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A review of Photoplethysmography Based Measurement of Blood Pressure and Heart Rate Variability

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Abstract

Photoplethysmography (PPG) is a simple optical measurement technique used for blood pressure and heart rate monitoring. PPG signal and its derivative contain important health-related data which is used for the detection and diagnosis of cardiovascular diseases. High blood pressure is a cause for various physiological changes and leads to the cause of death throughout the world. Heart Rate Variability (HRV) is also an important factor for diagnosing cardiac disorders and to analysis the physiological conditions of human body. The growth of signal processing techniques, has opened the door for the development of cuff less and continuous monitoring of heart rate variability and blood pressure from the PPG signal. This article describes some of the current developments and challenges of PPG-based heart rate variability and blood pressure monitoring technologies .

Keywords: Photoplethysmography • Heart Rate Variability • Non-invasive • blood pressure • systolic peak • diastolic peak

Introduction

Blood Pressure (BP) and Heart Rate (HR) are the risk factors for serious diseases including cardiovascular diseases such as stroke and heart attack [1]. Hypertension (BP) and heart failure are the leading cause of death throughout the world. Hence, BP and heart rate variability(HRV) must be monitored regularly for early detection and treatment of stroke, cardiovascular diseases and hypertension screening. In the existing methods, the BP and HRV are measured from pervasive monitoring mechanism like Sphygmomanometery and electrocardiography, which require inflatable cuff and a series of electrodes attached to the body. Research has also adopted photoplethysmography (PPG) for the development of wrist-worn sensing smart watches and fitness trackers. PPG is a non-invasive optical technique for measuring the blood volume changes per pulse. It utilizes the low-cost, portable pulse oxi-meter which illuminates the skin and measures the blood volume changes in the microvascular bed of tissue [2]. For the invasive measurement of PPG signal, PPG sensors are designed in two types of modes namely transmission and reflectance. The PPG sensor consists of a Light Emitting Diode (LED) and a photo detector. The LED emits light to illuminate the skin surface and the photo detector measures the changes in light absorption over a period of time. PPG signal is described by two components, one is pulsatile (volume pulse) component and the other is baseline (blood volume) component. Accordingly PPG signal containing alternating current (AC) components, which contain information regarding the arterial blood pulsation, and direct current component(DC) caused by various factors such as respiration, constant flow of arterial and venous blood and absorption from non-vascular tissue.

The heart pumps blood to the periphery for each cardiac cycle. PPG sensor emits light to the skin and measures the intensity of light which is reflected back or transmitted through the skin as shown in Fig 1. Change in arterial blood volume causes a variation in PPG signal depend on the amount of blood rushing into the vascular bed, the optical absorption of blood, skin pigmentation, ambient light and its wavelength.

As the volume of blood changes with the cardiac cycle, the light intensity also changes with the cardiac rhythm, which can be employed to extract heart rate (HR) information. PPG has been used for determining heart rate, atrial stiffness, blood oxygen saturation, blood glucose levels as well as measuring blood pressure(BP). The objective of this paper is to review PPG based BP and HR measurement utilizing machine learning algorithms. The paper is organized as follows.

We first begin by providing a summary of the BP machine learning based methods available in the literature and their limitations in section II. This is followed by HR estimation algorithms in Section III. Discussion of the works and their challenges is given in section 1V. Finally, section Vconclude this paper by providing some suggestions for future research directions in this field.

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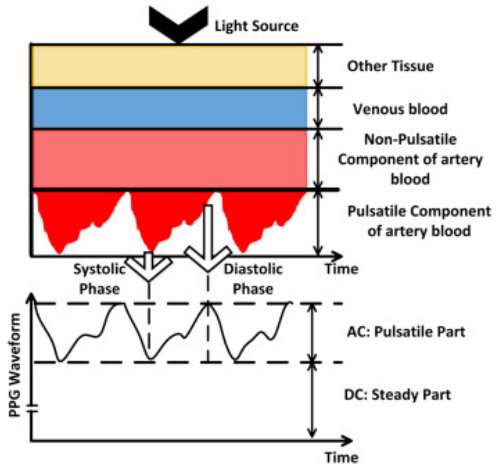

Figure 1. Variation in light attenuation by tissue.

