Biomedical Signal Processing and Control 47 (2019) 196–206

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Blood pressure estimation from appropriate and inappropriate PPG signals using A whole-based method

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ARTICLE INFO

Article history:
Received 17 May 2018
Received in revised form 16 July 2018
Accepted 20 August 2018

Keywords:
Blood pressure
Photoplethysmography
Whole-based
Parameter-based
Cuff-less

ABSTRACT

Background and objective: Blood pressure (BP) is one of the four vital signals that provides valuable medical information about the cardiovascular activity. In recent years, extensive studies have been conducted on non-invasive and cuff-less BP estimation using photoplethysmography (PPG) signals. PPG is a non-invasive optical method for measuring blood volume changes per pulse. In other words, the PPG waveform represents the mechanical activity of the heart.
Methods: In this paper, a new method for estimating the Mean Arterial Pressure (MAP), Diastolic Blood Pressure (DBP) and Systolic Blood Pressure (SBP) is proposed using only the PPG signal regardless of its shape (appropriate or inappropriate). Our proposed algorithm called whole-based, uses raw values of the PPG signal at a given time interval for estimating the BP. In other algorithms called parameter-based, use features which are extracted from PPG signals in time or frequency domain. These features related to precise spotting in the form of the PPG signal. In fact, compared to parameter-based methods, our algorithm is independent of the form of the PPG signal.
Results: Using the proposed algorithm, our results are completely met by the Association for the Advancement of Medical Instrumentation (AAMI) standard for both MAP and DBP estimations. The results are also very close to the standard boundary with an average error close to zero for SBP estimation. Also, according to the British Hypertension Society (BHS) standard, the proposed algorithm for DBP estimation got grade A, whereas it got grade B for estimation of MAP and got approximately grade C for SBP estimation.
Conclusion: The results demonstrate the applicability of the proposed algorithm in estimating BP noninvasively, cuff-less, calibration-free, and only by using the appropriate or inappropriate PPG signal.

1. Introduction

Cardiovascular disease is one of the most important causes of death in the world. According to the report of the European Heart Journal, 4.1 million people die annually due to this disease [1]. Hypertension is the main cause of cardiovascular disease. In 2014, the prevalence of hypertension was 1.3 billion people worldwide as such, it is anticipated that by 2030, 1.56 billion people will suffer from hypertension [2,3].

Blood pressure (BP) is one of the significant parameters of the human body whose measurement provides valuable information for physicians. Frequent BP measurement can avail early detection, control, and treatment of diseases associated with BP such as hypotension and hypertension [4]. BP shows the resistance of the body vessels to the movement of the blood and its amount depends on the function of the heart and vascular features, such as elasticity and thickness of the walls of the vessel [5]. The upper and lower bounds of this pressure are called Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP), respectively [6]. Another BP called Mean Arterial Blood Pressure (MAP) can be approximated to the following equation:

$$MAP = (2DBP + SBP)/3 \quad (1)$$

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https://doi.org/10.1016/j.bspc.2018.08.022
1746-8094/

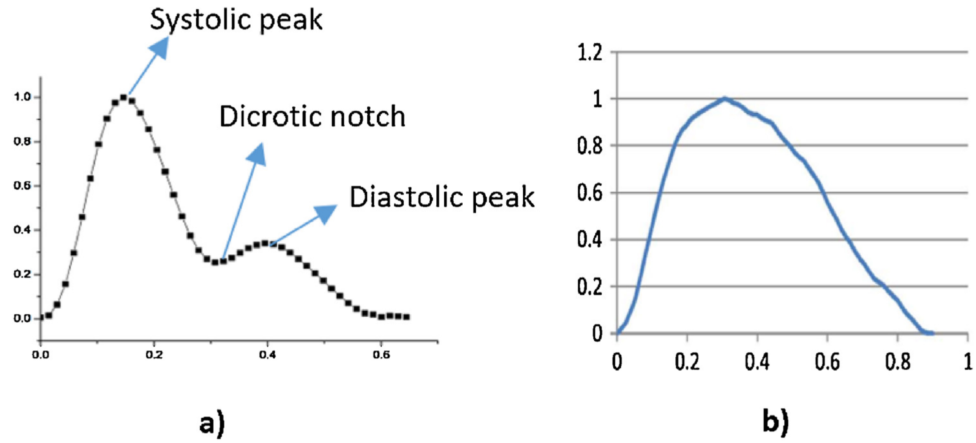

Fig. 1. PPG signal for a) A healthy individual [18] and b) A patient [19].

Based on the report of National Heart, Lung, and Blood Institute (NHLBI), in Hypertension, the SBP and DBP are in the ranges higher than 120 and 80 mmHg, respectively [7]. In health centers, BP is generally measured with cuff. Sphygmomanometer mercury is the most common method of measuring BP [8]. Insufficient accuracy in BP measurement with cuff during movement, discreet BP monitoring, excessive weight of the cuff, discomfort inflations and deflations of the cuff in specific situations such as exercise stress test and ambulatory blood pressure monitoring (ABPM) are some of the important challenges of continuous BP measurement [5,9,10]. In the recent two decades, extensive studies have been conducted to measure BP non-invasively and without the use of any cuff.

