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# Methods for reliable estimation of pulse transit time and blood pressure variations using smartphone sensors

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ABSTRACT

Hypertension is known to affect around one third of adults globally and early diagnosis is essential to reduce the effects of this affliction. Today's Blood Pressure (BP) monitoring cuffs are obtrusive and inconvenient for performing regular measurements, and continuous non-invasive blood pressure devices are too complex and expensive for ambulatory use. Hence, there is a strong need for affordable systems that can measure blood pressure (BP) variations throughout the day as this will allow to monitor, diagnose and follow-up not only patients at risk, but also healthy population in general for early diagnosis. A promising method for arterial BP estimation is to measure the Pulse Transit Time (PTT) and derive pressure values from it. However, current methods for measuring this surrogate marker of BP require complex sensing and analysis circuitry and the related medical devices are expensive and inconvenient for the user. In this paper, we present new methods to estimate PTT reliably and subsequently BP, from the baseline sensors of smartphones. This new approach involves determining PTT by simultaneously measuring the time the blood leaves the heart, by recording the heart sound using the standard microphone of the phone, and the time it reaches the finger, by measuring the pulse wave using the phone's camera. We present algorithms that can be executed directly on current smartphones to obtain clean and robust heart sound signals and to extract the pulse wave characteristics. We also present methods to ensure a synchronous capture of the waveforms, which is essential to obtain reliable PTT values with inexpensive sensors. Additionally, we combine Autocorrelation and Fast Fourier Transform (FFT)-based methods for reliably estimating the user heart rate (HR) from his/her heart sounds, and describe how to use the calculate HR to compensate for the camera frame rate variations and to improve the robustness of PTT estimation. Our experiments show that the computational overhead of the proposed processing methods is minimum, which allows real-time feedback to the user, and that the PTT values are fully accurate (beat-to-beat), thereby enabling state-of-the-art smartphones to be used as affordable medical devices.



## 1. Introduction and related work

With an ageing society and increasing prevalence of noncommunicable diseases, there is a strong need for systems that can provide quick and continuous healthcare of people. Cardiovascular diseases (CVDs) are the leading causes of disability and death in the world. According to a recent World Health Organization (WHO) report, 17.3 million people died from CVDs in 2008. A large percentage of the CVD can be prevented, but they continue to increase due to the lack of adequate screening and timely availability of diagnostic and preventive measures. More than 50% of CVD related deaths arise from complications of hypertension and 40% of adults aged 25 and above were diagnosed with hypertension worldwide in 2008 [1]. In this endemic scenario, prevention and early diagnosis are key to reduce the economic and social costs related to hypertension.

During the last decades, ambulatory measurement of arterial blood pressure (BP) has been prescribed to patients suspected to suffer from hypertension [2]. Current 24 h ambulatory blood pressure monitoring (ABPM) devices, nevertheless, are cumbersome equipments based on mechanical or oscillometric recordings and require a pressure cuff to be placed on the patient's upper arm or wrist. The periodic inflation of the cuff, usually every 20 min, is uncomfortable and noisy, disturbing the patient sleep and interfering with the BP measures themselves. Moreover, other continuous

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non-invasive beat-to-beat BP monitoring devices [3] are too complex and expensive, and thus not convenient for ambulatory monitoring. It is, therefore, clear that there is a strong need for new Non-Invasive Blood Pressure (NIBP) measuring methods that are able to track BP variations throughout the day, in order to monitor, diagnose and follow-up patients at risk, as well as for healthy people for early diagnosis.

Several recent works have presented novel ways of measuring BP using different sensors [2–9]. The most promising ones measure the pulse transit time (PTT) differences between different waveforms, such as the electrocardiogram (ECG), photo-plethysmogram (PPG), phonocardiogram (PCG), impedance cardiogram (ICG), electrical impedance tomography (EIT) or a combination of them.

The underlying principle of the PTT-based approach is that arterial stiffness increases with BP in a predictable manner, also affecting the pulse wave velocity (PWV) along the arterial tree. Hence, by measuring the time the pulse wave takes to travel from one point of the arterial tree to another, it is possible to calculate the PWV and estimate BP using elasticity-based models of the blood vessels.

The use of PTT to derive BP variations has been explored over the last decades. For example, the Casio BP-100 [10] was a pioneering consumer watch that could measure pulse and ECG (by touching the watch from the other hand) and derive the PTT-based BP variations. A more recent approach is presented in [2] where a chest sensor is proposed to assess PTT using ECG, PPG, and ICG. By acquiring all signals on the chest, the PTT is computed over the elastic arteries and, according to the authors, this results in more accurate PTT measurements.

