Design and Validation of an Optical and USB-Powered Device for Heart-Rate Measuring

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A portable and low-power device is a great importance to heart-rate (HR) monitoring in medical practices. Due to usage electrode in contact with patient's body, nowadays Electrocardiograms (ECG) lead to discomfort for patients. Meanwhile, the another device such as Pulse Oximeters only give the HR numbers, without the displaying of signal, so that it can't used for importance of the bio-signal analysis. In this paper, the optical and USB-powered device to the HR monitoring has been designed and developed. The process of monitoring was carried out based on the detection of the optical absorbance of blood vessels due to heart's pump activity in fingertip's patient. In addition to as communication to a personal computer (PC), USB system was also used as a component to provide the power for the device. The programmed software was used to generate the spectra and determine the HR of the obtained signal. Twenty of measurement data of healthy volunteers, aged 19 to 57 years were obtained and validated by a commercial Pulse Oximeter. The correlation analysis and Bland-Altman plot show that the HR measured by both devices are positively correlated and most of their differences within the limitation of confidence interval.

Keywords: Validation, Optical, USB-Powered, Device, heart-rate, monitoring

1. Introduction

The word plethysmography comes from the two Greek words 'plethysmos' (increase) and 'graph' (written). Photoplethysmography (PPG) is a non-invasive technique used optically to obtain arterial blood volume changes in blood vessels close to the skin surface (e.g. at the fingertips or earlobes) [1]. The major use of PPG in medical practice is the Pulse-Oximeter, which measures the arterial oxygen saturation in human bloods and heart rate (HR). The principle is based on the fact that spectra of oxy and de-oxyhemoglobin have different absorption at the wavelengths of 660 nm (red light) and 905 to 940 nm (infrared light) [2]. Pulse Oximeter has many advantages over other techniques such as the use inexpensive optical sensor (e.g., LED and photodiode), non-invasive, safe, and easy-to-use properties. The simple configuration of PPG consists of an infrared or red LED as a light source and a photodiode as a light detector placed in a small probe package or optical probe.

Currently, much research effort has been directed to the analysis of the PPG signal waveform obtained from a single pair of infrared light and photodetector [3]. In general, the PPG signal contains useful information for cardio-vascular assessment [4], skin microcirculation analysis [5], diabetes mellitus diagnostic [6], respiration rate determination [7,8], and etc. Use the only infrared LED has been considered to be adequate for importance of the PPG signal analysis requiring no the red LED, such as the principle of the pulse oximetry. The measurement of PPG signal depends on the fact that blood absorbs infrared light many times more strongly than the remaining skin tissues [9].

Due to need low cost, simple, low-power, and portable technology, the PPG method has been the object of extensive research in the later decades. Therefore, in this paper a simple, portable, low power, and computerized device has been designed and developed for the heart rate (HR) extraction through the processing of PPG signal. The demand of low power device is provided by USB-powered requiring no external power adaptor. The designed device uses commercial of the near-infrared (NIR) LED (905 nm in wavelength) as a light source and the photodiode as detector. Use NIR LED has several advantages, as such penetrating more depth in tissue than the red LED [10], compact, and small size. The low cost of the microcontroller is programmed to acquire the PPG signal using its embedded analogue to digital converter (ADC). The data acquisition of PPG signal is gathered and controlled by a personal computer (PC) for the importance of advanced signal processing. Therefore, the designed and developed device can be potentially more sensitive, low power, simple and portable. In addition to the heart rate extraction, the device can also display the waveform heart signal (PPG signal), which useful for the advanced analysis of heart activity.

2. Subject & Methods

Principle of PPG relies on the change in light absorption due to blood arterial pulsations. In a typical configuration, light at near-infrared wavelength illuminating one side of tissue (e.g., a fingertip) will be detected on the opposing side (transmission mode) after through the vascular tissues between the light source and the photodetector. When a fingertip is simplified as a hemispherical volume, the detected light intensity is described by the Beer-Lambert law as follow:

$$I = I_0 e^{-(\mu_T L_T + \mu_V L_V + \mu_A L_A)} \quad (1)$$

where I_0 is the incident light intensity, I is the light intensity detected by the photodetector, and μ_T, μ_V, μ_A and L_T, L_V, L_A are the absorption coefficients and optical path length of the bloodless tissue layer, the venous blood layer, and the arterial blood layer, respectively [13]. The heart's pumping action generates arterial pulsations that result in relative changes in arterial blood volume, which adds an "AC" (pulsatile) component to the detected signal intensity by photodetector. These detected signal is called as photoplethysmography signal (PPG signal). The PPG signals can be commonly used to obtain vital physiological information as such blood oxygen content, cardiovascular activity, and respiratory patterns [5].

