Correlation Study Between Blood Pressure And Pulse Transit Time

Pereira, T.^{1,2}; Sanches, R.^{1,2}; Reis, P.^{1,2}; Pêgo, J.^{1,2}

¹ Life and Health Science Research Institute
University of Minho, Braga, Portugal

² ICVS/3B's - PT Government Associate Laboratory, Braga
taniapereira@ecsau.uminho.pt

Simoes, R.^{1,3}

³ Polytechnic Institute of Cávado and Ave, Campus do
IPCA, 4750-810 Barcelos, Portugal

Abstract—Blood pressure (BP) determination is a fundamental parameter in cardiovascular assessment. The gold standard method to measure BP is based on the inflatable arm cuff, however has several disadvantages for continuous monitoring. New techniques were developed to overcome these limitations using correlations between the pulse transit time (PTT) and BP. This work draws attention to the PTT rationale using several methods. In order to determine the PTT, an electrocardiogram (ECG) was used combined with multiple photoplethysmography (PPG) sensors applied to different arm locations, these signals were acquired with a bioPLUX device. The Ultrassound system (SonoSite Edge) was used to measure the artery diameter. As reference, BP was measured using a cuff-based sphygmomanometric device. Measurements were performed in a study population of 36 volunteers. The correlation coefficient for DBP determined and DBP measured was $r = 0,689$. The results suggest PTT deduced from different locations can be used to measure BP.

Index Terms—pulse transient time, blood pressure, photoplethysmography

I. INTRODUCTION

Blood pressure (BP) is a parameter used to assess the cardiovascular system of an individual, becoming pivotal since cardiovascular disorders are identified as the leading cause of death throughout Europe, including Portugal [1].

Generally, BP refers to the force exerted by the blood on the arteries wall in a cyclic pattern, corresponding to the pumping of blood by the heart from which derives two main components: systolic pressure (SP) and diastolic pressure (DP). The maximum pressure value (SP) in a given vessel corresponds to the systole (contraction of the heart muscle) while, diastolic pressure occurs during diastole when the heart rests, reflecting aortic valve closure (referred to as aortic notch) and the elasticity component of the arteries.

Blood pressure can be measured through invasive or non-invasive methods. Invasive methods (more precise and accurate [2]) are used in hospitals and critical care units, and involve artery catheterization for a continuously track-record of the BP. However, because it is an invasive method it has several drawbacks and implicit risks, so its applicability is solely reserved to situations justifying it. Non-invasive methods

enable punctual measurements. The gold standard method to measure blood pressure is based on the inflatable arm cuff; however, this conventional method has several disadvantages: is considered inconvenient for continuous monitoring and the cuff logistic and self-use undermine its precision and consistency [3]. It should be pointed out that blood pressure measurements based on the arm cuff have limitations and errors intrinsic to its use, as well as time-point fluctuations which may compromise the correct measurement of blood pressure [2].

Various efforts have been made to develop a non-invasive, continuous, and more comfortable method for indirect blood pressure measurement [4]–[6]. The most common approach uses blood volume pulse sensor (BVP) to monitor the curve function of the blood volume in the arteries that arises from the cardiac cycle and the blood pressure. However, these volume changes are not linearly related to blood pressure variation especially in the periphery (toes, ears, etc.), since there are other factors (caliber and elasticity of the artery) which vary from person to person that affect BP [7]–[9]. It's within this rational that follows our effort to measure different BVP wave properties (obtained at several locations) that may correlate with BP as referenced in literature [10]. In this sense, BVP wave parameters such as amplitude, slopes, min-max intervals, max-min, max-b among others (Figure 1) became subject of several studies [11], [12].

Figure 1. Representation of a PPG with the most important features of the wave: wave min, deri (maximum rate of pulse pressure), max and b point that corresponds to the aortic notch.

Pulse wave velocity, determined by the PTT (Figure 2) is another parameter considered determinant to blood pressure levels as demonstrated by Pruett et al. [10] and H. Gesche et al. [3], in which they show that PTT has an almost linear behavior at low values of pressure, while for higher values it grows exponentially.

PTT can be determined using several photoplethysmography sensors applied at different locations [10] or concomitantly using a ECG sensor to obtain the time between peaks (e.g. time from the R peak of the ECG to the PPG signal maximum) [3], [13], [14]. Several PTT's were targeted in this study, namely those corresponding to the aortic-brachial, brachial-radial, radial-finger path.