Non-invasive PPG based BP measurement

The current non-invasive gold standard for the measurement of blood pressure (BP) is the oscillometric cuff at the upper arm. The cuff method measures the blood pressure after a set interval, results in discrete measurement and inconvenience for patients due to cuff inflation and deflation. Arterial lines management is an invasive procedure that allows for continuous blood pressure monitoring. However, the invasive procedure leaves the patient vulnerable to infection. Hence, there is a need for a noninvasive, cuff-less, continuous BP monitoring system. photoplethysmography (PPG) is the more realistic approach to overcome these difficulties PPG signal has three distinct features namely systolic peak, diastolic peak, and a notch in between. as shown in Figure 2.

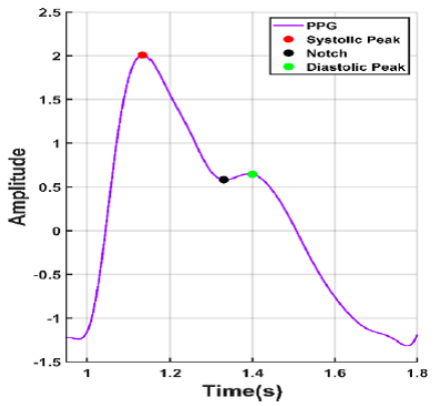

Figure 2. PPG signal with three peaks.

The photoplethysmographic wave describes changes in the attenuation of light energy in its pathway when transmitted or reflected light passes in tissues and bloodstream. This waveform is totally related to the systole and the diastole of the cardiac cycle. The PPG signal represented in Fig. 3 is extracted from a healthy person.

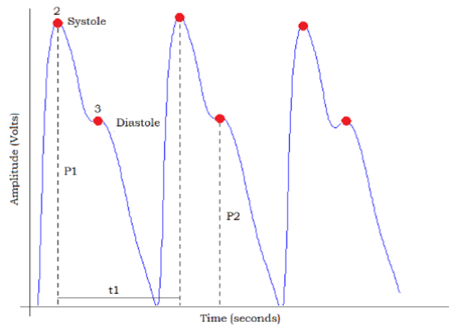

Figure 3. PPG signal from healthy person.

It is possible to estimate some parameters, such as the amplitude of the systole pulse wave, amplitude of the diastole pulse wave, time interval between beats etc. Heart rate and blood pressure can be calculated from the this. The increase in heart rate and pulse wave amplitude with number 2, reflects the growth of blood flow in the signal due to contraction of the left ventricle of the heart. The amplitude of the dicrotic minimum is represented with number 3, varies with arterial vascular elasticity and depends on the interaction of the initial pressure wave, when the heart contracts, and with the pressure wave that is reflected due to peripheral arteries. The commonly used method for analysis of the PPG signal is to detect its peak values, corresponding to the systolic phases of the cardiac cycle, and register the time passed between maximum PPG successive values. Several techniques to estimate BP from PPG were proposed in the recent works namely characteristic of the pulse, linear regression model, neural network and deep learning models [2].

Characteristic of the Pulse

Biometrics of PPG incorporate waveform analysis and estimation of BP. Bio-inspired mathematical model was proposed in the literature to predict estimating systolic BP (SBP) and diastolic BP (DBP) through careful mathematical analysis of the PPG signals. Pulse Transit Time (PTT), Pulse Arrival Time (PAT) and pulse wave velocity (PWV) are the characteristics of PPG wave used to estimate the BP. PTT based approach is a cuff-less non-invasive BP measurement method. PTT is the time delay for the pressure waveform to travel between two arterial sites (between the proximal and distal PPG waveforms). There is a inverse correlation between BP and pulse transit time. Common sites for PTT measurements are fingers, ears and toes. PTT can also be measured as the time difference from mid-point of the falling edge of the proximal PPG to the peak of the peripheral PPG. Pulse Arrival Time (PAT) is the time difference between the peak of the PPG signal within the cardiac cycle, indicate the pressure wave propagation in the blood vessel. It is the time interval between the electrical activation of the heart and arrival of the pulse wave at a location on the body like the finger, toe, and forehead. Although PAT is simple, it reduces the diastolic pressure accuracy. During contraction(systole) and expansion(diastole) of the ventricle blood is pushed from central arteries to smaller arteries. This changes the potential of the vessel wall , which in turn affects the velocity of the pressure pulse. Pulse wave velocity is measured by dividing the distance between the two artery points by pulse transit time proposed a method to determine the continuous PTT by calculating consecutive time delays of photoplethysmography (PPG) waveforms. The average time delay is determined by moving the segmented PPGs. This method overcomes PPG waveform uncertainty by omitting feature detection step. Once PTT, PAT or PWV parameters are estimated, BP can be derived through mathematical models. All these methods require two synchronized sensors with different sampling rates. Also require signal processing techniques to remove the motion artifacts occurs during signal acquisition in the sensors. For continuous measurement of BP, these methods requires per person calibration. The arterial potential varies between individuals [3].