Fig.1 shows a graphical representation of the detected PPG signal. The amount of light absorbed by the tissues contains two significant aspects. The first is the constant absorbance, or DC component, influenced by the non-vascular tissues and the residual arterial and venous blood volumes. The second is a modulated absorbance, or AC component, caused by the variations in arterial blood volume. Together, they affect the amount of light that illuminates the photodiode (PD) to produce a pulsatile waveform.

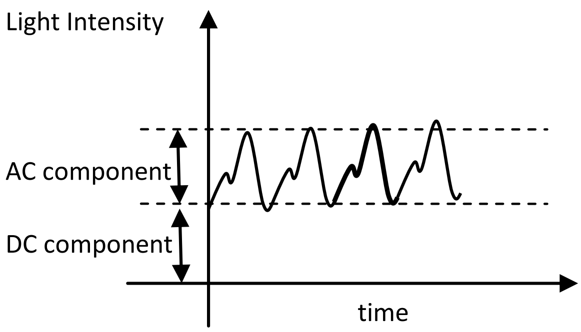


Fig.1 Graphical representation of PPG signal

The functional block diagram is shown in Fig. 2. A PPG experiment setup consists of three main units: an optical probe, an electronics module that hosts an analog amplifier, signal conditioning element, and microcontroller, and a personal computer (PC) that receives, processes, displays, and stores data from the circuit module. Basically, the experiment consists of a near-infrared transmitter (NIR) LED and a sensor photodiode, and then both are clipped on one of the fingertips of the volunteer (subject) in the package of the optical probe. The LED emits near-infrared light beam (optical signal) to the fingertip of the subject. The photodiode detects the transmitted light beam and measures the change of blood volume through the fingertip artery due to the heart activity. The detected signal by the photodiode is called as analog of PPG signal and then it is fed to electronics circuit module based on a microcontroller for the ADC (analog to digital converter) process. The digital of PPG signal is sent to PC through the USB system. And then, the software is programmed to the controlling experiment, processing, and displaying the signal in the computer screenshot. So, the designed device is computerized in system.

A screenshot software for single-channel of PPG signal measurement has been developed and written using Delphi Visual Program. The software consists of four part namely for data acquisition, processing, storage, and display for the PPG signal in a PC screenshot monitor. The signal processing parameters such as, DC offset; the filtering data, and FFT spectral of signal were also provided in the developed software.

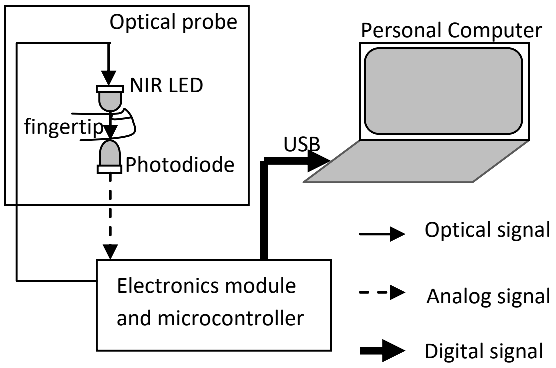


Fig. 2. Functional block diagram of experimental setup

Fig. 3. Photograph of the electronics circuits module

In addition to as tool of communication with a personal computer, the USB system is also designed to provide the power supply of the device so that the requiring no any external power supply. The users are just plug into the USB ports in PC. Thus, the designed and developed PPG device propose a device of low energy (USB-powered), simple (just plug), portable (lightweight), and cost-effective. The designed device is also compatible for importance of the mobile research.

Photograph result of the electronics module based on microcontroller ATmega 16 is shown in Fig. 3. Meanwhile, the photograph of the experimental setup is shown in Fig. 4. It consists of the fingertip probe, electronics module, and personal computer (PC). The probe contains a near-infrared (NIR) LED as a light source and a photodiode as the photodetector. The subject of fingertip is clipped between them in the probe system. The operation of the electronics module is based on microcontroller ATmega16 to process the data acquisition. The communication to PC is designed through USB system.