Figure 2. Original traces of the electrocardiogram and peripheral pulse wave of PPG (finger) showing the detection of R-wave and the determination of the pulse transition time.

In addition, a survey on several previous studies (based on fluid mechanics) disclosure simplified mathematical models using PTT to the blood pressure calculus:

- Model Cattivelli and Garudadri: $BP = a + b \cdot PTT$
- Model by Wong an Poon: $BP = a \cdot PTT + b \cdot HR + c$
- Model by McCombie et al: $BP = (a / PTT^2) + b$
- Model considered by Fung et al: $BP = a \cdot \ln(b \cdot PTT)$

The constants (a, b, c) are specific to each subject, HR is the heart rate and correlate with BVP curve properties. A calibration step based on these constants can be relevant [10], and some insightful and robust assays showed some correlation factor with blood pressure, however no model studied showed strong correlations, especially for pathological cases, with pressure values outside of the normal range. Therefore, there is still much to explore in order to find the model that best fits this problem.

This work tries new methods to determine the PTT using several combinations of sensors and measurements of diameter of arterial vessel where measured the signal.

II. MATERIAL AND METHODS

A. Measurement Systems

The *bioPLUX research* is a device that collects and digitalizes signals (PPG and ECG) from the sensors, transmitting them via bluetooth to the computer where the signals are shown in real-time. The *bioPLUX* device is a certified system for clinical ECG usage, allowing a sample frequency of 1000 Hz with a 12 bits ADC resolution and wireless signal transmission using Bluetooth protocol.

The *bioPLUX* device and Kendall/Tyco ARBO disposable surface electrodes (48x34mm) were used for ECG acquisition. Each ECG signal was collected using a 3-lead ECG sensor. Disposable surface electrodes were used as they provide good skin fixation and stable skin acquisition during time.

The photoplethysmography sensors applied to different arm locations (brachial and radial) and in the finger (see Figure 3). The PPG sensors were connected with the same *bioPLUX*, which allows synchronizing with ECG wave.

The Ultrassound system (SonoSite Edge Portable Ultrasound) was used to measure the artery diameter in order to assess its significance in the PTT and blood pressure. The measurements were done in the radial and brachial artery (Figure 4). These arteries were chosen for the position of PPG sensors in the arm.

Figure 3. Photography of the test performed in one volunteer.

Figure 4. Ultrasound image of the radial and brachial artery and respective measurement of vessel dimensions.

B. Study Population

The characteristics of the volunteers in this study are presented in Table I. The group consisted of 36 subjects with 12 males and 24 females.

TABLE I. MAIN CHARACTERISTICS OF THE VOLUNTEERS

Characteristics	Range values
n, Males/Females	36 (12/24)
Age, years	29.2 ± 9.3
Height, cm	167.4 ± 7.6
Weight, kg	64.4 ± 9.7
BMI, kg/m^2	27.1 ± 2.6
Brachial SBP* (mmHg)	120.4 ± 13.4
Brachial DBP* (mmHg)	69.8 ± 10.1
Heart Rate* (bpm)	69.7 ± 10.3

Values are numbers or means $\pm$ SD.

BMI indicates the body mass index (weight/height²).

* Measure in brachial, with commercial sphygmomanometer (blood pressure cuff).

C. Study Protocol

All the subjects were volunteers and gave a written informed consent. The subjects rested for 5 minutes, reached the physiological baseline conditions, in a standardized temperature environment and then, blood pressure was measured in the booth arms with a cuff, before each measurement and acquired signals. Each trial consisted of the first measure of BP (with a cuff); then the determination of diameter of brachial and radial artery; following the blood pressure was measured again; the signals of ECG and PPG were acquired and finally one more measurement of BP.

D. Signal Processing

The signal processing developed in this work allows the determination of difference between the time of ECG R-peak and the time of the corresponding PPG.

Signal processing algorithms were used in order to extract the desired features from the acquired ECG. According to the literature, it is known that an R-peak has a power spectrum density up to 20 Hz [15]. Thus, a second order low pass Butterworth filter with a cut frequency of 25 Hz and sampling rate of 1000 Hz was applied in order to remove the frequencies that do not match the R-peak.

In this study the data have around 2 minutes of signal acquisition, the algorithm processes all signal in 5 second windows. In the first step of algorithm the local maxima of the two signals was identified in a window sample of 5 seconds. In the peak determination an adaptive algorithm have been employed to improve peak detection, even in the presence of signal artefacts. Peaks correspondence is checked by a smart set of conditions.