Linear regression model

Selected four PPG features(width at 1/2 and 2/3 amplitude, systolic time and diastolic time) and find the relationship between arterial BP and PPG using a linear regression model. The correlation between the extracted features and BP were evaluated, and only features with the highest correlation to BP are selected for regression analysis. Diastolic time has a higher correlation with Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP) than other features. Mean square error and standard deviation between estimated BP and the reference BP are low. However two different models are required for estimating SBP and DBP design a more generalized model for accurate BP monitoring. They derived a regression model for estimating SBP without the need for calibration for every individual subject investigated the correlation between BP and PTT under different circumstances (pre and post-exercise) using least-square regression. The regression coefficient obtained is failed to predict BP well in all subjects when the blood pressure values changed. The mean error and standard deviation are high due to the change of blood pressure baseline between different subjects. Also, this model cannot estimate both SBP and DBP simultaneously and requires two different models. Two sensors are required for measuring the PTT parameters proposed a beat-to-beat BP estimation method using a combination of data mining techniques and a mechanism-driven model. The features are extracted from first and second derivative of PPG and ECG signals. Features with highest influence on SBP and DBP estimation for each subject are selected using genetic algorithm. A multi-variate linear regression (MLR) and support vector regression are established to evaluate the effectiveness this method. The error of the proposed models deteriorates and stabilized after long calibration periods. Moreover, their method requires two sensors, and not suitable for handling time series data for continuous BP estimation measure the Pulse Transit Time (PTT) between two separate photoplethysmogram (PPG) signals to estimates SBP and DBP based on a linear regression model [4]. The BP is estimated from the time difference between the peaks of the PPG signals from the index fingers of each participant. Environmental and physiological noise gathered during the experiment is minimized by applying filtration and smoothing on the PPG signals. Error rates of this method are lower than accurate BP estimation standard. However, two smartphones are acquired to capture the PPG signals from the fingertips of the left and right hands to evaluate the accuracy of the PTT and BP estimations. Ruiz-Rodriguez et al. Proposed[39] two specific methods to determine mean arterial blood pressure (MABP), SBP and DBP. The first method(initialization based method) needs an initial value of blood pressure along with PPG signal acquisition. The second method uses a learning based non-parametric regression technique without requiring any prior information.

Neural network model

Since DBP and SBP are strongly correlated, learning both using a single model would improve the estimation. Training the neural network using shared data representations would estimate both SBP and DBP simultaneously using one model proposed a recurrent neural net-work passing information learnt from previous instant along with the present input features for estimating BP values. Inclusion of PPG features would improve the model's generalization, which can provide continuous, accurate, and generalized BP prediction . However, this model does not account for the temporal variation in the extracted features presented a SBP measuring technique using error-correcting coding and Ada Boost classifier. The PPG features considered in this method are percussion wave, tidal wave, dicrotic notch and dicrotic wave. The feature set is relatively small and should not effectively model the relationship between PPG features and BP. As mean error and standard deviation are highly variable, this could not provide continuous SBP measurement. Moreover, AdaBoost is not appropriate for time domain analysis and for handling complex data; its accuracy will decrease for long run BP estimation proposed a cuff-less BP measurement based on 21 features from PPG features and 14 features from the second derivative of the PPG. A support vector machine is used for BP estimation. The major challenge in this technique is the five peaks in the second derivative of PPG signal are not visible for all patients. This model is only applicable for small dataset. The overall performance of the model is poor. Proposed a method to estimate BP using two types of features, namely, physiological parameters (heartrate, arterial stiffness index, augmentation index)and features that describe the shape of the PPG waveform. Principle component analysis has been utilized to reduce the dimensionality of 190 extracted features. Machine learning techniques have been used to achieve better accuracy model. However, it need two sensors, and not suitable for longer continuous BP monitoring since the SBP prediction did not satisfy the standards and their DBP accuracy was just on the acceptable limit of standards proposed continuous BP measurements with acceptable results using one sensor. Features are extracted from PPG signal using the multitaper method (MTM). Spectral components extracted by MTM are combined with two features from the PPG waveform, constitute the input feature vector for a feedforward neural net-work. This approach provides cuff-less continuous BP measurements with acceptable results using single sensor. Since the feedfor-ward neural network does not incorporate temporal dependencies in its estimation, which prevents long term accurate predictions extracted three features from the PPG waveform. The PPG signals were segmented into 5s frame after Savitzky-Golay filtering, baseline wandering and normalization. Segments with no reference to BP values are removed. Pulse area, pulse rising time and width at 25% are used as features for Regression tree, multiple linear regression and support vector machine to predict SBP and DBP. The decision tree outperformed the Support vector machine and the linear regression models. The mean error difference for the regression tree only within the standard and rest of the models had standard deviation above 8 mmHg. Since, the BP estimation was implemented on the basis of each PPG segments, this method does not allow continuous beat-to-beat BP estimation.

