Pulse Wave Velocity as a Function of Cuff Pressure – Extra Information About the Cardiovascular System

Á. Jobbágy, P. Nagy

Dept. Measurement and Information Technology, Budapest University of Technology and Economics, Budapest, Hungary

Abstract— **High blood pressure (BP) is one of the biggest global health risks as it often precedes heart disease, stroke, or kidney failure. Non-invasive methods determine only the momentary value of systolic- and diastolic BP. Knowing arterial rigidity would provide cardiologists with invaluable extra information.**

A Home Health Monitoring Device, HHMD, was developed at the Dept. Measurement and Information Systems, Budapest University of Technology and Economics. HHMD inflates and deflates the cuff slowly (6 mmHg/s) and records also ECG and photoplethysmographic signal (PPG) at both index fingertips. Among other parameters the pulse wave transit time, PWTT is calculated. Occlusion with the cuff causes a temporary alteration in the dynamic parameters of the brachial artery. The alteration can be characterized by the change of the PWTT.

170 were selected and analyzed from more than 1500 recordings taken from patients who underwent open-chest cardiac surgery and also from healthy control persons. The results confirm that the PWTT – CP function provides extra information about the state of the brachial artery. Parameters are suggested to express this information.

Keywords— **pulse wave velocity, cuff occlusion, artery rigidity, blood pressure.**

I. INTRODUCTION

The accurate measurement of the systolic (SBP) and diastolic (DBP) values seems to be simple but in fact, it is rather difficult [1].

Non-invasive methods determine the momentary value of SBP and DBP. This does not provide a good measure as both SBP and DBP fluctuate in time and also vary along the circulatory system. They exhibit short-term changes as well as variation during the day. Many internal and external factors influence the actual value of BP [2].

Knowing blood pressure changes of a person during the day is valuable diagnostic information. 24-hour monitoring might be applied to assess the blood pressure profile [3]. Even 24-hour non-invasive monitoring does not give information on short-term variation in blood pressure which is not necessarily negligible. Beat-to-beat change in systolic pressure – mainly as a result of breathing – easily reaches 5 mmHg. It follows that the ***momentary value*** – measured and/or calculated by the majority of presently used devices and methods – ***is not an optimal measure of blood pressure***. Nor is it good to characterize the state of the artery.

The oscillometric BP measurement method [4] is widely used as it does not require extra sensors, only CP has to be recorded and processed. The method basically estimates the mean arterial pressure. The calculated SBP and DBP values may have too high errors [5]. Arterial stiffness and pulse pressure have substantial impact on accuracy. As a result the trustiness of the method is rather good for those who have normal BP and questionable for those with cardiovascular diseases.

Research work has been active to find a simple, non-invasive and reliable procedure to characterize the cardiovascular system of a person. In this paper we suggest a new method based on the signals of extra sensors applied during oscillometric measurement.

II. MATERIALS AND METHODS

The velocity of the pulse wave, progressing through the arteries depends also on blood pressure. Many attempts have been made to make use of pulse wave velocity during blood pressure measurement. Pulse wave velocity (PWV) can be calculated by recording ECG and PPG signal. Blood pressure variation can be estimated based on PWV even without using a cuff [6], [7].

$$\mathrm{PWV} = \frac{\mathrm{L}}{\Delta \mathrm{T_{PT}}} = \sqrt{\frac{\mathrm{Eh}}{\rho \mathrm{d}}} \tag{1}$$

$$\mathrm{E} = \mathrm{E_0} e^{\mathrm{aBP}} \tag{2}$$

$$\mathrm{BP} = \frac{1}{\alpha}\left[\ln\left(\frac{\mathrm{L^2}\rho \mathrm{d}}{\mathrm{E_0 h}}\right) - 2\ln(\Delta \mathrm{T_{PT}})\right] \tag{3}$$

where PWV is pulse wave velocity, E is the Young modulus of arterial wall (E_0 is its value at a given BP_0), BP is blood pressure, h is the thickness, d is the inner radius of the artery, ρ is blood density, α is constant, L is the distance between the heart and the fingertip and ΔT_{PT} is the pulse transit time. The systole has two periods, the isovolumetric

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and the auxotonic ones [8]. The former lasts until the pressure in the left ventricle exceeds the diastolic pressure in the aorta. ΔT_{EP} is the sum of the pre-ejection time, ΔT_{PE} and the pulse transit time, ΔT_{PT}.

$$\Delta T_{EP} = \Delta T_{PE} + \Delta T_{PT} \quad (4)$$

Pulse wave velocity, as defined in (1) is an average over the distance from the heart to the fingertip. The diameter of the vessel changes as the pulse wave travels along it. This changes the Young modulus at the actual position of the pressure wave. The relation between the local pressure and flow in the artery is described in [9]. ΔT_{PT} cannot be measured easily; in general ΔT_{EP} is used instead. Assuming that ΔT_{PE} is constant, changes in ΔT_{PT} are equal to changes in ΔT_{EP}.