The delay between the R-peak from ECG and the systolic peak from PPG signal (or between PPG's peaks) was determined. PTT value in this sample is the average value of all detected delays between peaks detected (e.g. 5 seconds sample $\sim$ 5 PTT values). The algorithm then computes all PTT data excluding outliers in several iterations and according to a set of rules based on Ordinary Least Squares.

The PTT determined by the ECG and PPG signals was used to estimate the diastolic blood pressure based on a model of fluid mechanics that takes into account parameters such as the viscosity of the blood, diameter of vessel and velocity of pulse pressure waveform. The viscosity of blood was defined as a fixed value of viscosity at zero shear rate (0.056 Pa.s) and viscosity at infinite shear rate (0.00345 Pa.s) [16], due to the impossibility of measuring this parameter in these tests.

E. Statistical Analysis

Data is reported as mean values $\pm$ standard error with 95% confidence intervals and percentages were used to describe qualitative variables.

III. RESULTS

The mean value obtained for diameter of arterial vessels measured with Ultrasound system was 0.16 ± 0.03 cm for the radial artery and 0.31 ± 0.06 cm for the brachial vessel.

The mean values of distances between the sites of measure the PPG signals are presented in the table II.

TABLE II. MEAN VALUES OF DISTANCES BETWEEN THE SITES OF MEASURE THE PPG SIGNALS

Vessels of measurements	Distances (cm)
Aorta - Brachial	40 ± 2.4
Brachial - Radial	26 ± 2.1
Radial - Finger	18 ± 1.2
Brachial - Finger	43 ± 2.7
Aorta - Radial	66 ± 3.7
Aorta - Finguer	84 ± 4.4

Values are numbers or means $\pm$ SD.

The PTT was determined by the time delay between the combination of ECG and the three different sensors for the PPG in order to determine the best methodology to estimate the blood pressure. The next table presents the best value of correlation obtained by the diastolic pressure determined and the value measured by the sphygmomanometric device.

TABLE III. CORRELATION VALUES FOR THE DIFFERENT METHODS TO DETERMINE THE DBP.

DBP (PTT method)	Correlation
DBP 1 (ECG - PPG Finger)	0.360
DBP 2 (ECG - PPG Brachil)	0.480
DBP 3 (ECG - PPG Radial)	0.689
DBP 4 (PPG Radial - PPG Brachial)	0.433
DBP 5 (PPG Radial - PPG Brachial)	0.211
DBP 6 (PPG Braquial - PPG Finger)	0.376

Figure 5. Plot of diastolic blood pressure measured by cuff versus diastolic blood pressure calculated from the pulse transit time by method 3.

In the Figure 5 are represented the values obtained with the DBP 3 method using the ECG and PPG radial signals to determine the pulse transit time.

IV. CONCLUSIONS

This study explored new combinations of PPG with ECG for the determination of blood pressure, however, the results emphasize that the most commonly used methodologies and described in the literature are the best performing. The diastolic pressure estimated by the ECG and the PPG signal in the radial presents the best correlation with the reference values of DBP measured with sphygmomanometric device.

This work also presents a reference values for the diameter of important vessels.

Furthermore, a more exhaustive and discriminated analysis (basal and peak amplitudes, slopes, areas, min-max, max-b intervals) of the PPG waves (finger, brachial, radial) obtained can add some insights on its relative correlation with diastolic and systolic BP values.

Studies with different pathologies and cardiovascular diseases are fundamental to determine the best model to predict the blood pressure from the pulse transit time measured.

ACKNOWLEDGMENT

Foundation for Science and Technology, Lisbon, through the Quadro Comunitário de Apoio, the POCTI and FEDER programs, and project PEst-C/CTM/LA0025/2011. Project “Do-IT”, co-financed by the European Community Fund through COMPETE—Programa Operacional Factores de Competitividade. ing facilities for data collection.

