*Acta Universitatis Latviensis, 2009, Vol. 753, Biology, pp. 99–106*

# The shape and dimensions of photoplethysmographic pulse waves: a measurement repeatability study

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**Abstract**

Photoplethysmography (PPG) is a non-invasive, simple and well-known physiological method for recording and monitoring blood volume pulse, but still there are many unknown issues concerning this method such as individual variability and repeatability of the PPG waveform. In our study we recorded two PPG signals (from the radial artery and from the finger) several times in resting conditions to evaluate the individual repeatability of PPG wave shape. Arbitrary amplitudes of incisura and maximum of dicrotic notch and time from foot to anacrotic maximum had the greatest repeatability among PPG wave shape parameters in both radial artery and finger. Maximum of the first derivative in the anacrotic phase in the PPG waveform showed the highest variability. A possible explanation for the existing individual variability of PPG parameters might be temporal and spatial summation of fluctuations of heart cycle length and changes of peripheral resistance in magistral artery and microcirculatory vessels.

**Key words:** blood volume pulse, photoplethysmography, pulse wave analysis, radial artery.

## Introduction

The application of photoplethysmography has continued to expand and has become widely used for clinical research involving cardiovascular parameters (Allen 2007). The main advantages are it's non-invasiveness and reduced morbidity for subjects.

Extensive studies have been conducted on photoplethysmography to determine the ideal settings for measuring pulse wave velocity (Allen, Murray 2002; Alnaeb et al. 2007). In the last ten years much research has focused on the possibility on using a PPG signal to replace the pre-existing invasive procedure for cardiovascular parameter measurements. Many successful applications for PPG have been introduced: use of PPG in identifying flow mediated vasodilation and thus as a diagnostic for endothelium dysfunction (Donald et al. 2006); determination of arterial pressure wave shape and amplitude with high accuracy (Allen, Murray 2004), allowing virtual reconstruction of central arterial pressure wave (Munir et al. 2008) and calculation of "ankle-brachial" index; as an application for evaluating the mechanical properties of arterial walls using the finger volume pulse shape

analysis (Chowienczyk et al. 1999; Millasseau et al. 2002).

The output of an infrared PPG transducer is proportional to changes in the volume of red blood cells in the peripheral microvascular beds. In addition, fluctuation in RBC volume is associated with each heart beat, and thus can be associated with PPG transducer recordings.

There are two PPG operational configurations: transmission (transillumination) mode operation where the fingertip is placed between the source and detector, and reflection (adjacent) mode operation where the LED and detector are placed side-by-side (Crabtree et al. 2006). The detected optical radiation waveform comprises a pulsatile ("AC") component attributed to cardiac synchronous changes in the blood volume with each heart beat, and is superimposed on a slowly varying ("DC") baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation (Gonzalez et al. 2008).

The origins of the DC and AC components of the PPG signal are not fully understood, but it is generally accepted that they can provide valuable information about the cardiovascular system. The PPG signal (mentioned AC component) has a direct relationship to arterial pressure waves (Allen 2007). The PPG signal starts as a wave propagation from central arteries to the peripheral vasculature. In the periphery, the more resistant vessels will induce reflection of the wave, and finally the summation of the propagating and reflected waves will produce the PPG signal.

Detailed investigations in arterial pressure wave shape started in the early 1940s (Hamilton 1944). Similar shapes for the PPG and arterial pressure waves has been noted, thus it is reasonable to rely and use the previous arterial pressure pulse shape method for PPG wave shape analysis. Every individual has a unique characteristic shape for their photoplethysmography signal, but in previous research not enough attention has been focused on the existence of this variation, and on the reproducibility of PPG measurements when repeated at different times.

In our study we recorded two photoplethysmography signals: in reflection mode from the radial artery and in transmission mode from the fingertip, with the aim to evaluate the individual repeatability of PPG wave shape parameters recorded from finger and artery in rest conditions.

## Materials and methods

### *Subjects*

The study included 13 healthy adults (three men) with mean age ± standard deviation 21.3 ± 2.8 years. The main inclusion criterion was individuals with no cardiovascular diseases. This study was approved by the local ethics committee and each subject gave informed consent.