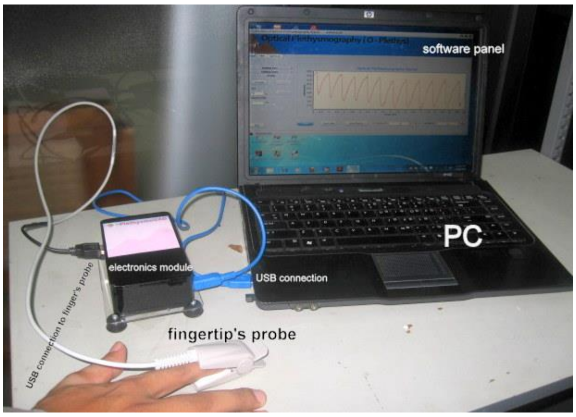


Fig.4 Photograph of experimental setup

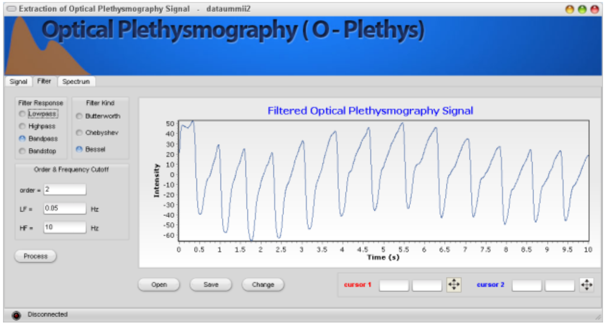
The performance of designed and developed device is tested on 20 fingertips of healthy volunteers, aged 19 to 57 years. A volunteer was seated in a comfortable seat. The measurement protocol was used as follows: each subject in sitting condition, right hand, was placed on the table, each volunteer was asked to relax and to take the most comfortable position, and the fingertip probe was attached to the right index fingertip. In order to keep the finger relatively motionless, the data acquisition process was carried out for short time measurement (10 seconds). The stable measurement is importance to reduce any noise (artifact) on the obtained signal [10]. The next, a commercial of Pulse Oximeter instrument was used to measure the heart rate (HR) of volunteer as comparation of measurement.

3. Results and Discussion

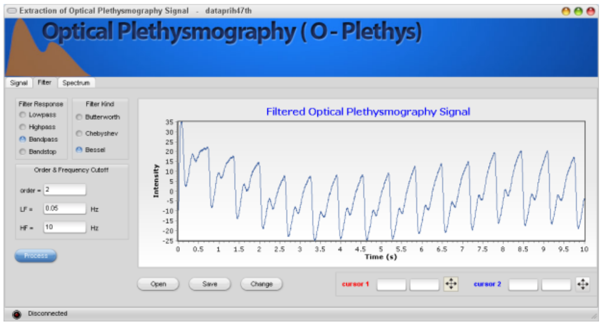
Example of the testing results are shown in Fig.5 for (a) female 41 year old and (b) male 47 year old, respectively. The PPG signal is gathered by software in time setting for 10 s and sampling rate 2 ms. In the figure show that the 'AC' component (pulsatile) of extracted PPG signal is clearly determinated. Peak to peak of PPG signal pulse represents a heart's pump activity in human blood system. Therefore, the PPG signal can be used to obtain vital physiological information as such blood oxygen content, cardiovascular activity, and respiratory patterns [9].

To reduce the noises, a 2rd order band-pass Butterworth filter with a cut-off frequency of 0.05 Hz (low frequency) to 10 Hz (high frequency) embedded in the software was applied to the obtained PPG signals. In addition the removal of either noise of low frequency or high frequency, the another objective of these filter application is to get the heart frequency (heart rate) range from the PPG signal. To get the heart frequency (heart rate) of the PPG signal, the embedded Fast Fourier Transform (FFT) algorithm in the developed software was applied to the filtered PPG signal. The frequency corresponding to heart rate can be detected as a dominant peak from the spectral of PPG signal.

Fig. 6 shows the results of FFT spectra associated with time domain of the filtered PPG signal in Fig.5. It can show in Fig.6 that the dominant (magnitude) peaks were achieved consistently in the frequency range of heart rate where in the healthy adult subjects the frequency heart rate about 1 – 1.5 Hz [11]. So that, the heart rates obtained using PPG device are about 1.22 Hz x 60 = 73.20 = 73 BPM (beat per minute) of Fig.6a, and 1.59 Hz x 60 = 95.40 = 95 BPM, respectively.

