Estimation of heart rate variability from peripheral pulse wave using PPG sensor

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Abstract – **Heart rate variability (HRV) analysis is gaining acceptance as a potential non-invasive means of cardiac assessment in clinical as well as research domains. Although it is a standard practice to derive HRV from the R-R peaks of electrocardiogram (ECG), there have been attempts to deduce it from peripheral pulse wave signal. HRV is measured using photoplethysmographic (PPG) pulse wave signal in this work. A versatile algorithm governed by the physiology of the cardiovascular system developed by the authors is used to derive peak intervals from the PPG signal. In addition to normal time and frequency domain techniques, sequential trend analysis (STA) is applied to analyse HRV. Out of 20 subjects monitored, the results of three, one healthy and two with known cardiac problems, are presented and discussed. In all cases monitored, the results of HRV deduced from PPG are in tune with clinical picture of the subjects. The usefulness of STA in the analysis of HRV is also discussed.**

Keywords – **Heart rate variability, Photoplethysmography, Sequential trend analysis, Vagal, Sympathetic.**

I. INTRODUCTION

Heart rate variability analysis is fast emerging as a noninvasive research and clinical tool for assessing cardiac and autonomic nervous system function [1]. Hon and Lee [2], in 1965, first noted that fetal distress was preceded by alterations in inter beat intervals. HRV analysis is based on the fact that heart beat is not absolutely regular even in healthy subjects. Heart rate and its embedded rhythm are governed basically by sinoatrial node, which is influenced by autonomic nervous system. Vagal and sympathetic nervous systems constantly act to regulate the heart and circulatory system [3].

Usually HRV is analyzed in time and frequency domains using the variations in successive R-R intervals taken from electrocardiogram (ECG). However, various workers have explored the use of photoplethysmographic signal for the study of heart rate variability. Teng and Zhang [4] found that variability of peak intervals in PPG and R-R intervals in ECG was almost same. Further, it was reported that the LF component of HRV spectra in resting position was almost same whether it was estimated using peak intervals from PPG or R-R intervals from ECG [5-7]. These studies point to the possible use of PPG signal for HRV estimation.

Reduced HRV indicates the blunted autonomic nervous system and is associated with patients having chronic heart failure. Frequency domain techniques use the power spectral distribution of HRV, which gives insight into the health of vagal and sympathetic nervous system [8]. In this background, the present work is aimed at deriving HRV from PPG instead of ECG. Further sequential trend analysis is applied to HRV along with frequency and time domain techniques.

II. METHODS

A. PPG Sensor and Data Acquisition

In photoplethysmography red light using a LED (KLSL 3228 SR, 660nm) is allowed to pass through the finger and the transmitted light is detected by a photodiode. The pulsations in arterial blood modulate the transmitted light owing to the absorption of the red light by hemoglobin. When the blood in the artery is at its peak the absorption of light passing through it is also high keeping the transmitted light minimum. Between the pulsations when the blood recedes in the artery, the absorption of the light is also minimum and a peak is produced in the transmitted light. The transmitted light is detected and amplified by OPT101, which combines photodiode with a transimpedance amplifier in a single IC. The output of OPT101 is inverted to make the peaks in the signal correspond to the peaking of arterial blood due to left ventricular contraction. It is pertinent to take note of the fact that the ventricular contraction starts immediately after the R peak of ECG. This signal is acquired with a DAQ card, PCI 6014 of National Instruments, having 16-bit resolution and 200 KHz bandwidth. The signal is band limited before it is acquired by a Butterworth filter of third order with a low frequency limit of 0.4 Hz and high frequency cutoff at 5 Hz, to minimize the effect of noise and motion artifacts. The acquired signal is processed using LabVIEW7.1. The heart beat intervals, which are traditionally obtained by taking R-R peaks from ECG, are obtained here by calculating the time interval between the peaks in PPG signal. PPG signals are recorded for 2-minutes on each subject, resting comfortably in sitting posture, using index finger. The data base consisted of 20 volunteers between the age of 23 to 59 years.

