.12	0.45	0.54	0.39	0.47	0.25
3	0.05	0.03	0.63	0.67	0.66	0.57	0.44
4	0.12	0.01	0.53	0.31	0.38	0.55	0.11
5	0.03	0.06	0.18	0.36	0.13	0.26	0.07
6	0.08	0.16	0.53	0.56	0.42	0.55	0.51
7	0.13	0.07	0.71	0.74	0.76	0.74	0.56

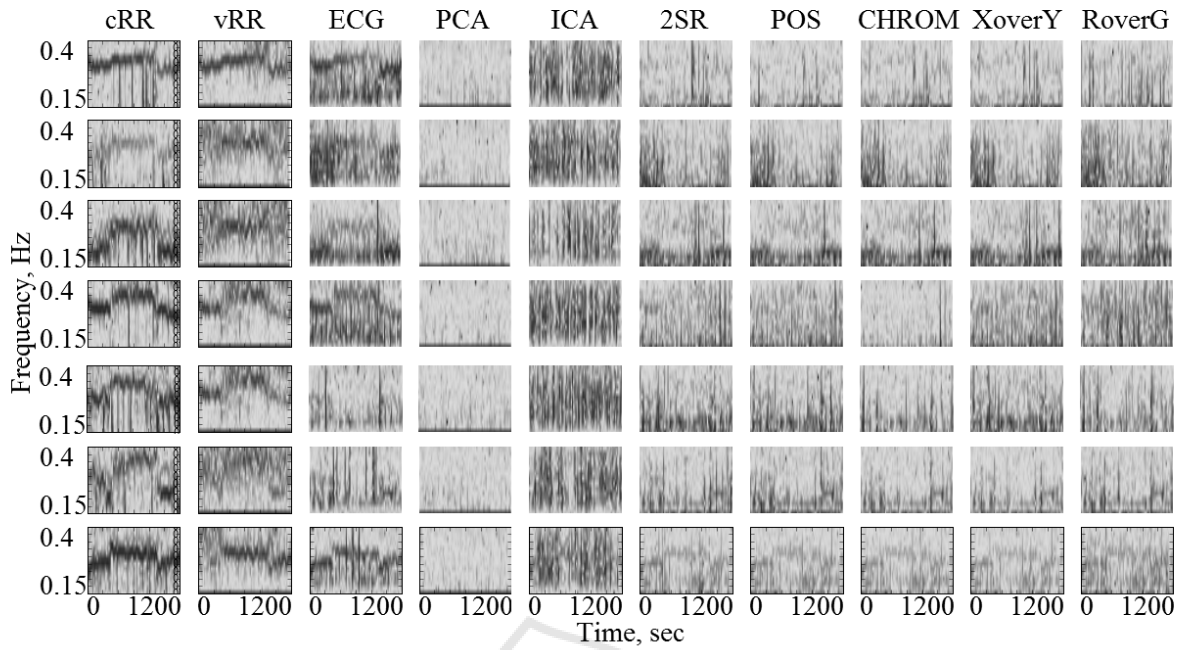

Figure 2: The spectrograms of HRV signals obtained by rPPG and ECG, and respiration signals measured by video (vRR) and respiration belt (cRR).

Table 7: The comparision of RR signals measured by video and respiration belt.

Subjects	mean	std	cRR_{min}	vRR_{min}	cRR_{max}	vRR_{max}
1	0.03	0.09	0.15	0.35	0.47	0.50
2	0.07	0.09	0.15	0.33	0.45	0.51
3	0.11	0.10	0.18	0.27	0.42	0.55
4	0.01	0.05	0.33	0.33	0.53	0.56
5	0.04	0.06	0.23	0.27	0.53	0.57
6	0.02	0.05	0.30	0.30	0.45	0.52
7	0.03	0.09	0.15	0.35	0.47	0.55

Table 8: Pearson correlation coefficient between ECG HRV and rPPG HRV in HF (0.4 - 0.3 Hz) sub-band.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	0.03	0.02	0.43	0.47	0.49	0.43	0.34
2	0.02	0.09	0.41	0.50	0.30	0.46	0.18
3	0.01	0.01	0.41	0.39	0.43	0.32	0.26
4	0.15	0.04	0.47	0.11	0.27	0.46	0.01
5	0.00	0.11	0.06	0.19	0.05	0.04	0.02
6	0.06	0.11	0.39	0.34	0.22	0.32	0.29
7	0.14	0.01	0.66	0.66	0.70	0.67	0.47

According to the whole set of data some of which are presented in Figure 2, signals vRR match well with signals cRR. Table 7 shows the comparision of accuracy for cRR and vRR signals. The first column corresponds to the mean deviation RR for 60-second time intervals with 30 second overlap. The second column shows the values of the standard deviation. Other columns contain the values which correspond to minimal (cRR_{min} and vRR_{min}) and maximal (cRR_{max} and vRR_{max}) measured values.

Table 9: Pearson correlation coefficient between ECG HRV and rPPG HRV in HF (0.3 - 0.15 Hz) sub-band.

Subjects	PCA	ICA	2SR	POS	CHROM	XoverY	RoverG
1	0.04	0.02	0.47	0.51	0.53	0.43	0.28
2	0.10	0.14	0.47	0.57	0.44	0.47	0.31
3	0.08	0.07	0.74	0.78	0.77	0.69	0.55
4	0.09	0.00	0.60	0.49	0.48	0.64	0.19
5	0.04	0.01	0.34	0.46	0.24	0.40	0.11
6	0.08	0.21	0.62	0.69	0.53	0.67	0.63
7	0.10	0.14	0.73	0.79	0.80	0.78	0.63

It can be seen that the HRV ECG signals were slightly modulated by respiration. In many cases, they contain other fundamental frequencies. In HRV rPPG signals the breath in fact is absent. HRV signals obtained by ICA and PCA methods in HF band look like noise.

We hypothesized that for frequencies below the mean breathing rate the correlation will be high. The HF band was divided into two sub-bands 0.4 - 0.3 Hz and 0.3-0.15 Hz. The Pearson correlation coefficients for the signals in these sub-bands are shown in Tables 8 and 9 respectively.

According to Tables 8 and 9, the lower frequency sub-bands of HRV rPPG and HRV ECG are more correlated. In this case the value of correlation coefficient has increased in all studies.

Therefore, RR measured by rPPG methods should be tested additionally, for example, using the method of chest movement evaluation.

4 CONCLUSION

One of the main results of this study is the comparison of existing real-time rPPG methods. It was shown that the most common methods ICA and PCA have the worst assessment of HR and HRV. Recently introduced POS method has the greatest accuracy in HR and HRV estimation. It allows to detect rPPG signals even under changing light conditions.

Another conclusion is that the existing rPPG techniques allow to measure the parameters of HRV with a low-cost camera in VLF (0.04 - 0.003 Hz) and LF (0.15-0.04 Hz) bands with high-precision accuracy. The HRV in HF band has the lowest reliability. Our study showed that the low frequency sub-band of the HF has a larger correlation with HRV ECG than the high frequency sub-band.

RR is another parameter which can be checked by video. It was shown that under normal conditions HRV rPPG signals contain almost no information about respiration. Instead of this, the accuracy of motion detection method proved to be the most reliable for breathing detection. Therefore, the best way to determine RR is the estimation of chest movements.

In future works, we plan to investigate the possibilities of rPPG methods in clinical practice, and using the rPPG as the biofeedback method for neuroelectrostimulation.

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