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RESEARCH ARTICLE

Validation of novel single spot photoplethysmography monitoring device to measure the autonomic status of the individual

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ABSTRACT

Background: In this study, the validation of electrocardiogram (ECG) and photoplethysmography (PPG) signals is performed. The pulse readings are recorded for ten healthy volunteers, and simultaneously ECG readings were recorded for the duration of 30 min. **Aims and Objectives:** Pulse rate variability (PRV) is an approach used to assess the changes in the autonomic nervous system of an individual. The primary method of deriving the PRV is to acquire the PPG signal. The acquired PPG signal is validated with ECG signals to ensure that single spot PPG monitoring device can be used as an alternative measurement to heart rate variability (HRV). **Materials and Methods:** With the approval from Ethics Committee, ten healthy subjects, aged from 18 to 24, took part in this study. The ECG and PPG readings were recorded in the early morning between 7 and 9 a.m. During PPG recording process, the peak to peak interval from PPG signals was monitored. Simultaneously, the ECG readings were recorded from RMS Vagus HRV Software. The RR interval from ECG signals was monitored during the ECG recording process. **Results:** Both ECG and PPG readings were monitored, and a close accuracy with an average percentage error for beats per minute was around 7%, and RR interval was around 5% which was achieved. **Conclusion:** With the development of single spot PPG monitoring devices can be used as an alternative measurement to HRV even during non-stationary conditions. PPG sensors can be placed on fingertip, wrist which offers more flexibility to the users. Furthermore, with the development of wearable devices for monitoring biomedical signals suggested that it is possible to monitor pulse rate through PPG signals due to the simplicity of PPG waveforms.

KEY WORDS: Photoplethysmography; Pulse Rate Variability; Autonomic Nervous System; Heart Rate Variability; Electrocardiogram

INTRODUCTION

Psychological stress is one of the major mental health problems in modern society. It is related to many mental health issues such as anxiety and depression disorders. It is known to disturb the autonomic nervous system and later leading to physiological derangements. The autonomic nervous system is the part of the nervous system which is responsible for controlling involuntary functions such as heartbeat and blood flow and has two main divisions: Sympathetic and parasympathetic system. In general, the sympathetic division prepares the body for stressful situations, and it increases heart rate and expands the airway which helps to breathe easier. The parasympathetic division controls body processes during ordinary situations, and therefore it decreases the heart rate and restores body to normal state. Several parameters such as electroencephalograph, pulse rate variability (PRV),

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and blood pressure, among others quickly respond to any change that occurs in mental stress level. PRV is one of the most reliable indicators of stress, and photoplethysmography (PPG) is a simple and low-cost optical technique which is efficient in computation of PRV. PRV has the unique character of measuring the condition of autonomous nervous system. Logier *et al*.[1] describes the PRV analysis that can be used as an alternative to heart rate variability (HRV) for portable systems available on the market. The correlations between HRV and PRV parameters in time domain and frequency domain are 0.96. This enables us to establish the fact that there is a link between HRV and PRV parameters. Ghamari *et al*.[2] incorporate a wireless device to monitor the heart rate based on PPG technique. An Android app was also used to enable the smart device to display the received PPG signal. A MATLAB program was used to analyze and detect the R-R peak intervals of the PPG waveform. Finally, by feeding the PPG signal peaks into the Kubios software, the HRV analysis report was generated. Mohan *et al*.[3] work on HRV that is determined by using PPG. During this process, the stress level of the subject is assessed from the HRV data. Data are collected from persons in rest position also with variable breathing rates to simulate stress. Low-frequency (LF)/high-frequency (HF) ratio is calculated which is a measure of stress of a person.

The existing system deals with monitoring of stress based on HRV parameters through electrocardiogram (ECG) signals. It requires the individual to be in resting condition, and couple of electrodes is placed at particular locations during the acquisition of ECG signal. This serves as a drawback as it confines the flexibility of the users and also real-time software is not developed to perform HRV analysis.

To overcome this drawback, this study considers the acquisition of PPG signal using pulse sensor.[4] Pulse sensor is based on PPG principle, as shown in Figure 1. It is a non-invasive method and measures changes in blood volume in tissues using an optical source and detector. The change in blood volume is related to every heartbeat which is used to calculate the heart rate.

Pulse sensor consists of an light-emitting diode (LED) and a photosensor. When a sensor is placed on the fingertip, it is irradiated by the light coming from the LED and the photosensor receives the light from the skin tissue which is placed on the other side. From Figure 2, the pulse rate is detected by the light emitted by green LED on APDS-9008 light sensor. The sensor has an inbuilt amplification and noise cancellation circuit. The signal is amplified by the MCP-6001 Op-Amp. The analog signal from this amplifier has a frequency of 0.5–4 Hz.

