Performance Evaluation of PPG Signal using Time-Frequency Features

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Abstract

The performance of photoplethysmograph (PPG) signals using time-frequency features has been evaluated in this study. The data were collected from 45 healthy subjects between the age group of 19-22 years. The photoplethysmograph is an optical measurement technique that can be used to detect changes in the blood volume in the micro vascular bed of tissue. Power Ratio (PR) is calculated from the power spectral density (PSD) of the acquired signal and it is used as an important parameter to classify PPG signal as normal or abnormal. Analysis of variance (ANOVA) is performed to eliminate null hypothesis and non significant values. A positive correlation coefficient is obtained for several features using the acquired parameters, several cardiac and respiratory abnormalities can be detected during prognosis.

1. INTRODUCTION.

Photoplethysmograph (PPG) signal is the representation of the volumetric changes in blood vessels[1].The principle of operation is based on registration of a useful signal by two possible methods, 1 - transmissive method: when light passes through the tissues, 2 – reflective method: when light is reflected by the tissues [2]. PPG signals originate by absorption of optical radiation by the pulsating blood volume and contain valuable clinical information. The plethysmographic signal can be acquired from finger, earlobes, forehead or toes of the leg with the help of photoelectronic transducers [3].

The pulsatile component of the PPG waveform is called the AC component and it has its fundamental frequency at around 1Hz. This AC component is superimposed on a large DC component that relates to the tissue and average blood volume. The DC component may vary due to respiration, vasomotor activity, vasoconstrictor waves and thermoregulation [4]. Qualitatively, the rising front and systolic peak corresponds to heart condition and activity, while the following part generally determines elasticity and the other features of vascular system. The rising edge of the pulse is defined as anacrotic phase and the falling edge as catacrotic phase [5]. The most comfortable location for the PPG sensor is the index finger of the hand because of the high signal strength [6].

Several time and frequency domain features are extracted for analysis of several body parameters. PPG signals are not strictly repeating and periodical as there are slight fluctuations in the signal amplitude, baseline and period. The PPG signal shape contains certain coded information regarding the cardiovascular and respiratory state of the subject and a detailed shape analysis eventually provides clinical data for early cardiovascular and respiratory abnormalities. A crest time measurement from the rising edge of the pulse waveform was derived on comparison of PPG to mechanical plethysmography in arteriopaths [7]. This crest time was prolonged for subjects with vascular disease or hypertension. The potential for extracting diagnostic information from the PPG has been reviewed [8]. Several time domain features such as peak to peak PPG rise time, peak-to-peak time (PPT), amplitude, shape and variability in these have been investigated.

Studies have shown that PPG signal has information about vascular mechanism. During apnea, vasoconstriction occurs and it is reflected in the PPG signal by a decrease in the fluctuation of amplitude. Heart Rate Variability (HRV) is an electrophysiological signal very broadly studied for apnea diagnosis. HRV exhibits frequency components from 0-0.5 Hz which are associated with the autonomic nervous system branches. Frequency components in the 0.15 -0.4Hz represent Vagal tone and these frequencies are known as High Frequency (HF) components. Frequencies from 0.04-0.15Hz manifest the activation of parasympathetic and sympathetic nerves and are labeled as Low Frequency (LF) components. The ratio between LF and HF is defined as the Sympatho-vagal balance [9]. In this work, detailed spectral analysis and time domain analysis has been carried out.

2. MATERIALS & METHODS.

2.1 SUBJECTS.

The study was performed in 45 healthy, non-smoking and non-athletic volunteers (25 Male and 20 Female subjects) without symptoms of cardiac or respiratory diseases. Consent was obtained from all volunteers before data was acquired.

2.2 DATA ACQUISTION.

The PPG signal was acquired using BIOKIT Physiograph(Version 4.1 Build 3), TekSys Electronics. The sensor used is LED and LDR, optical transmit receive type finger sensor (wavelength 940nm) with input impedance of 1MΩ and a gain of ×5K maximum. Frequency response was recorded at 2-40Hz. Casing includes PCB mounted transmitter and receiver in a Velcro belt. The PPG signal was acquired from the right index finger. Subject is made to sit in an upright position with the forearm placed in a relaxed position on the thigh. Care is taken to reduce motion artifact due to respiration. After a short resting period for stabilization, the PPG data was acquired for 5 minutes. It is to be noted that all the readings were taken under post-prandial condition about 30 minutes after food. During the procedure, the subjects breathed spontaneously at more than 12 cycles/min and the signals were recorded at 1000Hz sampling frequency. Room temperature was regulated at 28 degree Centigrade with humidity at 50%.