Soon after the cuff occludes the upper arm artery pulsation in the PPG at the fingertip stops. During deflation pulsation restarts when CP drops below SBP. This helps determine SBP [10]. However, when pulsation in PPG stops during inflation CP is usually higher than its value during deflation when pulsation restarts [11].

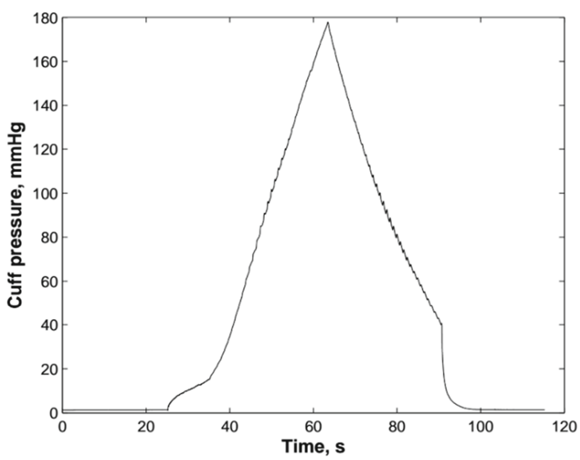

Fig. 1. Cuff pressure vs time profile applied in HHMD.

HHMD [12], [13] inflates and deflates the cuff slowly. During the first 24 s the cuff is completely deflated. Inflation lasts until max. 180 mmHg. Should HHMD detect SBP at lower CP, inflation is terminated. Slow deflation lasts until CP reaches 40 mmHg. At this point a ventil opens and CP abruptly drops to 0 mmHg. ECG and PPG is recorded for a further 24 s. The pressure change rate is approximately 6 mmHg/s. The actual value depends on how strong and toned the patient's upper arm is and how tightly the cuff is wrapped around it. HHMD records ECG in Eithoven I lead and PPG signal from the index fingers. The cuff pressure, ECG and PPG are sampled with 1 ksample/s using a 12-bit A/D converter. Figure 1 shows the CP vs. time profile.

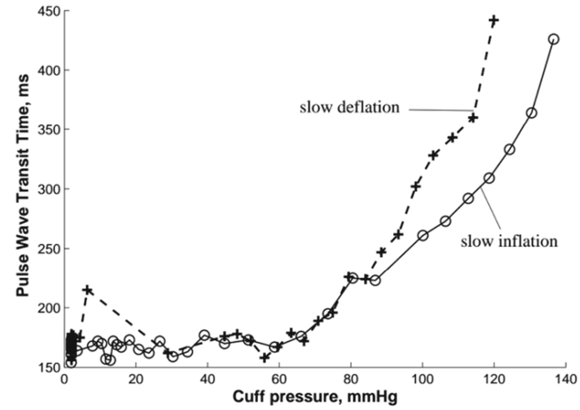

Fig. 2. Typical PWTT vs. CP curve.

A typical PWTT – CP curve is given in Figure 2. PWTT can be calculated until CP is lower than SBP. At higher CP values the brachial artery is completely occluded and pulsation in PPG at the fingertip ceases.

When CP is between DBP and SBP, PWTT is generally higher during deflation than during inflation at the same CP. Longer PWTT for the same person presumes less rigid artery. The actual value and shape of the difference is determined mainly by the change in the dynamic parameters of the brachial artery caused by the occlusion with the cuff.

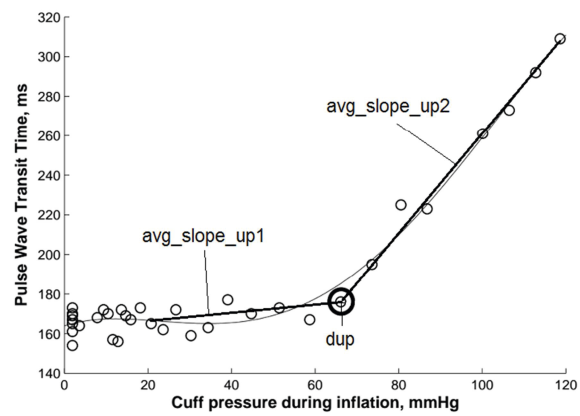

Fig. 3. Typical change in PWTT during inflation.