From Figure 3, to acquire the finest PPG signal, the LED wavelength should be within the absorption peaks of HbO_2 around 540 nm and 570 nm. The green LEDs emitting around 535 nm are utilized for heart rate monitoring. The firmware computes pulse rate expressed in beats per minute (BPM), and interval between adjacent PPG pulses called RR interval is obtained.[5] After determining RR intervals, the time domain, frequency domain, and geometric domain analysis are computed. This analysis indicates overall balance in autonomic nervous systems, as shown in Figure 4.[6,7] In the time domain analysis, the standard deviation of RR intervals (SDNN) is applied to RR interval series, and the root mean

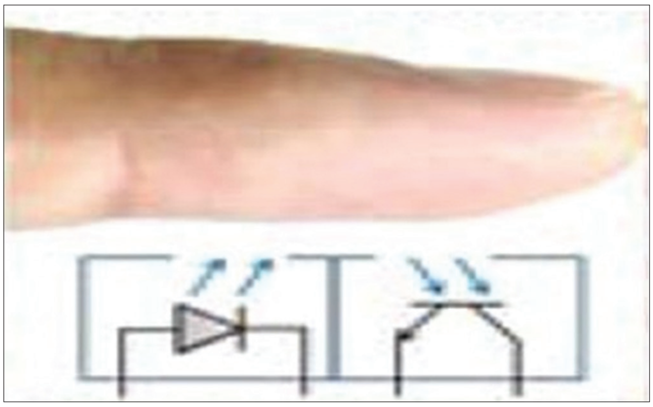

Figure 1: Principle of photoplethysmography[2]

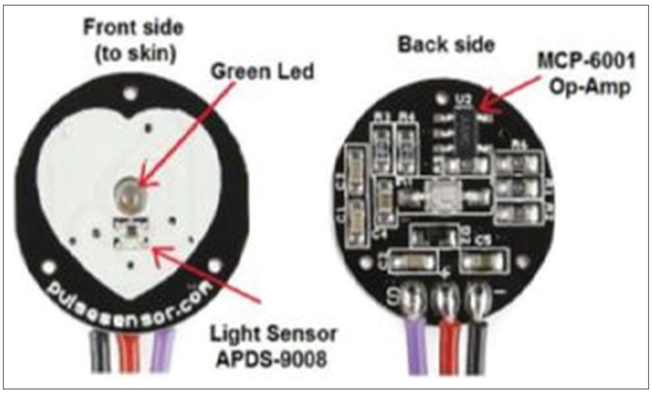

Figure 2: Pulse sensor front and rear side (https://www.researchgate.net/publication/327976264)

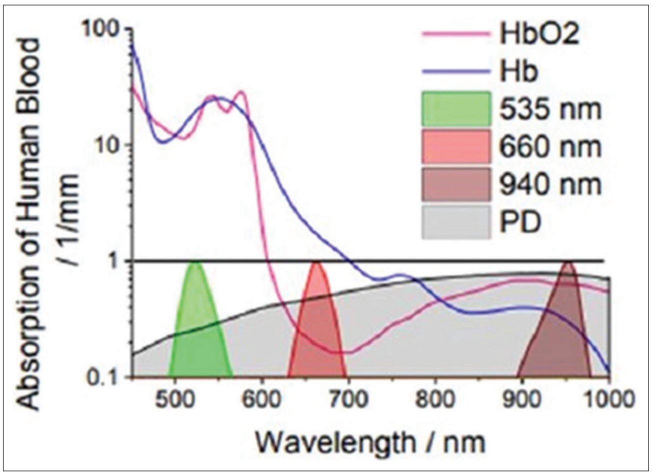

Figure 3: Graph of absorption of human blood versus wavelength of light ("SFH 7050 – photoplethysmography sensor," Hubert Halbritter, Rolf Weber, Stefan Struwing, June 2014)

