Using Pulse Transit Time for estimating Blood Pressure

Guillermo Mapel, J. Santiago Ascué, Adriana Costafreda

Universitat Politècnica de Catalunya, Spain
Escuela Técnica Superior de Ingeniería de Telecomunicación de Barcelona (ETSTEB), Barcelona, Spain

Abstract

This paper highlights the importance of cardiovascular health and presents an algorithm utilizing Pulse Transit Time (PTT) for blood pressure estimation. A custom code was developed for real-time monitoring, and calibrated with an oscillometric device. Initial results showed some discrepancies. The paper discusses algorithm specifics, strengths, and limitations, concluding with a way of continuity for refining the system. Findings are contextualized within existing literature, guiding future iterations for enhanced continuous blood pressure monitoring.

1. Introduction

Cardiovascular diseases (CVDs) are the world's biggest killer, representing 32% of all global deaths [1]. Hypertension is the leading preventable risk factor for cardiovascular diseases (CVD) being the most common and potentially lethal condition that may result in heart attack, stroke, myocardial infarction, cerebrovascular accident, congestive heart failure, myocardial ischemia, etc. if it is not detected early and treated properly [2]. Hypertension is highly prevalent, affecting more than 40% of adults worldwide, and is expected to increase dramatically due to the ageing of the population and the increasing prevalence of obesity [3]. The big problem with hypertension is that it rarely causes symptoms in the early stages, leading to low awareness and a low treatment rate. However, the treatment of hypertension is highly efficient, thus there is a need to increase the early diagnosis of this hazardous condition which is crucial to reducing cardiovascular risk and its associated morbidity and mortality.

The basis of high blood pressure (HBP) diagnosis is early, accurate and regular Blood Pressure (BP) monitoring. BP is a measurement of the force exerted by the heart against the arteries during the pumping of blood. To date, there are two clinical gold-standard ways of monitoring BP. The first one is considered the gold standard for critically ill patients [4] via arterial catheterization and the second approach being non-invasive and considered the gold standard for diagnosing hypertensive patients. [5] In the past years, it has become evident that office BP measurements are not sufficient for the proper diagnosis and control of hypertension. [6][7] As a result of these limitations, ambulatory BP and self-measured BP have gained interest and have shown to be superior for controlling and diagnosing hypertension. [7] Ambulatory BP measurements have advantages such as providing information about BP oscillations during daily activities and sleep. In addition, self-measured BP monitoring is beneficial for patients to identify risk factors in hypertension and increase treatment adherence. [7]

Although ambulatory and self-measured BP monitoring has notable advantages, it is worth noting that they can only provide a snapshot of dynamic BP readings, but not continuous BP monitoring, being long-term changes in BP a more accurate determinant of cardiovascular risk. Therefore, there is a major need for methods that permit continuous blood pressure monitoring for early prevention, detection, management, and treatment of hypertension. However, the major challenge for continuous monitoring is that blood pressure is measured using an inflated cuff since a force needs to be exerted by the heart against the arteries. Arterial tonometry, arterial volume clamp and pulse wave velocity (PWV) are three primary techniques to obtain continuous BP in a non-invasive way. In this paper we will focus on PWV as a promising alternative for continuous cuffless BP measurement. [8]

2. State of the Art

As it was previously stated, blood pressure can be measured using direct or indirect methods. Moreover, over the past years, new techniques to measure blood pressure such as wearable blood pressure measurement devices and non-invasive continuous blood pressure estimation from pulse transit time have emerged. Despite these advancements, none of these techniques currently provide the level of accuracy that doctors depend on for the precise diagnosis and management of high blood pressure conditions. [9]

2.1. Indirect Methods

2.1.1. Auscultatory Devices

Auscultatory devices, such as the mercury and aneroid sphygmomanometer or automated auscultatory devices, involve a trained observer using an inflatable cuff and a stethoscope to listen to Korotkoff sounds produced by blood under the cuff. The cuff is inflated to stop blood flow, and as it deflates, sounds indicate the resumption of blood flow. The initial sound corresponds to peak (systolic) pressure, while the final sound represents relaxation (diastolic) pressure. Although auscultatory measurement has been a traditional method, mercury sphygmomanometers, once the gold standard, are being replaced by oscillometric devices due to mercury's toxicity. Training is required for accurate interpretation of auscultatory sounds. [10]

2.1.1. Oscillometer Devices

Oscillometric devices measure blood pressure by inflating a cuff around a limb to temporarily halt arterial blood flow. As the cuff gradually deflates, the device monitors pressure changes and detects pulse waves. Utilizing the maximum volume change during cuff inflation, these devices estimate the average of systolic and diastolic blood pressure within the artery. Algorithms based on pressure wave characteristics and rate of change are employed to determine accurate blood pressure values. [10]