Deep learning methods

An Artificial Neural Network (ANN) is used to extract morphological features. The ANN is connected with two stacked Long Short Term Memory (LSTM) layers, which consider the temporal variation of the features extracted by ANN in the lower level. This paper argues that it is hard to obtain correct features from the ECG and PPG signals since the waveform contour changes from one subject to another, and hence the position of these features varies or may not be visible for all patients. Both signals are segmented into a fixed length of three consecutive peaks to avoid varying number of cycles per fixed number of seconds between subjects. This automatic feature extraction technique combined with an LSTM model provides a much better accuracy. However, this method requires two signals sampled at two different sampling rate, fine tuning of two models, which is difficult, time-consuming and data size dependent proposed a SBP estimation method using partial least-square (PLS) regression, which used the Level Crossing Features (LCF) extracted from the contour drawn on the second derivative of the PPG signal. The PLS method is not appropriate for long-term BP measurements and the LCF features are not ideal for BP estimation proposed a BP estimation models based on PTT approach in addition to PPG waveform characteristics. The optimized features are selected using genetic algorithm and are given to SVM and multivariate linear regression models to predict BP values. The experimental results shows that the performance of PTT based models decreases for long term monitoring due to the termination of the PTT parameter and the outperformance of the SVM for long term monitoring. In Ripoll and Vellido, proposed a Restricted Boltzmann Machine(RBM) BP estimation model based on the PTT approach. Three different RBMs are developed using single input feature(PTT,1/PTT and log PTT) for each. The overall performance of this method is acceptable. However, this method need two sensors, calibration is necessary for every 6 min to maintain the accuracy of the model.

Non-invasive PPG based HRV measurement

The heart rate variability is a vital signal, which reflects the physical condition of a patient such as respiratory, cardiac arrest, cardiac insufficiency, systolic arterial pressure. Based on the literature the methods used for the measurement of HRV are divided into linear and nonlinear methods. Linear methods are of two types: time domain method and frequency domain method. The parameters extracted from the PPG signal for the estimation HRV in time domain or frequency domain can provides valuable information about the control of the cardiovascular system. The statistical time-domain indices for beat-to-beat determination are: SDNN—standard deviation of all t1 intervals read in a time interval, SDANN—standard deviation of the means of the intervals t1, SDNNi—mean of the standard deviation of the intervals t1, rMSSD—the square root of the square mean of the differences between adjacent intervals t1, pNN50—the percentage of the adjacent t1 intervals with duration difference greater than 50 ms. The SDNN, SDANN and SDNNi represents the sympathetic and parasympathetic activities, but they do not allow differentiation when HRV changes are due to increased sympathetic tone. On the other hand, the rMSSD and pNN50 indices represent the parasympathetic activity, as they are found from the analysis of adjacent RR intervals. Triangular index (RRtri), Triangular interpolation of RR intervals (TINN), Plot of Poincaré are the Geometric Indices used for HRV measurement and analysis, The triangular index and the TINN are calculated from a histogram of density of heart rate intervals (systole and diastole). The Poincaré plot is a two-dimensional graphical characterization of the correlation between consecutive cardiac pulses. In frequency domain method either Fourier transform or power spectral density is used for the estimation HRV. In nonlinear methods analysis of trend fluctuations, correlation function, exponent of Hurst, Fractal dimension and the exponent of Lyapunov are used to analyze HRV. A supervised learning approach was proposed by to detect heart beats at each position of a PPG HRV is estimated from the beat samples. The classifier used is the Random Forest, which give good result compared to Linear discriminant, Quadratic discriminant and nearest neighbor classifiers. proposed a neural network based HR estimation method. Probability is assigned to each spectral peak of the PPG signal, which corresponds to a heart rate peak. The pre-processed PPG signal was used to extract 11 time-domain features and then clustered into different groups based on motion and physiology of the subjects [5]. Multi-layer perceptron (MLP) network of three layer with 22 neurons is used for feature extraction and selection. Deep learning based CorNET is proposed by D to predict HR from PPG signals. CorNET uses convolutional neural network (CNN) and long-short term memory (LSTM). The supervised learning framework, negates the need for manual feature extraction. Although, these early developments would require comprehensive exploration for embedded implementation at real-time operations, the complexity involved in feature engineering and numbers of training parameters are high.