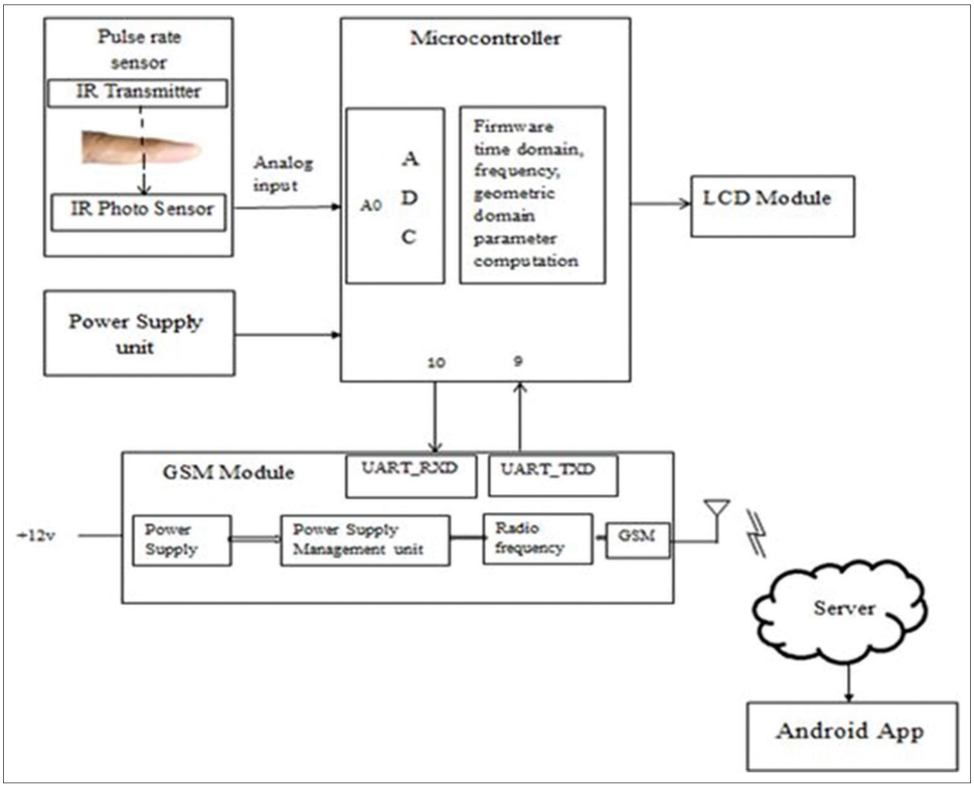

Figure 4: Block diagram of photoplethysmography monitoring system

square successive difference (RMSSD) of RR interval (RMSSD) is computed according to standardized procedures. SDNN and RMSSD are computed to determine the capability of the heart that reacts toward stress. In frequency domain analysis ratios of LF and HF is calculated, and geometric domain analysis includes calculation of ratio of standard deviation (SD) of SD2 and SD1 to check balance in sympathetic and parasympathetic nervous system. The PRV parameters are then transmitted to the server through GSM module. With internet connection, the values from the server are retrieved and displayed on an Android app by connecting through a proper channel with the channel id of the server.

MATERIALS AND METHODS

Materials

Pulse sensor, microcontroller (ATmega 328P) for the acquisition of PPG signals, GSM module (SIM 800C), liquid-crystal display module for display of PRV parameters, 9V battery for powering the microcontroller, and universal serial bus module for powering GSM module.

Methods

Participants

Ten healthy subjects, aged from 18 to 24, took part in this study. Before the experiment general information about age, gender, height, and weight of the subject were considered. A participant informed consent form was distributed in which the participant was informed about the nature of this study. Then, a perceived stress level questionnaire form was distributed to the participants to check the level of stress, the individual has experienced in the previous months.

PPG and ECG recordings were excluded from the study if any one of the following criteria was met:

- Known history of alcohol consumption and smoking
- Suffering from a thyroid disorder, anemia, cardiac illness, congenital heart disease, and hyperdynamic circulatory conditions
- Any recent stressors such as emotional disturbances, breakup, family issues, and recent trauma
- Any recent acute illness such as fever, cough, upper respiratory tract infections
- Menstrual phase of the menstrual cycle for woman.

Procedure

The ECG and PPG readings were recorded in the early morning between 7 and 9 a.m. The test procedure will be carried out in two stages:

- For ten subjects, the PPG readings will be recorded using Arduino software which is open source software which allows to write the code and upload it on Arduino board. It runs on Windows, Mac OS X, and Linux. During PPG recording process, the peak to peak interval from PPG signals will be monitored
- Simultaneously, the ECG readings will be recorded from RMS Vagus HRV Software. The RR interval from ECG signals will be monitored during the ECG recording process

- The ECG analysis from the HRV software and PPG analysis from Arduino software provides information about time domain (SDNN and RMSSD), frequency domain parameters (LF, HF, and LF/HF ratio), and geometric domain (SD2/SD1 ratio) parameters.

PRV parameters

PPG signal is acquired from the pulse sensor. The interval between adjacent PPG signals called RR interval is determined. Then, time domain, frequency domain, and geometric domain parameters adopted in PRV analysis were extracted from RR interval in PPG recording.[8] Table 1 indicates definition of PRV parameters. In time domain analysis, SDNN and RMSSD were computed. SDNN is the estimate of overall PRV and examines the ability of the heart to respond to stress. SDNN values predict unhealthy conditions. Below 20 ms is an indication of chronic stress-related disease.

SDNN is computed as indicated in Equation 1:

$$SDNN = \sqrt{\frac{}{n \quad 1}\sum_{i=1}(RR \quad \overline{RR})} \tag{1}$$

Where RR_i denotes the time from the i^{th} to the $(i+1)^{st}$ Rpeak and $\overline{RR}$ is the average interval, giving n intervals in total.

RMSSD estimates high-frequency variations in pulse rate in short-term RR recordings. The decrease in RMSSD below 10 ms results in the development of cardiac disease.