2.2. Direct Methods

Direct methods of blood pressure measurement involve invasive techniques using an arterial catheter, allowing for continuous and precise monitoring of hypertensive and hypotensive states. This method is particularly beneficial for high-risk patients who require continuous hemodynamic monitoring. Invasive blood pressure (IBP) monitoring entails replacing a section of the arterial wall with a stiff membrane connected to a pressure transducer. This requires cannulation of an artery with a short, stiff catheter and a tube connecting it to the transducer. Maintaining a hydrostatic reference level, often the right atrium, is crucial for accurate pressure measurement, and constant attention to the reference level is necessary throughout the monitoring process. [11]

2.3. Other Methods

There are many innovations in the market which are cuff-less and calculate the BP from other parameters as it was mentioned in the Introduction Section. These include Pulse transit time, Ultrasound or Magnetic method, Machine learning algorithms, Tissue characteristic methods, Heart-rate variation and heart-rate power spectrum ratio, Photoplethysmography, Heart rate, and smartphone technology. However, none of these technologies have been validated, yet they are not regulated, and there is no unified, standard system to evaluate their accuracy, performance, or use. [9]

2.3.1. Pulse Transit Time

In this article, we will focus on the method based on PWV. This method relies on variation of the velocity of the arterial pressure pulse propagating along the arterial system with the physiological variation, which is closely related to BP. PWV can be measured from Pulse Transit Time (PTT), which refers to the time it takes a pulse wave to travel between two places in the cardiovascular system. [8]

3. Materials and Methods

3.1. Hardware

For our project, we have used the Bitalino device to acquire both Electrocardiogram (ECG) and photoplethysmography (PPG) signals. Specifically, for ECG monitoring, we have used three electrodes that were positioned in a unipolar configuration to ensure accurate and comprehensive signal acquisition. The device used for PPG is the one sold by PulseSensor.com. In Figure 1 it can be seen all the hardware that has been used.

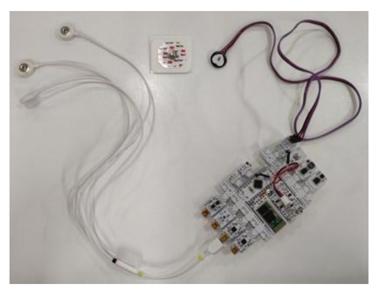

Fig 1. Project Hardware.

Signal acquisition and device-related challenges encompass various issues, notably distortion originating from low bandwidth measurement systems. This distortion is predominantly attributed to the incorporation of high-pass filters, specifically designed to attenuate low-frequency components. However, the implementation of these filters inadvertently introduces alterations in the acquired signals. In addition to this, the broader context of challenges involves interference from noise and the device's sensitivity, which may lead to the saturation of PPG signals. Achieving optimal performance requires meticulous attention to precise positioning.

3.2. PTT Definition

PTT can be easily obtained from two cardiac pulse signals, such as electrocardiogram and photoplethysmogram . In our project, we define Pulse Transit Time as the duration between the Q peak of an ECG and the corresponding maximum derivative of the PPG signal. PTT, a crucial physiological parameter, represents the time taken for a pulse wave to travel between two points in the cardiovascular system. Its appeal lies in its noninvasive nature, reliability, cost-effectiveness, and ease of use. The versatility of PTT has led to its widespread adoption in various clinical applications, including measuring respiratory effort, evaluating arterial stiffness, and estimating blood pressure (BP). Notably, PTT has been extensively studied for unobtrusive and continuous BP monitoring.

Despite the increasing utilization of PTT in scientific and engineering domains over the past 50 years, there remains a lack of standardized terminology for this parameter. Different research groups employ varying definitions for PTT, and confusion often arises due to its interchangeability with pulse arrival time (PAT) [8]. Our project addresses this by specifically defining PTT as the time interval between the R peak of the ECG and the corresponding maximum derivative of the PPG signal, providing clarity and precision in our approach to measuring and interpreting this essential cardiovascular parameter.

We have computed the derivative signal with the following operation:

$$x'(i) = \frac{2\cdot(x(i)-x(i-1))+x(i+2)-x(i-2)}{8} \quad Eq.\ 1$$

Figure 2 shows how our algorithm detects the required points for PTT calculation.

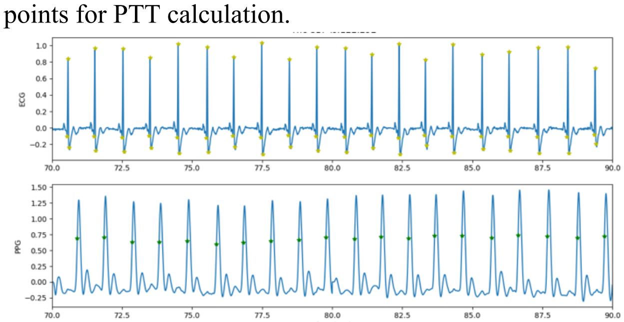

Fig 2. ECG and PPG signals with detected key points.