Discussion

The PPG technique is a simple method of monitoring the HRV and blood pressure. Non-invasive BP and HR measurements can be divided into techniques that use only a PPG sensor and techniques that use a hybrid approach of PPG sensor and the ECG. Research regarding this technique has been showing significant progress, such that some researchers in the medical and biomedical engineering fields are giving preference to utilization of this technique over ECG. The benefits of the PPG approach compared to ECG is simpler and not necessity of attaching electrodes to the patient’s chest. PTT or PAT are used in hybrid approach. PTT is the time that takes the blood pressure wave to travel between two points on the body and PAT is the time interval between the electrical activation of the heart and arrival of the pulse wave at a location on the body peripheral. Both methods require two measurement sensors that need to be synchronized, and placed on fixed positions on the body which is hard and inconvenient for patients to maintain during measurements. Both sensors have different sampling rates in real time and are very sensitive to motion artifacts during the recording which require signal processing techniques before the signals are used for analysis. PPG signals are highly susceptible to movement, which makes their use in exercise testing There are research works in which this problem can be minimized. The effects of noise and artifacts to the PPG signal can be reduced in different ways through the adequate processing of the PPG signal. Moving average filter is a basic filter, which is used in application to reduce the artifacts. It works well for a limited range of artifacts. Adaptive filter is also used for noise removal, which need a reference signal that was obtained by additional hardware. Due to the dynamic nature of the biological systems, most of the biological signals are non-stationary and their properties varies over time. Time–frequency methods such as the wavelet transform can be applied to PPG signals for noise removal. Wavelet preserve information related to heart rate, heart rate variability, blood pressure while removing PPG signal artifact movements

Conclusion

This paper presented a comprehensive review on PPG based blood pressure and HRV estimation methods. This article presents details on algorithm development for cardiac disorder prediction from PPG, facilitating vital parameter estimation targeting key applications. Monitoring HRV and blood pressure is effective for the diagnosis of several cardiovascular diseases. This is only possible when interlinking the technique with IoT technologies, genetic algorithms and artificial intelligence. Deeper investigation of this topic, facilitate new studies, which can help doctors in the early diagnosis of cardiac diseases.

References

1. Mukkamala, Ramakrishna, Hahn Jin-Oh. "Toward ubiquitous blood pressure monitoring via pulse transit time: Predictions on maximum calibration period and acceptable error limits." IEEE Trans Biomed Eng 65, (2017): 1410-1420.
2. Castaneda, Denisse, Ghamari Mohammad, Soltanpur Cinna,and Nazeran Homer et al. "A review on wearable photoplethysmography sensors and their potential future applications in health care." Int J Biosens Bioelectron 4, (2018): 195-203.
3. Tao, Kun-ming, Sokha Sann, Yuan Hong-bin. "Sphygmomanometer for Invasive Blood Pressure Monitoring in a Medical Mission." Anesthesiology 130, (2019): 312-312
4. Khushhal, Nichols Simon, Evans Will, and Page Richard et al. Validity and reliability of the apple watch for measuring heart rate during exercise, Sports Med Int Open 1, (2017) :206–211.
5. John Allen. Photoplethysmography and its application in clinical physiological measurement, Physiol Meas 28, (2017): 1-39.

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