RMSSD is computed as shown in Equation 2:

$$RMSSD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n-1}(RR_{i+1} - RR_i)^2} \tag{2}$$

Frequency domain analysis includes LF/HF ratio which is a measure of overall balance between sympathetic and parasympathetic systems. It is computed as shown in Equation 3:

$$\frac{LF}{HF} = \frac{\int_{0.04}^{0.15} f(\lambda)d\lambda}{\int_{0.15}^{0.40} f(\lambda)d\lambda} \tag{3}$$

Where f (λ) is determined from RR interval series that is f(λ) = (120* RR interval + 660).

Geometric domain analysis includes the ratio of SD2 and SD1 which reflects sympathetic to parasympathetic activity. It is computed as per the Equations 4 to Equation 7.

$$SD_1 = \sqrt{Var\ (x_1)} \tag{4}$$

$$SD_2 = \sqrt{Var\ (x_2)} \tag{5}$$

Var (x_1) and Var (x_2) is the variance of x_1 and x_2.

x_1 and x_2 is calculated as shown in Equations 6 and 7:

$$x_1 = \frac{RR_i + RR_{i+1}}{\sqrt{2}} \tag{6}$$

$$x_2 = \frac{RR_i - RR_{i+1}}{\sqrt{2}} \tag{7}$$

RESULTS

The findings of the following study are depicted in Tables 2-7 and Figures 5 and 6.

Table 1: Definition of pulse rate variability parameters

Parameter	Unit	Units description
RR interval	ms	Interval between consecutive normal R waves in photoplethysmography waveform
SDNN	ms	Standard deviation of the RR intervals
RMSSD	ms	RMSSD in RR intervals
LF/HF ratio		Ratio of LF to HF
SD2/SD1 ratio		Ratio of standard deviation

RMSSD: Root mean square successive difference, LF: Low frequency, HF: High frequency

Table 2: Demographic parameters of the study participants

Gender	Male
Age (years)	19.5±3.24
Height (m)	1.67±0.075
Weight (kg)	58.6±6.16
BMI (kg/m^2)	20.7±1.77
Perceived stress scale score	16.4±1.83

Table 3: Ground truth as per the perceived stress level questionnaire

Subjects considered	Perceived stress scale score
Subject-1	Perceives stress level – 16
Subject-2	Perceives stress level – 17
Subject-3	Perceives stress level – 19
Subject-4	Perceives stress level – 18
Subject-5	Perceives stress level – 14
Subject-6	Perceives stress level – 18
Subject-7	Perceives stress level – 17
Subject-8	Perceives stress level – 16
Subject-9	Perceives stress level – 16
Subject-10	Perceives stress level – 13

DISCUSSION

PPG signal acquired from the pulse sensor is validated by comparing with ECG signal. ECG signal analysis is performed using RMS Vagus software. PPG signal analysis is performed using Arduino software. As shown in Figure 5, PPG signal and ECG signal are simultaneously monitored over 30 min. The demographic parameters are indicated in Table 2. Tables 4 and 5 indicate the PPG and ECG readings for ten subjects.

The validation of ECG and PPG signal implies that PRV can be used as an alternative measurement to HRV as indicated in Tables 4 and 5.

As shown in Figure 6, a close accuracy was achieved between ECG and PPG signal. The average percentage error for BPM was around 7%, and RR interval was around 5% when compared with ECG signal for mean values of ECG and PPG readings, as indicated in Table 5. The values obtained from PPG and ECG recordings, as shown in Table 6 specify that all the parameter readings are in the standard range which is an indication of increase in PRV of the individual which indicates healthy condition. It is verified by perceived stress level questionnaire to determine the stress level of an individual which helps to classify between average stress level and high stress level. If the stress level is within the range from 13 to 19, it is classified as average stress level; if the stress level is >20 then it is classified as high stress level.

Table 4: Parameters obtained from (a) PPG signal (b) ECG signal

Parameters	Pulse rate	RR interval	SDNN	Root mean square of successive difference	Low-frequency/High-frequency ratio	SD2/SD1 ratio
PPG signal						
Subject-1	74	768	35.33	32.68	1.02	1.71
Subject-2	89	698	40.73	34.27	1.03	1.28
Subject-3	86	674	42.2	38.43	1.03	2.79
Subject-4	83	648	54.56	36.45	1.04	2.55
Subject-5	84	656	50.5	39.68	1.07	2.5
Subject-6	81	772	33.46	25.31	1.09	3.9
Subject-7	75	720	30.74	27.41	1.08	2.4
Subject-8	78	766	41.8	25.99	1.07	2.6
Subject-9	87	650	35.36	29.85	1.03	3.39
Subject-10	91	625	33.63	27.6	1.4	3.01
ECG signal						
Subject-1	78	764	30.29	28.9	1.41	1.84
Subject-2	88	679	34.34	38.33	1.1	1.48
Subject-3	85	700	38.29	31.34	1.9	2.22
Subject-4	90	659	48.54	34.41	1.17	2.62
Subject-5	88	675	42.8	30.75	1.4	2.58
Subject-6	82	725	30.89	28.09	1.08	3.25
Subject-7	80	722	32.11	24.62	1.14	2.84
Subject-8	80	743	41.27	23.21	1.43	2.48
Subject-9	88	616	33.6	28.1	1.33	3.24
Subject-10	93	620	32.9	29.1	1.96	3.2