2.3 FEATURE EXTRACTON.

PPG has a lesser sophisticated morphology than other physiological signals and this also means peak detection of PPG relatively easy because there are few specific points. However, PPG could have an enormous baseline drift and wondering followed by physiological condition and movement, moreover it frequently happens. It was demonstrated that PPG contains fluctuation caused by respiratory and sympathetic activity, even arousal changes such as drowsiness causes PPG baseline wandering or drift[10]. These artifacts could be explained with the three major interferences of PPG, motion artifact, respiration effect and low perfusion. Baseline wandering can be removed using linear de-trending. Noise is removed by applying a digital FIR Band pass filter of the 8th order. Cut-off frequency ranges between 0.01-40Hz. This preprocessing helps increase the Signal to Noise (SNR) ratio. All these signal processing stages are implemented using MATLAB (The Math Works Co. MATLAB® version 7.0). Several features were extracted in the time domain for analysis of the normal PPG signal. The typical PPG signal is shown in the Fig.1 [11].

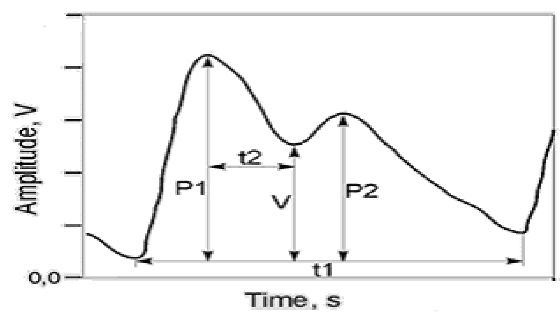

Figure 1 Typical PPG signal.

Stiffness Index (SI) is a measure of the arterial dispensability and is used to find out age related problems such as arterial stiffness. The Stiffness Index is calculated from the body height divided by the time delay between the pulse systolic peak and the inflection point of the reflection wave (units m/s) [12].

$$SI = \frac{Height\ of\ the\ subject(m)}{Peak\ to\ Peak\ Interval(s)}$$

The second time domain feature extracted is the Reflection Index (RI) [12]. The RI is found to fluctuate less under apnea condition. The equation for RI is given by

$$RI = \frac{Amplitude\ of\ P2(mV)}{Amplitude\ of\ P1(mV)}$$

Several frequency domain features were extracted for analysis of the PPG signal. Power Ratio (PR) is a bench mark parameter in evaluating the power distribution in the acquired signal[13]. The equation for PR is given as follows:

$$Power\ Ratio(PR) = \frac{PSD\ value\ in\ LF\ Band}{PSD\ value\ in\ HF\ Band}$$

LF power is both a quantitative marker for sympathetic modulations and sympatovagal activity [14]. HF power is considered to be a cardiac parasympathetic vagal nervous activity [15].

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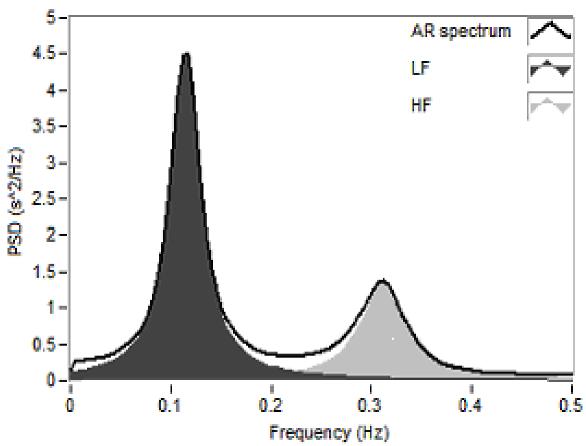

Fig. 2 Power spectrum density of PPG with the dominant LF and HF component being illustrated

Some other features used for analysis are Mean Peak-to-Peak Interval (PPI), width in the LF and HF bands, Power Cent Ratio (PCR) in the LF and HF bands have been obtained.

3. Results/Discussion.

The volunteers participating in this study have a mean age of 20.43 years(range 19-22) and the mean Body Mass Index(BMI) was 21.1977(range 19-25). The physical characteristic of the subjects from whom data has been acquired has been shown in Table 1.