3.3. Blood Pressure Model

A wide variety of studies have been conducted involving the development of analytical models of the relationship between PTT and BP to achieve BP estimation. In this project we have used the one called Poon's algorithm to achieve the values of the systolic (SBP) and diastolic (DBP) blood pressure components: [8]

$$DBP = MBP - \frac{1}{3}\cdot PP_0\cdot\left(\frac{PPT_0}{PPT}\right)^2 \quad Eq. 2$$

$$SBP = DBP + PP_0\cdot\left(\frac{PPT_0}{PPT}\right)^2 \quad Eq.\ 3$$

Defining MBP as:

$$MBP = MBP_0 + 2\cdot\gamma\cdot \ln ln\left(\frac{PPT_0}{PPT}\right) \quad Eq.\ 4$$

The calibration variables are computed as:

$$PP_0 = SBP_0 - DSP_0$$

$$MBP_0 = \frac{SBP_0+DSP_0}{2}$$

γ is a constant typically between 0.016 and 0.018 and it is an individual dependent. For our measurements we used γ=0.017

3.4. Real Time Processing

For our project we have developed a system that enables us to work with real-time and recorded data, but the main idea of the project is to work in real-time, as it is integral to the core concept of utilizing PTT for continuous blood pressure measurement. The primary motivation behind employing PTT is its potential for seamless and continuous monitoring of blood pressure, offering a dynamic and comprehensive understanding of cardiovascular health.

However, the real-time processing of PTT data has presented challenges, particularly in dealing with aberrant measurements induced by subject movement and other factors. The dynamic nature of real-world scenarios, including variations in subject posture and motion, introduces complexities that necessitate robust mechanisms for treating and managing outliers or anomalous readings. In our project, we tried to solve some of them, but we couldn't achieve a robust code, so our real-time data can only be used when the subject is not moving.

Figure 3 shows a typical signal deformation due to the subject movement that can produce a failure in our system.

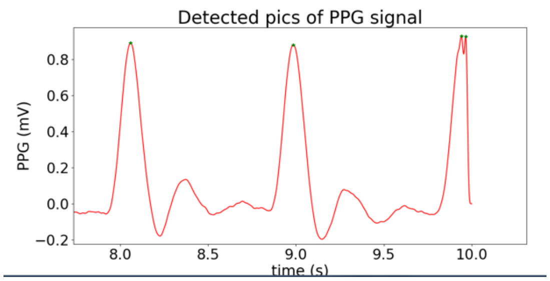

Fig 3. Signal deformation due to the subject movement.

4. Results

Our program features an interface displaying real-time values for heart rate, PTT, SBP and DBP. The interface includes plotted ECG and PPG waveforms for quick fault detection and code improvement. This design streamlines monitoring and ensures the reliability of our application by allowing quick detection and improvement of code faults.

Figure 4 shows how this UI looks.

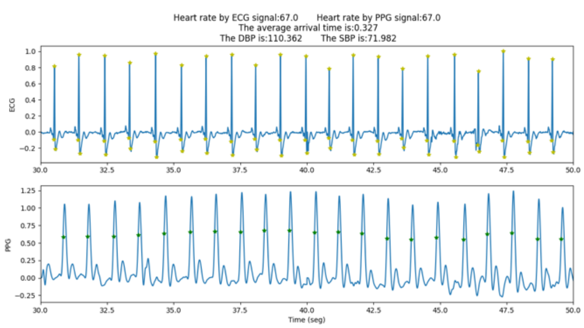

Fig 4. UI of our project.

To calibrate our system, we did measurements using an oscillometric device. Shortly after, we utilized the same oscillometric device to compare the SBP and DBP values obtained from our program. Notably, we observed variations between the two sets of values, with differences reaching up to 10 mmHg. Our program indicates room for improvement, this outcome underscores the necessity to refine our system. This preliminary comparison prompts us to enhance the accuracy of our program for more reliable results.

5. Discussion

As evidenced by our observations, the system designed for measuring BP based on PTT demonstrates a degree of imprecision. While we successfully obtained viable numerical values of BP aligned with those from a clinical device, it is crucial to note that the system relies entirely on calibration values derived from a validated BP measurement device. Consequently, each time an individual seeks to assess their BP using our system, calibration with an external device is imperative, rendering our system contingent on this external dependency.

In our project, due to time constraints, we were unable to achieve conclusive results as we faced challenges in developing a robust code for wide-ranging real-time measurements. This limitation prevented us from conducting the necessary correlation studies to derive meaningful outcomes.

Moving forward with this project, it is imperative to address two key steps. Firstly, a dedicated effort is required to refine and extend the code to accommodate a more extensive range of time measurements. This enhancement would facilitate more comprehensive studies, thereby augmenting the reliability of the results obtained.