ECG: Electrocardiogram, PPG: Photoplethysmography

Table 5: Mean values of PPG and ECG readings

Parameters	Computed from PPG (Mean±SD)	Computed from ECG (Mean±SD)
Beats per minute	82.6±3.43	89±5.43
RR interval (ms)	642±35.18	677.28±35.91
SDNN (ms)	38.55±9.97	37.70±6.61
Root mean square successive difference (ms)	26.98±8.61	20.36±6.62
Low-frequency/High-frequency ratio	0.97±0.005	2.19±1.48
SD2/SD1 ratio	2.69±0.49	3.72±0.73

ECG: Electrocardiogram, PPG: Photoplethysmography, SD: Standard deviation, SDNN: Standard deviation of the RR intervals

Table 6: Effect of audio-visual stimulus on pulse rate variability parameters for 35 subjects

Subjects	Parameters	Normal	Audio-visual stimulus	Impression	Recovery time	Ground truth as per perceived stress scale questionnaire
Subject-1	Pulse rate	82	87		4 min after ending audio-visual stimulus	Perceived stress level 16-average stress level
	RR interval	698	590	Decrease		
	SDNN	46.38	38.68	Decrease		
	RMSSD	28.83	27.38			
	LF/HF	1.03	1.04			
	SD2/SD1	1.99	2.74	Increase		
Subject-2	Pulse rate	79	76		3 min after ending audio-visual stimulus	Perceived stress level 17-average stress level
	RR interval	694	626	Decrease		
	SDNN	53.06	49.26	Decrease		
	RMSSD	52.85	34.4	Decrease		
	LF/HF	1.03	1.02			
	SD2/SD1	2.97	2.85			
Subject-3	Pulse rate	74	82	Increase	5 min after ending audio-visual stimulus	Perceived stress level 21-high stress level
	RR interval	690	654	Decrease		
	SDNN	65	53.01	Decrease		
	RMSSD	64	56.91	Decrease		
	LF/HF	1.07	1.03			
	SD2/SD1	1.24	2.78	Increase		
Subject-4	Pulse rate	86	89		6 min after ending audio-visual stimulus	Perceived stress level 28-high stress level
	RR interval	594	582	Decrease		
	SDNN	46.33	38.45	Decrease		
	RMSSD	25.89	26.52			
	LF/HF	1.04	1.05			
	SD2/SD1	2.3	2.41	Increase		
Subject-5	Pulse rate	80	74		6 min after ending audio-visual stimulus	Perceived stress level 22-high stress level
	RR interval	696	694			
	SDNN	52.84	37.39	Decrease		
	RMSSD	46.64	38.62	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.9	2.26			
Subject-6	Pulse rate	74	79		5 min after ending audio-visual stimulus	Perceived stress level 18-average stress level
	RR interval	698	720			
	SDNN	52.24	38.8	Decrease		
	RMSSD	32.77	22.1	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.93	1.68			
Subject-7	Pulse rate	65	61		4 min after ending audio-visual stimulus	Perceived stress level 17-average stress level
	RR interval	858	850			
	SDNN	64.49	44.32	Decrease		
	RMSSD	66.15	56.62	Decrease		
	LF/HF	1.06	1.07			
	SD2/SD1	3.04	1.93			
Subject-8	Pulse rate	86	89		2 min after ending audio-visual stimulus	Perceived stress level 14-average stress level
	RR interval	626	632			
	SDNN	62.96	51.99	Decrease		
	RMSSD	66.36	48.22	Decrease		
	LF/HF	1.04	1.05			
	SD2/SD1	2.1	2.57	Increase		

(*Contd...*)

Table 6: (*Continued*)