Table 1. Physical characteristics of the subjects. All the subjects were within the 19-22 age group with Body Mass Index (BMI) in the normal range(19-25).

PARAMETER	MALE	FEMALE
Number of Subjects	25	20
Age(years)	20.7692±0.438	20.0909±0.8312
BMI(kg/m^2)	21.567±1.9724	20.8285±1.2808
Height(m)	1.737±0.0657	1.6045±0.0644

The acquired PPG signal was pre-processed to remove any motion artifact and baseline wandering. Peak detection algorithm was implemented. The raw PPG signal is shown in Fig 3.

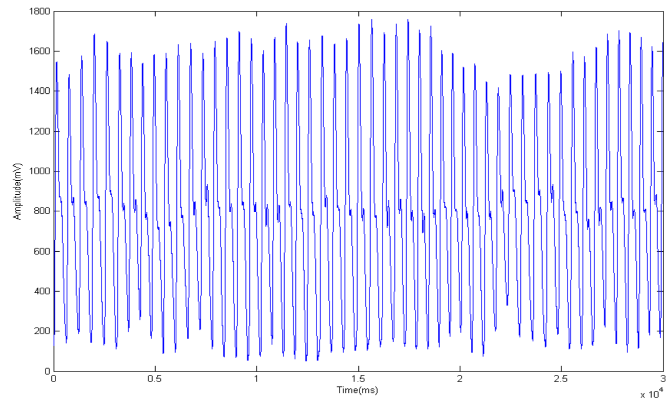

Fig. 3. Acquired PPG Signal

Peak P1 and P2 were detected and the PPT interval was calculated. Time domain features were calculated for all the subjects. The results have been shown in the Table 2. The pre-processed signal is shown in the Fig. 4.

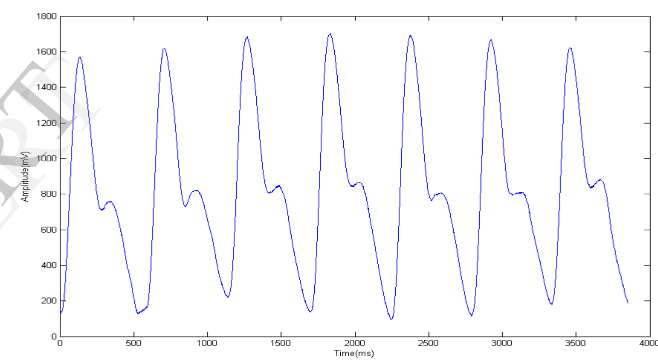

Fig. 4. PPG signal after preprocessing using FIR Band-pass filter of the 8th order

Peak detection algorithm has been implemented to detect the systolic peak and the reflected wave peak. Fig. 5 shows the peak detected PPG signal.

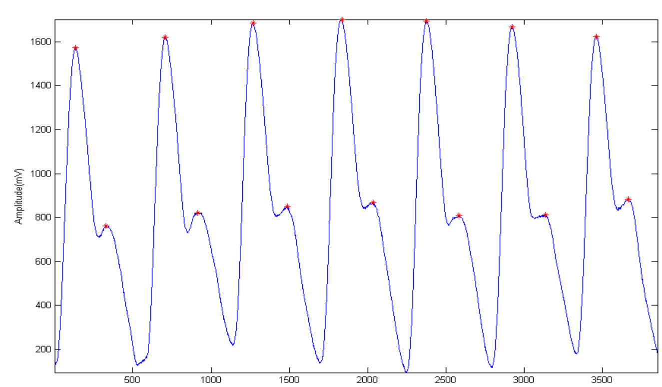

Fig 5. Peak detection for acquired PPG signal

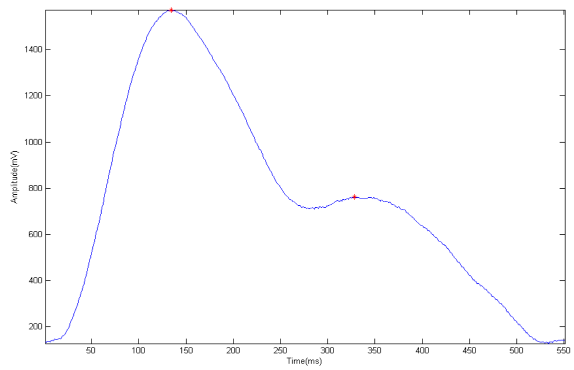

Fig. 6. Peak detection (The detected peaks are denoted by red dots)

The time and frequency domain parameters have been tabulated in Table 2 and 3.The Power Spectral Density of the normal PPG signal is shown in the Fig 6.