The slope of the PWTT – CP curve is also characteristic for the cardiovascular system. We determined the CP belonging to the steepest change. During inflation it is denoted by *dup*, during deflation by *ddown*. During inflation the average slope is calculated for the 20 mmHg – *dup* CP range (called *avg_slope_up1)* and for the *dup* – SBP CP range (called *avg_slope_up2*), see Fig. 3. During deflation these parameters are *avg_slope_down1* (CP range 40 mmHg – *ddown*) and *avg_slope_down2* (CP range *ddown* – SBP).

HHMD was used for two months by eight patients who underwent open-chest cardiac surgery. The tested patients started each measurement by pressing a button on the device. Patients could place one hand on the ECG and PPG sensors only after recording had been started. PWTT before cuff inflation (PWTTbefore) was averaged over the 16^{th} – 24^{th} second interval. During deflation when CP reaches 40 mmHg its value changes abruptly. This also causes a transient thus PWTT after cuff deflation (PWTTafter) is an average of the last 8 s period of the recording. The ratio of the two PWTT values is

$$\Delta\text{T Ratio} = \frac{\text{PWTTbefore}}{\text{PWTTafter}} \quad (5)$$

Even though they were trained to handle HHMD home usage was uncommon for the patients. This resulted in an extraordinarily unfavorable signal to noise ratio, especially for the PPG signal. From more than 1500 recordings selection of 170 with acceptable signal to noise ratio is an effective way of feature extraction. Three groups were tested: patients with cardiovascular disease: 3 females and 3 males, age 55-60, 121 recordings. Senior healthy persons: 2 females and 3 males, age 55-60, 24 recordings. Young healthy persons, 1 female and 9 males, age 19-27, 25 recordings. Further research work is going on to find an appropriate filtering method for the rest of the recordings.

III. RESULTS

Occlusion with the cuff causes a temporary change in the dynamic properties of the brachial artery. This is demonstrable by the difference between *dup* and *ddown*. The average absolute difference and its standard deviation are practically the same for the three tested groups, see Table 1. Three parameters are recommended to characterize the temporary change caused by the occlusion.

Table 1 Difference between dup and ddown.

Tested persons	mean diff., mmHg	average absolute diff., mmHg	std. dev., mmHg
young healthy persons	-0.4	5.4	7.0
senior healthy persons	0.5	5.7	7.2
patients with cardiovascular disease	0.6	5.3	6.6

A. The difference between dup and DBP

For all the three tested groups *dup* correlates with DBP. We assume that during slow inflation the abrupt change in PWTT originates from the complete occlusion of the brachial artery which first happens when CP exceeds DBP. The difference between *dup* and DBP determined by HHMD are given in Table 2. The difference is smallest for the young healthy group. Values for the senior healthy persons and for the patients are similar.

Table 2 Difference between dup and DBP, dup-DBP.

Tested persons	mean diff., mmHg	average absolute diff., mmHg	std. dev., mmHg
young healthy persons	-0.4	1.6	1.9
senior healthy persons	-0.7	2.3	3
patients with cardiovascular disease	-1.0	2.8	3.2

B. The change of PWTT

The effect of inflation and deflation is demonstrated in Figure 4. In most cases PWTT is greater after than before occlusion, thus ΔT Ratio < 1. It can be interpreted that occlusion temporarily increases the elasticity of the brachial artery. For patients with cardiovascular diseases ΔT Ratio can exceed 1. The value of ΔT Ratio is an indicator of arterial rigidity; it correlates neither with SBP nor with DBP.

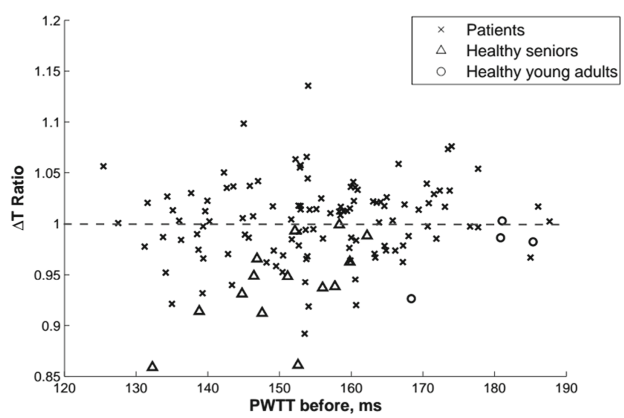

Fig. 4. ΔT Ratio is the ratio of PWTT before and after cuff occlusion.