Subjects	Parameters	Normal	Audio-visual stimulus	Impression	Recovery time	Ground truth as per perceived stress scale questionnaire
Subject-9	Pulse rate	70	86	Increase	2 min after ending audio-visual stimulus	Perceived stress level 16-average stress level
	RR interval	806	618	Decrease		
	SDNN	73.25	49.82	Decrease		
	RMSSD	69.91	35.75	Decrease		
	LF/HF	1.02	1.04			
	SD2/SD1	2.82	3.73	Increase		
Subject-10	Pulse rate	66	67		2 min after ending audio-visual stimulus	Perceived stress level 13-average stress level
	RR interval	848	796	Decrease		
	SDNN	68.02	49.43	Decrease		
	RMSSD	50.9	42.7	Decrease		
	LF/HF	1.02	1.07			
	SD2/SD1	2.07	2.76	Increase		
Subject-11	Pulse rate	72	67		5 min after ending audio-visual stimulus	Perceived stress level 26-high stress level
	RR interval	788	798			
	SDNN	51.25	38.49	Decrease		
	RMSSD	39.47	33.21	Decrease		
	LF/HF	1.02	1.02			
	SD2/SD1	2.28	3.16	Increase		
Subject-12	Pulse rate	77	83		2 min after ending audio-visual stimulus	Perceived stress level 14-average stress level
	RR interval	746	666	Decrease		
	SDNN	50.3	42.28	Decrease		
	RMSSD	45.5	21.94	Decrease		
	LF/HF	1.02	1.03			
	SD2/SD1	1.82	2.71	Increase		
Subject-13	Pulse rate	62	68		2 min after ending audio-visual stimulus	Perceived stress level 16-average stress level
	RR interval	818	798	Decrease		
	SDNN	75.36	58.8	Decrease		
	RMSSD	69.2	60.29			
	LF/HF	1.02	1.06			
	SD2/SD1	2.84	3.73	Increase		
Subject-14	Pulse rate	83	88		3 min after ending audio-visual stimulus	Perceived stress level 19-average stress level
	RR interval	634	638			
	SDNN	43.12	25.81	Decrease		
	RMSSD	31.7	22	Decrease		
	LF/HF	1.04	1.05			
	SD2/SD1	2.81	2.2			
Subject-15	Pulse rate	72	77		3 min after ending audio-visual stimulus	Perceived stress level 21-high stress level
	RR interval	732	714	Decrease		
	SDNN	44.24	34.98	Decrease		
	RMSSD	33.46	25.92	Decrease		
	LF/HF	1.02	1.03			
	SD2/SD1	2.87	2.48			
Subject-16	Pulse rate	71	75		2 min after ending audio-visual stimulus	Perceived stress level 20-high stress level
	RR interval	812	804	Decrease		
	SDNN	54.22	39.55	Decrease		
	RMSSD	52.76	42.44	Decrease		
	LF/HF	1.02	1.03			
	SD2/SD1	2.24	2.81	Increase		

(*Contd...*)

Table 6: (*Continued*)

Subjects	Parameters	Normal	Audio-visual stimulus	Impression	Recovery time	Ground truth as per perceived stress scale questionnaire
Subject-17	Pulse rate	64	60		3 min after ending audio-visual stimulus	Perceived stress level 18-average stress level
	RR interval	814	836			
	SDNN	77.59	64.45	Decrease		
	RMSSD	69.26	40.48	Decrease		
	LF/HF	1.02	1.08			
	SD2/SD1	2.64	2.2			
Subject-18	Pulse rate	82	77		2 min after ending audio-visual stimulus	Perceived stress level 15-average stress level
	RR interval	672	716			
	SDNN	60.09	32.6	Decrease		
	RMSSD	47.85	31.06	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.07	2.51	Increase		
Subject-19	Pulse rate	65	64		4 min after ending audio-visual stimulus	Perceived stress level 22-high stress level
	RR interval	882	874			
	SDNN	61.02	49.62	Decrease		
	RMSSD	52.68	30.61	Decrease		
	LF/HF	1.02	1.07			
	SD2/SD1	1.82	2.4	Increase		
Subject-20	Pulse rate	88	93	Increase	3 min after ending audio-visual stimulus	Perceived stress level 21-High stress level
	RR interval	524	514	Decrease		
	SDNN	69.6	50.7	Decrease		
	RMSSD	59.7	37.08	Decrease		
	LF/HF	1.05	1.06			
	SD2/SD1	2.35	2.3	Increase		
Subject-21	Pulse rate	72	63		3 min after ending audio-visual stimulus	Perceived stress level 22-high stress level
	RR interval	834	866			
	SDNN	57.32	33.67	Decrease		
	RMSSD	36.16	34.91	Decrease		
	LF/HF	1.07	1.08			
	SD2/SD1	2.61	2.75	Increase		
Subject-22	Pulse rate	83	81		2 min after ending audio-visual stimulus	Perceived stress level 13-average stress level
	RR interval	670	666			
	SDNN	44.97	37.67	Decrease		
	RMSSD	46.95	37.2	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.45	2.59	Increase		
Subject-23	Pulse rate	65	68		3 min after ending audio-visual stimulus	Perceived stress level 15-average stress level
	RR interval	784	870			
	SDNN	48.52	31.03	Decrease		
	RMSSD	26.28	27.02	Decrease		
	LF/HF	1.02	1.07			
	SD2/SD1	2.32	2.77	Increase		
Subject-24	Pulse rate	74	80	Increase	3 min after ending audio-visual stimulus	Perceived stress level 26-high stress level
	RR interval	706	640	Decrease		
	SDNN	60.86	47.26	Decrease		
	RMSSD	67.92	48.96	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.75	2.56			