Table 2. The time domain parameters such as Peak to peak Time interval (PPT), Stiffness Index (SI) and the Reflection Index (RI) have been tabulated. The probability of variation (p value) for the corresponding parameters has been shown.

FEATURE	MALE	FEMALE	p
PPT(s)	0.2404±0.0273	0.29548±0.04	<0.05
SI(m/s)	7.1456±0.9044	6.5979±0.911	<0.05
RI	0.5148±0.1616	0.6074±0.138	<0.05
Mean PPI(s)	0.7918±0.0826	0.7832±0.080	<0.05

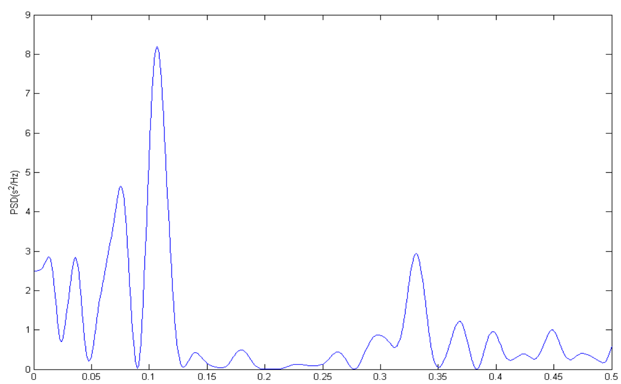

Fig. 7. The Power Spectral Density (PSD) of the normal PPG signal

Differences in the PPT, Widths in the frequency bands, PCR, ratios SI, RI and between multiple acquisitions were compared using the statistical program ANOVA (Table 2 and 3). This analysis tool performs a simple analysis of variance (ANOVA). The P column gives a P value (Probability value) for rejection of the null hypothesis that the parameter is zero (i.e. not a significant linear factor). The probability of variation (p value) for the corresponding parameters have also been shown.

Table 3. The frequency domain parameters -Power Ratio (PR) is the ratio between the powers in the LF and HF bands.

FEATURE	MALE	FEMALE	P
PR	2.1194±0.359	2.0963±0.2909	<0.05
Width in LF Band(Hz)	0.0486±0.08	0.0793±0.1187	n.s*
Width in HF Band(Hz)	0.0205±0.028	0.0315±0.0424	<0.05
PCR in LF Band	0.13±0.1163	0.1332±0.1350	n.s*
PCR in HF Band	0.0636±0.058	0.0553±0.0416	n.s*

*n.s – Not Significant

4. CONCLUSION.

In this study, the time and frequency domain parameters for a normal PPG signal acquired for a particular age group were investigated. The features extracted from the normal PPG gives a reference for further comparative study to diagnose clinical conditions.

This analysis is inexpensive and noninvasive means for studying changes in the elastic properties of the vascular system with the age and disease. PPG signal contains lots of physiological significances resulting in better clinical diagnosis. Objective assessment of vascular ageing is very important since arterial stiffness is associated with hypertension, a risk factor for stroke and for heart disease. The blood vessels tend to get stiffer during the aging process, the reflected wave returns faster and due to the summation of waves the resultant pulse wave changes. The interval between the first and second peaks changes and the amplitude of the second peak decreases, as a result, the pulse wave lacks a dicrotic notch and is more rounded in shape, because the reduced wave reflection. This condition can be diagnosed by studying the shape of the PPG signal.

There exists a positive correlation coefficient between SI-LFHF and RI-LFHF. Since SI is a direct indication to the clinical conditions of the cardiac system and RI to the respiratory system, PPG can be used to diagnose and evaluate cardiac and respiratory abnormalities. The use of time domain measures SI, RI, PR along with the frequency domain parameters mentioned above will enhance the accuracy of PPG analysis for clinical diagnosis. This work can be further enhanced by expanding the database and designing a neural network based automated classification system for diagnosing cardiac and respiratory abnormalities by extracting the time and frequency domain parameters from the PPG signal.

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