### *Study protocol*

All measurements were recorded in a controlled and quiet environment at room temperature (17 ± 1 °C) after a 15 min resting period, during which personal information (name, age, gender) was obtained and the study protocol was explained to subjects. Then subjects were seated and systolic (SBP) and diastolic (DBP) arterial blood pressure as well as heart rate (HR) were measured immediately by pressure sensor application to the

subject in a systematic order thus ensuring possibility of occurrence of signal interactions. Measurements were performed continuously – beat per-beat during a period of 2 min while the subject was in a seated position with both arms bent in a 90 ± 5° angle and both forearms rested on an upholstered chair support frame. We allowed patients to keep their wrist and palm relaxed. All traces were recorded simultaneously for a period of 120 s, and the study protocol was repeated for each patient two to four times (with up to a 7-day resting period between measurements for each subject) to explore the variability and individual features of the PPG signal.

For measuring forearm blood flow (FBF) we used a venous strain-gauge plethysmograph (D.E. Hokanson Incorporated, Bellevue Washington USA). We placed the cuff on the upper left arm, the strain gauge was placed around the left forearm about 10 cm under the elbow and fixed with adhesive tape. We chose the shortest possible measuring interval (15 s), which allowed us to register BF data four times per minute. Continuous SBP, DBP and HR traces were obtained with a Finometer (Finometer model-2, FMS, Finapres Medical Systems B.V. Amsterdam, Netherlands); sensors were placed on the right arm. The PPG signal was recorded with an originally designed two-channel photoplethysmograph (LU ASI, Latvia) with two different sensors: reflecting probe sensor for the radial artery and transmission probe sensor for the finger. Diameter of the emitting area for reflecting probe was ~2 mm, radiant power ~10mW, peak wavelength ~940 nm, estimated mean penetration depth under the skin surface~2–3 mm. The analogue signals from PPG contact probes were digitized by an analogue-to-digital converter (16-bit accuracy, sampling rate 300 Hz) and transferred to the computer (Erts et al. 2005). We fixed the reflecting probe on the artery by taping and additionally bending it to the wrist. Skin temperature for each patient was constant during the measurements.

Fig. 1 shows the PRG parameters determined in this study: maximum of the first derivative in anacrotic phase of the PPG waveform ($I_A$), arbitrary amplitudes of anacrotic maximum ($h_s$), incisura minimum ($h_i$) and maximum of dicrotic notch ($h_d$), time intervals from foot to ancrotic maximum ($t_s$), incisura ($t_i$) and maximum of dicrotic notch ($t_d$) (Ratner 1993; Allen 2007). Amplitude parameters were measured in arbitrary units (a.u.).

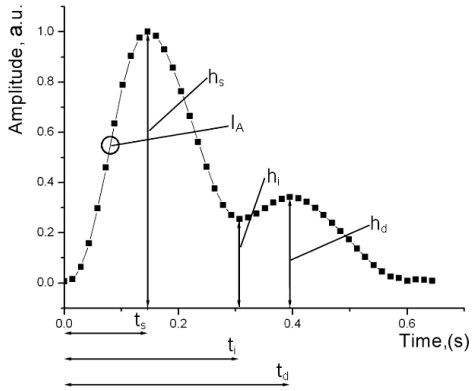


**Fig. 1.** Parameters of PPG signal studied in this work. $I_A$ – maximum of the first derivative in anacrotic phase of the PPG waveform; $h_s$ – arbitrary amplitude of anacrotic maximum; $h_i$ – arbitrary incisura minimum; $h_d$ – maximum of dicrotic notch; $t_s$ – time interval from foot to ancrotic maximum; $t_i$ – time interval from foot to incisura; $t_d$ – time interval from foot to maximum of dicrotic notch.

*Analysis*

Offline analyses were performed for all channels (PPG, FBF and BP signals) and data processed by custom-made software developed for Matlab. PPG and pressure channels were filtered and a continuous FBF curve was interpolated from intermittent recordings by cubic spline function. Normalization within pulse wave was performed to compare PPG signals in different registrations. The synchronized traces were initially handled manually to select the unaltered (cut off movement artifacts) traces only, which were then exported to MS Excel and processed there, using the program SigmaStat for statistical analysis (t-test, one way repeated measure ANOVA).

## Results

The rest period hemodynamic parameters DBP, SBP and HR, as expected, did not show statistically significant differences for each subject in the repetitions. The obtained parameters for the whole group (n = 13) were as follow: average systolic blood pressure 117.5 ± 8.9 mm Hg, diastolic blood pressure 75.5 ± 8.5 mm Hg, heart rate 66.4 ± 5.1 beats $min^{-1}$.

In our experiment regional circulation was only represented by the forearm blood flow, which showed slight variability; nine subjects of 13 showed no statistically significant differences between forearm blood flow in different repetitions.