(*Contd...*)

Table 6: (*Continued*)

Subjects	Parameters	Normal	Audio-visual stimulus	Impression	Recovery time	Ground truth as per perceived stress scale questionnaire
Subject-25	Pulse rate	84	74		2 min after ending audio-visual stimulus	Perceived stress level 19-average stress level
	RR interval	572	758			
	SDNN	50.39	35.63	Decrease		
	RMSSD	46.51	37.04	Decrease		
	LF/HF	1.02	1.04			
	SD2/SD1	2.57	2.34			
Subject-26	Pulse rate	84	86		3 min after ending audio-visual stimulus	Perceived stress level 18-average stress level
	RR interval	658	576	Decrease		
	SDNN	67.63	34.12	Decrease		
	RMSSD	58	21.59	Decrease		
	LF/HF	1.03	1.04			
	SD2/SD1	2.02	2.74	Increase		
Subject-27	Pulse rate	83	71		3 min after ending audio-visual stimulus	Perceived stress level 22-high stress level
	RR interval	684	762			
	SDNN	56.66	46.08	Decrease		
	RMSSD	65.3	40.41	Decrease		
	LF/HF	1.03	1.02			
	SD2/SD1	1.44	2.46	Increase		
Subject-28	Pulse rate	74	72		2 min after ending audio-visual stimulus	Perceived stress level 19-average stress level
	RR interval	778	758	Decrease		
	SDNN	53.3	44.51	Decrease		
	RMSSD	32.1	27.31	Decrease		
	LF/HF	1.02	1.07			
	SD2/SD1	2.07	2.85	Increase		
Subject-29	Pulse rate	64	68		3 min after ending audio-visual stimulus	Perceived stress level 16-average stress level
	RR interval	832	796	Decrease		
	SDNN	57.88	45.28	Decrease		
	RMSSD	64.53	33.9	Decrease		
	LF/HF	1.08	1.06			
	SD2/SD1	2.8	2.51			
Subject-30	Pulse rate	89	95		2 min after ending audio-visual stimulus	Perceived stress level 17-average stress level
	RR Interval	580	648			
	SDNN	48.41	21.31	Decrease		
	RMSSD	37.15	20.62	Decrease		
	LF/HF	1.04	1.05			
	SD2/SD1	1.8	2.35	Increase		
Subject-31	Pulse rate	89	82		2 min after ending audio-visual stimulus	Perceived stress level 15-average stress level
	RR interval	598	632			
	SDNN	45.64	38.89	Decrease		
	RMSSD	21.23	38.04	Decrease		
	LF/HF	1.04	1.05			
	SD2/SD1	2.13	2.55	Increase		
Subject-32	Pulse rate	71	69		3 min after ending audio-visual stimulus	Perceived stress level 24-high stress level
	RR interval	816	764	Decrease		
	SDNN	47.08	33.39	Decrease		
	RMSSD	42.37	39.22	Decrease		
	LF/HF	1.02	1.07			
	SD2/SD1	2.01	2.58	Increase		

(*Contd...*)

Table 6: (*Continued*)

Subjects	Parameters	Normal	Audio-visual stimulus	Impression	Recovery time	Ground truth as per perceived stress scale questionnaire
Subject-33	Pulse rate	76	77		7 min after ending audio-visual stimulus	Perceived stress level 28-high stress level
	RR interval	696	682			
	SDNN	45	20.78	Decrease		
	RMSSD	23.94	22.05			
	LF/HF	1.03	1.06			
	SD2/SD1	2.68	2.89	Increase		
Subject-34	Pulse rate	89	94	Increase	2 min after ending audio-visual stimulus	Perceived stress level 20-high stress level
	RR interval	612	600			
	SDNN	51.32	36.88	Decrease		
	RMSSD	48.42	26.47	Decrease		
	LF/HF	1.04	1.05			
	SD2/SD1	2.44	2.55	Increase		
Subject-35	Pulse rate	70	69		2 min after ending audio-visual stimulus	Perceived stress level 24-high stress level
	RR interval	884	820	Decrease		
	SDNN	56.83	49.41	Decrease		
	RMSSD	55.1	45.46	Decrease		
	LF/HF	1.02	1.08			
	SD2/SD1	2.45	3.01	Increase		

LF: Low frequency, HF: High frequency, RMSSD: Root mean square successive difference, SDNN: Standard deviation of the RR intervals