Pulse Transit Time (PTT) is one of the most commonly used methods for obtaining BP [11]. PTT is generally defined as the time that the heart beat pulse takes to propagate from the heart to the body peripherals. In most cases, researchers use Electrocardiograph (ECG) and Photoplethysmography (PPG) signals to measure this parameter. The measurement of PTT can be done with one ECG sensor and one PPG sensor or two PPG sensors [12]. Proper recording of the ECG signal requires at least three electrodes to be positioned at three different points of the body. Motion artifacts and non-contacting of the electrode with the skin surface and the electrode wires for long-term recording can add noise to the signal, which are the limiting factors of BP estimation with this method [9,13]. In recording two PPG signals to estimate BP, two distinct hardware are needed at two different points of the body. Thus, in this paper, estimating BP using only one PPG signal is intended.

Due to the elasticity of the human blood vessels, when the pressure pulse passes through them, the diameter of the vessels and then the blood volume inside them changes [14]. Plethysmography is a method for recording the change in the blood volume per heartthrob in the body while PPG is a non-invasive optical method for measuring blood volume change per pulse [15]. In this method, the light is emitted to a part of the body's tissue by a Light Emitting Diode (LED), and changes in light absorption are measured over a period of time using a Photo Detector (PD) [16]. If the changes in blood volume are accurately measured, PPG has a wave-like form and its frequency would be the same as the working frequency of the heart [17]. The PPG signal can be divided into two parts. The upper part of the signal is related to the contraction of the heart or the systole while the underside of the signal is related to cardiac expansion or diastole. In the PPG signal, there is a time-split variable between systolic and diastolic cardiac phases which is called dicrotic notch. In many recorded samples of the PPG signals from patients with hypertension, the dicrotic notch is not detectable. Fig. 1(a) shows an example of a PPG signal and its important points that belong to a healthy person, whereas Fig. 1(b) indicates the PPG signal which is for a patient with hypertension. In this study, a PPG signal is called appropriate if it is detectable in the three points of systole peak, dicrotic notch, and diastolic peak. Otherwise, the signal is called inappropriate.

The PPG signal is not only used for BP measurement, but also used in many cases such as studying the cardiovascular system [20], identifying individuals [21], extracting heart rate (HR) [22], determining the amount of oxygen-saturated blood [23], determining the arterial stiffness [24], determining blood-glucose levels, and measuring BP [25]. In recent years, researchers have investigated methods for measuring BP using only the PPG signal. In 2003, the first research in the field of BP estimation using PPG signals was conducted by Teng & Zhang that were able to estimate BP in a group of 15 people based on time interval and the amplitude of the PPG signal in the time domain, with mean error (ME) of 0.21 mmHg and standard deviation (SD) of 7.32 mmHg for SBP, and with ME of 0.02 mmHg and SD of the 4.39 mmHg for DBP [26]. Some other works have extracted specific features in the time domain of PPG signal and their results reveal the high correlation of the PPG signal with BP. In 2013, Kurylyak et al. with 21 features extracted from the PPG signal, could estimate SBP with a Mean Absolute Error (MAE) of 3.80 mmHg and SD of 3.46 mmHg and could estimate DBP with MAE of 2.21 mmHg and SD of 2.09 mmHg [27]. Some of these time domain features as illustrated in Fig. 2, are Systolic Area, Systolic Upstroke Time, Diastolic Area, Cycle Duration and Diastolic Time.

For better estimation of BP, another set of features can be defined by the first and second derivative of the PPG signal (SDPPG) that contains information about stiffness and aortic compliance and BP is highly affected by these factors. In 2016, Gaurav et al. extracted 46 features from the PPG and the second derivative of PPG signals, then used six neural networks of which each had 4 hidden layers. According to the results, DBP and SBP were estimated with MAE of 21.3 and 47.4 mmHg, respectively [29]. There have also been other studies which are based on new linear and nonlinear feature extraction of the PPG and SDPPG signal in the time domain [14]. The SDPPG consists of five waveforms called Initial Positive Wave (IPW), Early Negative Wave (ENW), Late Up sloping Wave (LUW), Late Down sloping Wave (LDW), and Diastolic Positive Wave (DPW) and these waveforms are designated with 'a', 'b', 'c',' d', and 'e', respectively. Fig. 3 shows some of the extracted features based on PPG and SDPPG.

In 2000, Millasseau et al. reported a new method for feature extraction in the frequency domain based on the generalized transfer function (GTF) and Fast Fourier Transform (FFT) [30]. Also, Wang et al. extracted features in the frequency domain but based on discrete cosine transform (DCT) [31]. In all studies of time and frequency domain, after the formation of the feature vector, the