According to variability of PPG parameters from the radial artery signal, the most stable PPG parameters were hi, hd and ts. The difference of these parameters within a subject was only ≤ 2 % (one out of 37 recordings differed significantly ($p < 0.05$).

A slightly larger variability was shown by $h_d$, $t_i$ and $t_d$, which differed significantly ($p < 0.05$) in 7 - 18 % (three to seven out of 37 recordings). $I_A$ was the only parameter that was variable within an individual subject and within the study group; the variability of this parameter was very high and significant differences ($p < 0.05$) between $I_A$ values of individual subjects when repeated measurements were performed was found in more than 59 % (21 out of 37 recordings of subjects). Even within the same measurement the $I_A$ parameter showed a very large fluctuation in values (mean ± SD; 0.84 ± 0.17). An example of a subject's both radial artery and digit hemodynamic and PPG parameters is shown in Fig. 2.

The most stable parameters in the PPG recorded from the finger were $h_i$ and $t_s$, as in only 2 % (one out of 37 recordings) of cases they did not show significant differences ($p < 0.05$) between different recording times within a subject. Similar to the arterial PPG parameters, a larger variability was observed for $h_d$, $t_i$, $t_d$ un $I_A$ in the finger PPG signal. Altogether 11 to 30 % of recordings (four to 11 out of 37) showed a significant difference ($p < 0.05$).

## Discussion

Previous research has confirmed that peripheral arterial PPG signal measurements can be used for diagnostic purposes (Allen 2007; Alnaeb 2007). The variation in heart rate allows us to understand individual characteristics of physiological regulatory mechanisms in the autonomic neurohormonal system.

Pulse wave velocity and multi-body site PPG measurements provide us with valuable