Table 7: Mean values of pulse rate variability parameters for 35 subjects

Parameters	Normal condition (Mean±SD)	Audio-visual stimulus (Mean±SD)	Ground truth
Beats per minute	75.66±8.20	76.66±9.78	As per perceived stress level questionnaire
RR interval	724.26±94.53	715.33±99.65	
SDNN	57.24±9.62	42.16±9.44	
Root mean square successive difference	49.55±14.55	35.44±10.85	
Low-frequency/High-frequency ratio	1.03±0.016	1.04±0.017	
SD2/SD1 ratio	2.36±0.47	2.60±0.42	

SD: Standard deviation, SDNN: Standard deviation of the RR intervals

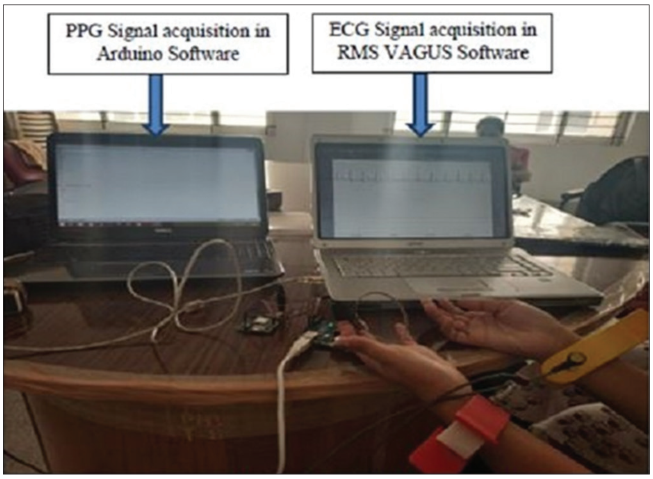

Figure 5: Validation of electrocardiogram with photoplethysmography signal

From Table 3, it is observed that the perceived stress scale score of the subjects is in the range of 13–19 so it is classified as average stress level.

Therefore, the PPG monitoring system serves as a substitute with existing system which deals with monitoring of stress based on HRV parameters through ECG signals.

CONCLUSION

A non-invasive PPG monitoring system has been designed and implemented to extract PRV parameters. This system offers flexibility to the user by replacing ECG electrodes with a single spot PPG sensor. Furthermore, real-time software has been developed to perform PRV analysis. The result obtained indicates a close accuracy achieved between PPG signal and

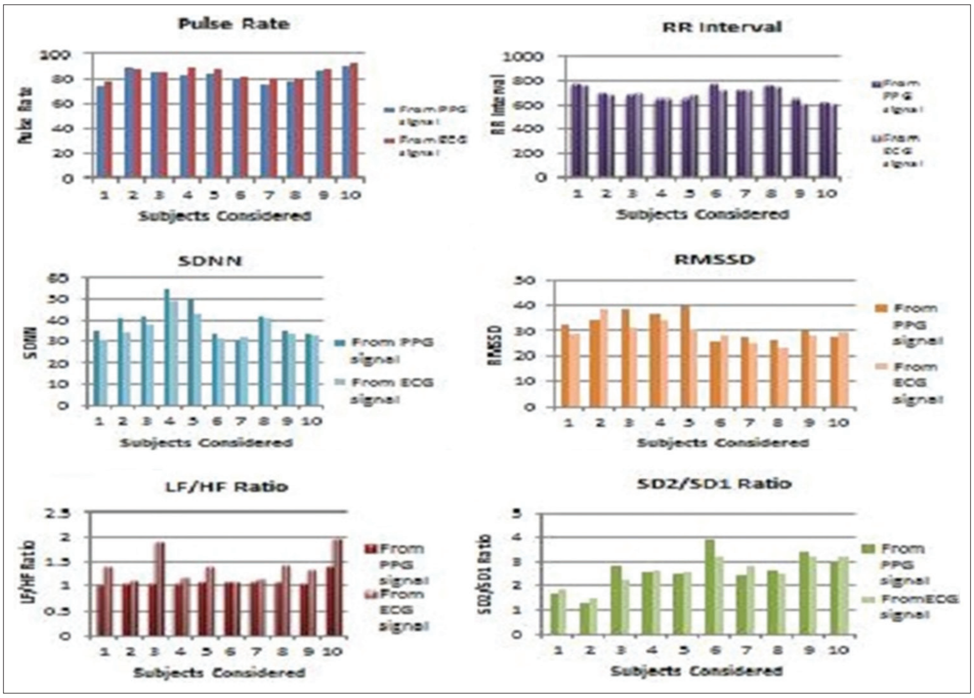

Figure 6: Comparison of photoplethysmography and electrocardiogram readings

ECG signal. Furthermore, with the development of Android app to display PRV parameters, it is easier to monitor the stress anywhere and anytime.

This system can be used to diagnose mental disorders in rehabilitation centers. This helps in providing relevant timely treatment. It is a very powerful tool in the field of psychiatry research for studying various psychiatric disorders. Furthermore, it can be used to quantify stress levels in traditional destressing treatments such as Yoga and allied holistic practices used to improve overall health and well-being.

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