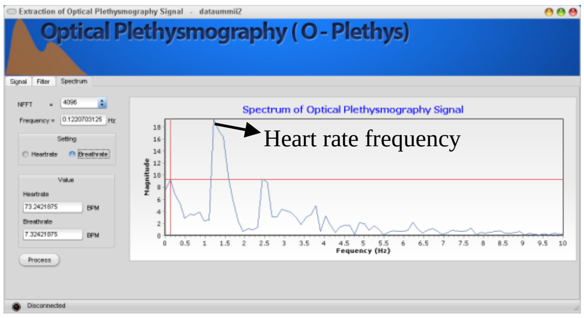


(a) female 41 year old

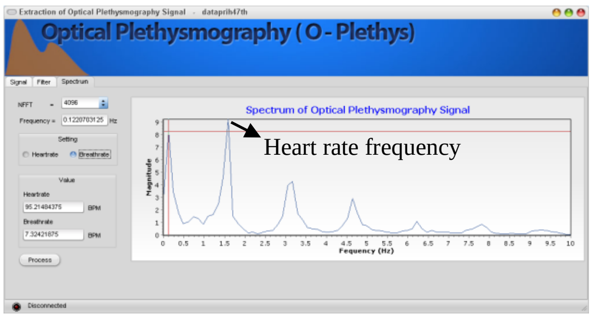


(b) male 47 year old

Fig.5 Example of the PPG signal obtained by device



(a) female 41 year old



(b) male 47 year old

Fig.6 Frequency spectra of the filtered PPG signals

A. *Statistical Validation*

In this paper, the obtained heart rates (HR) using PPG device will be statistically validated with respect to the obtained HR using a commercial Pulse Oximeter as gold standard instrumentation. As known, the value of oxygen saturation and HR are mainly displayed in commercial Pulse Oximeter without included the waveform PPG signal. Two statistical tools used to validate such comparation between two measurement HR will be presented and discussed.

Firstly, the correlation method is used to ascertain the nature of the relationship between the two HR measurement. A scatter plot of the measuring results of both devices is shown in Fig.7. It shows that the designed PPG device is comparable to the Pulse Oximeter commercial as a monitor of heart rate. In view on correlation analysis of the measured HR using both device, it can be shown that the HR data is positively correlated (R = 0.9832). The corresponding coefficient of determination (R^2) is 0.9667. These results show that the correlation between the measured HR by both the designed PPG device and Pulse Oximeter are almost perfectly linear.

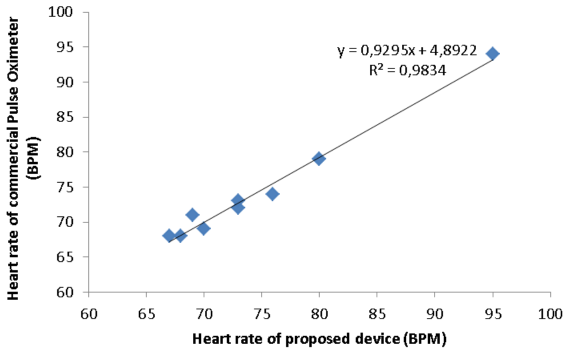


Fig. 7. Scatter plot for heart rate measured by both devices

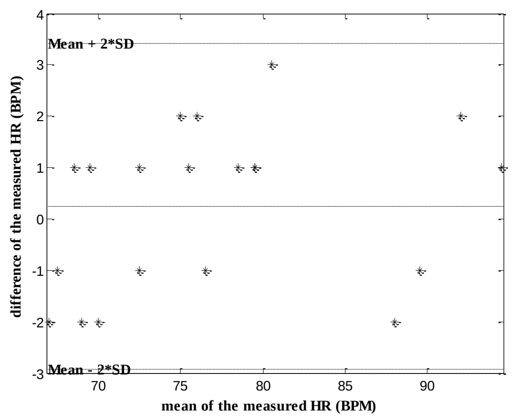


Fig. 8. Bland-Altman plot of the HR measured by both devices

Secondly, Bland-Altman test is used to determine the limits of agreement for the errors between the two HR measurement [12]. The Bland-Altman analysis is plotted as shown in Fig.8. This analysis plots the difference (error) between the two heart rate (HR) measurement with the respect to means between the two HR measurement. Assuming that the mean difference between the devices is normally distributed, 95% confidence interval can be calculated at Mean ± 2*SD, where Mean is mean of the difference of two HR measurement and SD is the standard deviation between the difference of two HR measurement.

The plot in Fig.8 shows that the most of differences between the two HR measurement within the limitation of confidence interval. It indicates that the HR measured by the designed PPG device through the FFT spectra of PPG signal are in good agreement with that by the Pulse Oximeter commercial. Thus, the displayed PPG signal in the designed device is accurately believed to be representative of heart activity.

7. CONCLUSION

A simple, USB-powered and computerized device of plethysmography based on optical detection has been successfully designed, developed, and tested to extraction the heart rate (HR) of PPG signal on fingertip of healthy volunteers. Due to the use a Near-infrared-LED, microcontroller as a main part of electronics module, and USB-powered, the designed device introduces simple, low power, and portable. The results of statistical validation show that the HR measured by both the designed device and a Pulse Oximeter commercial are positively correlated and no significant of the difference. So, the PPG signal obtained by the designed device is accurately believed to be representative of the heart activity of healthy volunteer. The validation of statistical method supports that the designed device can potentially be developed as a simple, low power, and portable device for the importance of biomedical research (mainly for processing biomedical signal) and clinical practices.

ACKNOWLEDGMENT

The authors would like to give their sincere thanks to DIKTI Depdiknas for finance supporting of Hibah Bersaing Grant 2012. The authors also would like to thank Mas Danu T for assistance in experimental set up process

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