Alternatively, due to project limitations, we drew insights from other studies employing the same algorithm, specifically Poon's method for BP calculation using PTT. Notably, these studies reported promising results, revealing estimation errors of 0.6 ± 9.8 mmHg for SBP and 0.9 ± 5.6 mmHg for DBP against reference blood pressure. This suggests that Poon's algorithm holds substantial potential, aligning with the AAMI standard. [8]

While cuffless blood pressure monitoring through the PTT method has seen progress, challenges impede its widespread adoption. The technique's accuracy falls short for replacing indirect measurement of arterial blood pressure in hypertensive cases and invasive methods for critically ill patients. Challenges include a narrow focus on estimating SBP with PTT, limited representation of dynamic blood pressure due to sole reliance on PTT as a variable, and the necessity for frequent calibration arising from assumptions about arterial dimensions. [8]

6. Conclusion

In conclusion, we have used BITalino for acquiring ECG and PPG signals. Moreover, defining PTT as the duration between the ECG's Q peak and the PPG's maximum derivative we programmed a system for measuring BP in a noninvasive nature.

Moreover, a real-time system was implemented, but challenges persist in handling abnormal measurements from subject movement. Despite attempts to overcome these issues, achieving a reliable real-time code has proven difficult, restricting the use during subject motion.

The results analysis highlighted the system's reliance on external calibration values, imprecision in measuring BP and challenges faced in developing a robust real-time code due to time constraints. Future steps involve refining and extending the code for a more comprehensive range of time measurements, addressing limitations, and enhancing reliability.

References

[1] The top 10 causes of death. http://www.who.int/en/news-room/fact-sheets/detail/the-top-10-causes-of-death. Accessed 20 Dec 2023.

[2] James PA, Oparil S, Carter BL, Cushman WC, Dennison-Himmelfarb C, Handler J, Lackland DT, LeFevre ML, MacKenzie TD, Ogedegbe O. 2014 Evidence-based guideline for the management of high blood pressure in adults: report from the panel members appointed to the Eighth Joint National Committee (JNC 8). JAMA. 2014;311(5):507–20.

[3] Chow, C. K. (2013). Prevalence, awareness, treatment, and control of hypertension in rural and urban communities in High-, Middle-, and Low-Income countries. JAMA, 310(9), 959. https://doi.org/10.1001/jama.2013.184182

[4] Romagnoli, S., Ricci, Z., Quattrone, D., Tofani, L., Tujjar, O., Villa, G., Romano, S. M., & De Gaudio, A. R. (n.d.). Accuracy of invasive arterial pressure monitoring in cardiovascular patients: an observational study. Critical Care, 18(6). https://doi.org/10.1186/s13054-014-0644-4

[5] Ismail, S. N. A., Nayan, N. A., Jaafar, R., & May, Z. (2022). Recent advances in Non-Invasive Blood Pressure Monitoring and Prediction using a machine learning approach. Sensors, 22(16), 6195. https://doi.org/10.3390/s22166195

[6] Hwang, K. O., Aigbe, A., Ju, H., Jackson, V. C., & Sedlock, E. (2018). Barriers to accurate blood pressure measurement in the medical office. Journal of Primary Care & Community Health, 9, 215013271881692. https://doi.org/10.1177/2150132718816929

[7] Muldoon, M. F., Kronish, I. M., & Shimbo, D. (2018). Of signal and noise. Circulation: Cardiovascular Quality and Outcomes, 11(5). https://doi.org/10.1161/circoutcomes.117.004543

[8] Ding, X., & Zhang, Y. (2019). Pulse transit time technique for cuffless unobtrusive blood pressure measurement: from theory to algorithm. Biomedical Engineering Letters, 9(1), 37–52. https://doi.org/10.1007/s13534-019-00096-x

[9] Siddique, S., Khan, A. H., Shahab, H., Zhang, Y., Tay, J. C., Buranakitjaroen, P., Turana, Y., Verma, N., Chen, C. H., Wang, T., Van Minh, H., Chia, Y. C., & Kario, K. (2021). Office blood pressure measurement: A comprehensive review. Journal of Clinical Hypertension, 23(3), 440–449. https://doi.org/10.1111/jch.14169

[10] Lewis, P., & British. (2019). Oscillometric measurement of blood pressure: a simplified explanation. A technical note on behalf of the British and Irish Hypertension Society. Journal of Human Hypertension, 33(5), 349–351. https://doi.org/10.1038/s41371-019-0196-9

[11] Lam, S. H. M., Liu, H., Jian, Z., Settels, J. J., & Bohringer, C. H. (2021). Intraoperative invasive blood pressure monitoring and the potential pitfalls of invasively measured systolic blood pressure. Cureus. https://doi.org/10.7759/cureus.17610