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B. Signal Processing and Analysis

A versatile algorithm developed by the authors based on the physiology of the cardiovascular system is used to identify the peaks and determine the intervals between them. The algorithm uses moving averages combined with multi-looping until all the dicrotic notches, ectopic pulses and peaks due to noise are eliminated. The algorithm was thoroughly tested and validated. The successive pulse intervals obtained from PPG signal are used to get tachograms where beat intervals are plotted against beat number. FFT is used to extract the power spectral density of HRV in each case. The statistical parameters such as mean and standard deviation are also computed. In addition to the above, sequential trend analysis (STA) of HRV is also carried out. In STA, the differences among successive beat intervals are plotted with Δt_n on one axis and Δt_{n+1} on the other. Δt_n gives the difference in heart beat intervals of n-1 and nth beats and Δt_{n+1} gives the difference in heart beat intervals of nth and (n+1)th beats. This plot has an advantage that it clearly segregates the moments that increase the heart rate and those which slow down it. Thus it separates the vagal tone from sympathetic activity and displays them separately in -/- and +/+ quadrants respectively. Whereas the other two quadrants -/+ and +/- show the transitions from vagal to sympathetic and vice versa. The number of points in each quadrant are calculated in absolute and percentile terms.

III. Results

Tachograms, power spectral density and STA plots of HRV along with PPG signal are given in Fig. 1, 2 and 3. Fig.1 gives the HRV of a young & healthy subject of 27 years age, while the Fig.2 pertains to a 53 year old subject with known heart problems. The HRV of a 43 year old patient with diabetic neuropathy is given in Fig.3. Table1 lists together the mean, standard deviation along with the percentile of points falling in each quadrant from STA plots, for all the three subjects.

IV. Discussion

The power spectral density of HRV from Fig. 1, 2 and 3 clearly show the two standard peaks, one in the LF (0.04 to 0.15 Hz) and the other in HF (0.15 to 0.4 Hz) regions. The LF peak in Fig.3 is much lesser signifying the reduced HRV due to diabetic neuropathy in subject 3 as against the normal LF peak of young and healthy subject in Fig.1. The conspicuous absence of LF peak in Fig.2 is reflective of the heart condition of subject 2 who is a known cardiac patient. Regarding HF peaks, it is prominent only for subject 1 and much less for subjects 2 and 3. These results are in tune with the findings of Daunping Liao et al [9] who reported the association of lower HRV among the diabetic patients developing coronary heart disease. Further, Phillippe van de Borne et al [10] identified near absence of LF component among heart failure patients. The HRV results of remaining 17 subjects are also consistent with their clinical picture.

The plots of STA exhibited distinct patterns for each of the three subjects. While it is closely clustered for subject 3 indicating lower HRV, the points are well spread in subject 1. The pattern for subject 2 is interestingly quite different from the other two and is indicative of frequent switching between vagal and sympathetic activity. The specific advantage of STA is that even if some errors crop up in the beat to beat interval data owing to noise, artifacts or ectopic beats they simply get scattered in the plot and do not affect or alter the character of the overall trend/result. Whereas in case of frequency domain analysis the presence of even one or two such errors will drastically change the power spectrum of HRV rendering it unusable.

Although ECG provide much more insight into the problems of the heart, the PPG based HRV can be used as a preliminary screening tool for large populations with increased risk of heart problems such as due to smoking, alcohol consumption, diabetes and genetic heredity. This is because PPG method is simple to use and takes much less time. Further, it does not require any electrodes. Even semi skilled workers can handle it. However, more investigations are needed to understand the influence of pulse transit time on pulse intervals of PPG.

Table 1

	Subject 1 Normal Age: 27 yrs	**Subject 2 Heart Patient Age: 53 yrs**	**Subject 3 Diabetic Age: 43 yrs**
Mean Interval	0.5848	0.5035	0.6087
Standard Deviation	0.0145	0.0084	0.0095
Percentile Fraction of points in +/+ quadrant	0.25	0.125	0.212
Percentile Fraction of points in -/+ quadrant	0.275	0.393	0.256
Percentile Fraction of points in -/- quadrant	0.193	0.081	0.262
Percentile Fraction of points in +/- quadrant	0.275	0.393	0.275

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