REFERENCES

- [1] D. Cérebro-cardiovasculares and V. Rodrigues, “Portugal,” 2013.
- [2] F. H. Messerli and D. Cotiga, “Masked hypertension and white-coat hypertension: Therapeutic navigation between scylla and charybdis,” J. Am. Coll. Cardiol., vol. 46, no. 3, pp. 516–517, 2005.
- [3] H. Gesche, D. Grosskurth, G. Küchler, and A. Patzak, “Continuous blood pressure measurement by using the pulse transit time: Comparison to a cuff-based method,” Eur. J. Appl. Physiol., vol. 112, pp. 309–315, 2012.
- [4] J. Fortin, W. Marte, R. Grullenberger, a. Hacker, W. Habenbacher, a. Heller, C. Wagner, P. Wach, and F. Skrabal, “Continuous non-invasive blood pressure monitoring using concentrically interlocking control loops,” Comput. Biol. Med., vol. 36, no. 2006, pp. 941–957, 2006.
- [5] J. Y. Wagner, J. S. Prantner, A. S. Meidert, A. Hapfelmeier, R. M. Schmid, and B. Saugel, “Noninvasive continuous versus intermittent arterial pressure monitoring: evaluation of the vascular unloading technique (CNAP device) in the emergency department,” Scand. J. Trauma. Resusc. Emerg. Med., vol. 22, no. 1, p. 8, 2014.
- [6] M. M. Islam, F. H. M. Rafi, A. F. Mitul, M. Ahmad, M. A. Rashid, and M. F. bin Abd Malek, “Development of a noninvasive continuous blood pressure measurement and monitoring system,” in Informatics, Electronics & Vision (ICIEV), 2012 International Conference on, 2012, pp. 1085 – 1090.
- [7] J. Blacher and M. E. Safar, “Large-artery stiffness, hypertension and cardiovascular risk in older patients,” Nat. Clin. Pract. Cardiovasc. Med., vol. 2, no. 9, pp. 450–5, Oct. 2005.
- [8] A. P. Avolio, L. M. Van Bortel, P. Boutouyrie, J. R. Cockcroft, C. M. McEniery, A. D. Protogerou, M. J. Roman, M. E. Safar, P. Segers, and H. Smulyan, “Role of pulse pressure amplification in arterial

- hypertension: experts' opinion and review of the data.," *Hypertension*, vol. 54, no. 2, pp. 375–83, Aug. 2009.
- [9] D. Agnoletti, Y. Zhang, P. Salvi, C. Borghi, J. Topouchian, M. E. Safar, and J. Blacher, "Pulse pressure amplification, pressure waveform calibration and clinical applications," *Atherosclerosis*, vol. 224, no. 1, pp. 108–12, Sep. 2012.
 - [10] D. B. McCombie, A. T. Reisner, and H. H. Asada, "Adaptive blood pressure estimation from wearable PPG sensors using peripheral artery pulse wave velocity measurements and multi-channel blind identification of local arterial dynamics," in *Engineering in Medicine and Biology Society*, 2006. EMBS '06. 28th Annual International Conference of the IEEE, 2006, pp. 3521 – 3524.
 - [11] M. Crilly, C. Coch, M. Bruce, H. Clark, and D. Williams, "Indices of cardiovascular function derived from peripheral pulse wave analysis using radial applanation tonometry: a measurement repeatability study.," *Vasc. Med.*, vol. 12, no. 3, pp. 189–97, Aug. 2007.
 - [12] J. E. Sharman, J. E. Davies, C. Jenkins, and T. H. Marwick, "Augmentation index, left ventricular contractility, and wave reflection.," *Hypertension*, vol. 54, no. 5, pp. 1099–105, Nov. 2009.
 - [13] F. a. F. Marques, D. M. D. Ribeiro, M. F. M. Colunas, and J. P. S. Cunha, "A real time, wearable ECG and blood pressure monitoring system," 6th Iber. Conf. Inf. Syst. Technol. (CISTI 2011), pp. 1–4, 2011.
 - [14] J. S. Kim, K. K. Kim, H. J. Baek, and P. K. Suk, "Effect of confounding factors on blood pressure estimation using pulse arrival time," *Physiol. Meas.*, vol. 29, no. 5, 2008.
 - [15] D. Abi-Abdallah, V. Robin, A. Drochon, and O. Fokapu, "Alterations in human ECG due to the MagnetoHydroDynamic effect: A method for accurate R peak detection in the presence of high MHD artifacts," *Annu. Int. Conf. IEEE Eng. Med. Biol. - Proc.*, pp. 1842–1845, 2007.
 - [16] B. Liu and D. Tang, "Influence of non-Newtonian properties of blood on the wall shear stress in human atherosclerotic right coronary arteries.," *Mol. Cell. Biomech.*, vol. 8, no. 1, pp. 73–90, 2011.