C. Slope of increase of PWTT during inflation

There is almost no difference among tested persons regarding the slope of increase of PWTT during inflation when CP exceeds *dup*, i.e. in the value of *avg_slpoe_up2,* see Figure 5. However, there are two patients, P3 and P9 who sometimes – not always – produced much higher values than the maximum of all other tests (6 s/mmHg). This indicates momentary increased rigidity of the arterial wall.

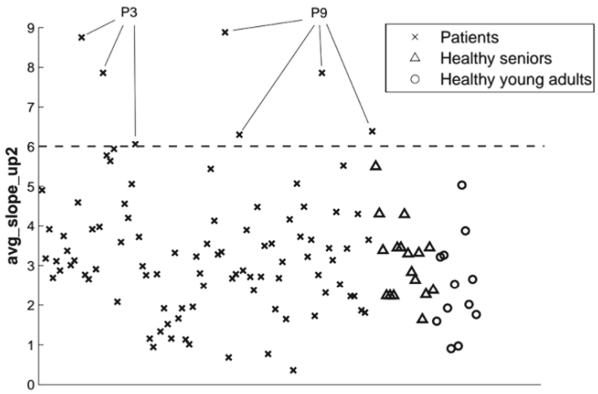

Fig. 5. Two patients can exhibit high values for avg_slope_up2.

IV. Conclusions

Measuring SBP and DBP at a given moment does not give a good characterization of the cardiovascular system. The occlusion is an excitation that can be used to assess the dynamic properties of the brachial artery. The parameters introduced in this paper are applicable for everyday usage. They are expected to provide cardiologists with invaluable extra information. A new, simple-to-use BP measuring device with the described abilities is under development.

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Conflict of Interest

Authors declare that they have no conflict of interest.

References

1. http://ec.europa.eu/health/scientific_committees/opinions_layman/sphygmomanometers/en/l-3/3.htm
2. Mancia G: Short- and Long-Term Blood Pressure Variability Present and Future. Hypertension, 2012; 60:512-517.
3. O'Brien E et al.: European Society of Hypertension Position Paper on Ambulatory Blood Pressure Monitoring. J Hypertens. 2013 Sep; 31(9):1731-68.
4. van Monfrans GA: Oscillometric blood pressure measurement: progress and problems. *Blood Pressure Monitoring* 2001, 6:287-290.
5. Babbs CF: Oscillometric Measurement of Systolic and Diastolic Blood Pressures Validated in a Physiologic Mathematical Model. http://www.biomedical-engineering-online.com/content/11/1/5
6. Chen W, Kobayashi T, Ichikawa S, Takeuchi Y, Togawa T: Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. Med. Biol. Eng. Comput., **38**, pp. 569-574, 2000
7. Lacković I, Šantić A: Accuracy improvement of noninvasive finger blood pressure measurement. Conf. proc. of MEDICON 2001, IX Mediterranean Conference on Medical and Biological Engineering and Computing 12-15 June, 2001, Pula, Croatia, pp. 281-284.
8. Fonyó A: Az orvosi élettan tankönyve. Második kiadás. (Textbook of Medical Physiology. Second edition. In Hungarian.) Medicina Könyvkiadó Rt., Budapest, 1999.
9. Khir AW, O'Brien A, Gibbs JSR, K. H. Parker KH: Determination of wave speed and wave separation in the arteries. Journal of Biomechanics 34, pp. 1145-1155, 2001.
10. Nitzan M, Patron A, Glik Z, Weiss AT: Automatic Noninvasive Measurement of Systolic Blood Pressure Using Photoplethysmography. http://www.biomedical-engineering-online.com/content/8/1/28
11. Jobbágy Á: Early Diagnosis and Objective Assessment of Patients with Neural and Cardiovascular Diseases. LAP Lambert Academic Publishing, ISBN 978-3-8383-5316-6
12. Csordás P, Mersich A, Jobbágy Á: Advanced Indirect Method for Measuring Blood Pressure. Periodica Polytechnica El. Eng., Vol. 53., 3-4, pp. 115-121.
13. Csordás P, Jobbágy Á: Shape Analysis of Oscillometric Pulses. In Proc. 6th European Conference of IFMBE. Springer, IFMBE Proceedings Volume 45, 2015, pp 427-430

Author: Á. Jobbágy
Institute: Budapest University of Technology and Economics
Street: Magyar Tudósok krt. 2.
City: Budapest
Country: Hungary
Email: jobbagy@mit.bme.hu