Recent research has shown that reliable BP measurements with PTT-based methods require, at least, an initial calibration to model the individual PTTxBP relationship [4], or even a periodic calibration process to compensate for intra-patient variations, specially due to the vasomotion phenomenon. Hence, a standard BP measurement device based on mechanical or oscillometric recordings is used during the calibration step to feed the model with the required parameters. In particular, [3] details a system to estimate BP at the femoral artery using an ECG and a PPG sensor placed on the patient's thumb to calculate PTT. The system includes a brachial pressure cuff to perform periodic calibrations (every 4-8 hours) to compensate for inter and intra-patient variations of the PTTxBP relationship, which shows the feasibility of meeting U.S. Food and Drug Administration (FDA) standards for medical grade devices using PTT-based methods.

Additional research on the calibration step using different points of the patient body is presented in [8], where a BP monitor consisting of twin in-line PPG sensors that measure the pulse arrival time (PAT) using the wrist and little finger is described. The PTT is calculated by subtracting one PAT from another. The calibration procedure is performed by a set of wrist movements that changes the external pressure applied by a band placed on the patient's wrist, but the results do not assess the precision of the calibration procedure. Similarly, [11] proposes the use of hydrostatic pressure changes, but no consistent experimental results have validated this approach so far.

Beyond the concern on calibration methodologies for PTT, the reality is that a large set of works have evaluated the use of PTT as a surrogate marker for BP. We refer the interested reader to Henning and Patzak [12], which provide a complete summary of most of the relevant works, and come to the conclusion that PTT is suitable for continuous monitoring of BP. The authors state that previous works results are encouraging enough for further clinical evaluation of PTT-based BP measurement methods.

The major challenge of using PTT to estimate BP, nevertheless, is the high degree of exactness and precision required in the acquisition and delineation steps. Usually, this is achieved by using expensive high-precision sensors and heavy signal processing techniques. However, to deliver an ambulatory solution for continuous NIBP measurements, low cost and ease of use are key factors.

A work that is more in line with these restrictions uses smartphones to measure PTT and estimate differential blood pressure using two different setups [5]. The first one uses two smartphones synchronized via a self-designed bluetooth synchronization protocol. One device records the PPG using the camera while the other is used to record the sounds from the heart. Due to this synchronization procedure, the smartphones must be rooted (i.e., user applications needs to be given permission to run privileged commands), replacing their stock configuration. The second setup uses one smartphone and a customized external microphone to record heart sounds, which outlines the capabilities of smartphones for PTT measurements. However, methods are still missing to perform robust and reliable PTT measurement using the baseline sensors of smartphones with stock configuration.

The use of smartphones for health applications is rapidly increasing [13], mainly due to the high penetration of this technology, which is becoming a very powerful tool to bring healthcare to remote and rural areas, specially in developing countries. Although the widespread adoption of smartphones to track health is still a challenge, many recent studies have proven that they can help to track and improve different conditions, such as type 1 diabetes [14], Parkinson's disease [15], etc.

In this work we describe new on-board robust methods to obtain clean heart sound signals and to extract the pulse wave characteristics using just baseline sensors of smartphones with stock configuration. We also present methods to ensure a synchronous capture of the waveforms, which is essential to obtain reliable PTT values with inexpensive sensors. We combine Autocorrelation and Fast Fourier Transform (FFT)-based methods for reliably estimating the user heart rate (HR) from his/her heart sounds, and describe how to use the calculated HR to compensate for the camera frame rate variations and to improve the robustness of PTT estimation.

The rest of the paper is structured as follows. In Section 2 we present the overview of the proposed solution and how all the subsystems work together. Then, Section 3 describes in detail the signal acquisition and processing steps for both PPG and PCG recordings. Some of the theories and experiments described in this paper were first presented in [16], Section 4, nevertheless, the current paper presents further improvements on the method, describing how the heart rate can be calculated from the heart sounds and how it can be used to improve the user experience and the accuracy of the method. Experimental results are presented next, in Section 5, followed by the discussions and conclusions in Sections 6 and 7.

## 2. Background and method overview

PTT calculation involves the acquisition of the pulse arrival time (PAT) at two different points of the arterial tree. Once the PATs are computed, the PTT can be calculated by the formula presented in Eq. (1).

$$PTT = PAT_1 - PAT_0 \tag{1}$$

The first point on the arterial tree, which corresponds to $PAT_0$, is usually called proximal point, and the point used to determine $PAT_1$ is called distal point. The method we describe in this section uses the smartphone's internal microphone and camera to reliably compute the PATs at the proximal and distal points, respectively, and then calculate the PTT.

Differently from most of the previous works, here $PAT_0$ is computed from the heart sounds instead of the R-peak of the ECG wave. During the cardiac cycle, vibrations caused by the heart mechanical activity propagate through the chest, originating sounds