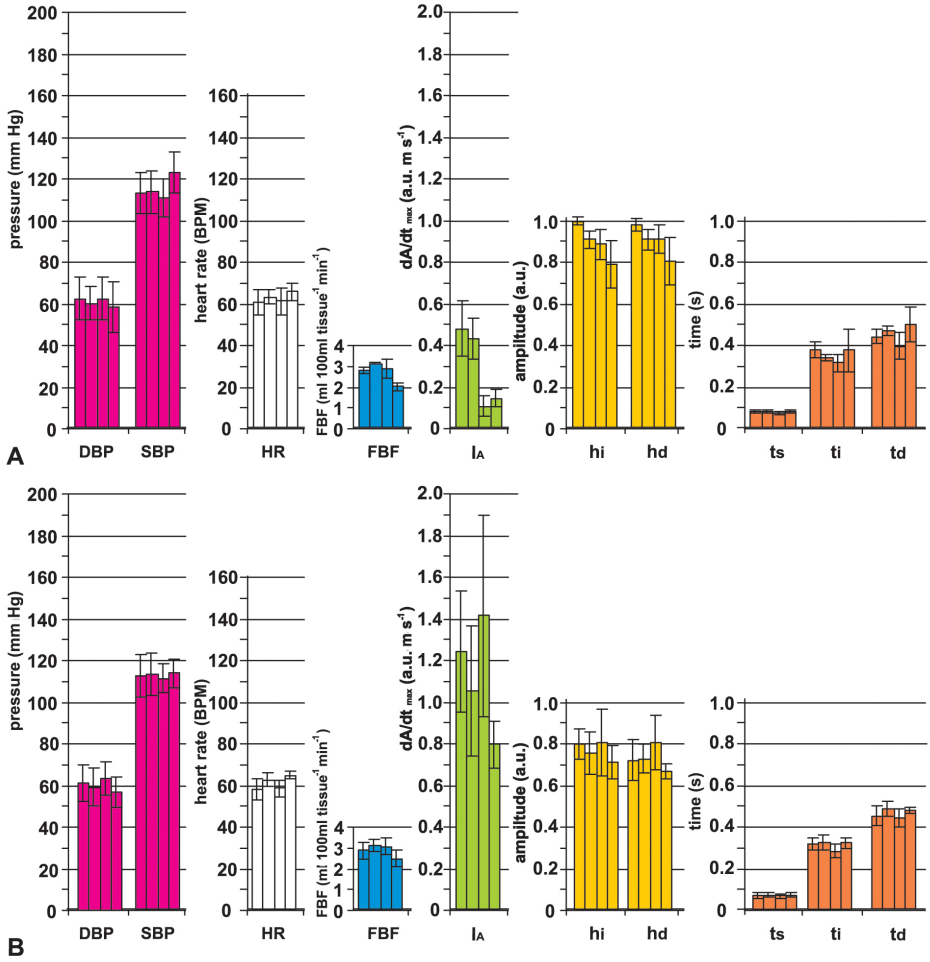


**Fig. 2.** A representative example for individual variability of one subject showing hemodynamic and PPG parameters. Recordings of four repetitions in two vascular beds (A - radial artery, B – finger). Data is shown as mean ± standard deviation; n = 43 cardiac cycles. SBP – systolic blood pressure (mm Hg); DBP – diastolic blood pressure (mm Hg); FBF – forearm blood flow (mL 100 mL$^{-1}$ tissue min$^{-1}$); $I_A$ – maximum of the first derivate in anacrotic phase of the PPG waveform ($dA/dt_{max}$); $h_i$ – arbitrary incisura minimum (a.u.); $h_d$ – maximum of dicrotic notch (a.u.); $t_s$ – time interval from foot to ancrotic maximum (s); $t_i$ – time interval from foot to incisura (s); $t_d$ – time interval from foot to maximum of dicrotic notch (s); HR – heart rate (bpm).

information concerning the mechanical properties of arterial walls, and thus will enable us to diagnose peripheral arterial occlusive diseases. Photoplethysmography also makes it possible to evaluate flow-mediated vasodilatation in an artery, allowing the specific endothelial functional state to be determined. In addition photoplethysmography can be used as an alternative method for ankle brachial pressure index calculations, which is a crucial parameter in the diagnosis of peripheral artery disease (Khandanpour et al. 2009). Finger PPG may also provide us with the ability to obtain the parameters of the heart left

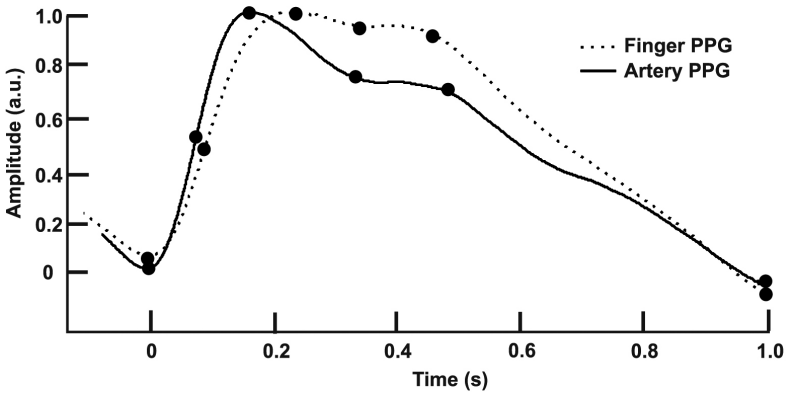


**Fig. 3.** Representative example of typical curve demonstrates shape differences for $PPG_{fing}$ and $PPG_{art}$. Pulse waves were recorded simultaneously in the rest conditions. The shape parameter measuring points are marked with the dots.

ventricular volume and filling time, which has an important application in the case of heart arrythmia (Zheng et al. 2008).

The arterial pulse shape has been extensively studied by recording arterial wall diameter changes or by the arterial pressure wave. By use of applanation tonometry it is possible to record the arterial pulse shape signal, which is also practically identical to the invasively measured intraarterial pressure signal. Detailed analysis of the tonometry signal has proven that the shape analysis contains the relevant information (Kelly et al. 1989). In a specially designed experiment, pulse wave analysis using radial applanation tonometry demonstrated high levels of repeatability (Crilly et al. 2007).

Research into the PPG signal shape was first implemented by Hertzman. In 1937 he introduced two basic abbreviations: the anacrotic phase being the rising edge of the pulse, and the catacrotic phase being the falling edge of the pulse; the dicrotic notch is usually seen in the catacrotic phase (Allen 2007). It was recommended to measure the anacrotic time, which is the crest time from the rising edge of the pulse waveform, and to normalise this to the heart rate. Later research introduced more PPG wave shape parameters ($I_A$, $h_i$, $h_d$, $t_s$, $t_i$, $t_d$ etc.) and it was recommended to normalise the values of these parameters to the heart rate and the amplitude of the pulse wave (Hamilton 1944; Kelly et al. 1989; Nitzan et al. 1998; Millasseau et al. 2000; Hayward et al. 2002; Millasseau et al. 2002; Gonzalez et al. 2008). In the finger pulse wave, special attention has been paid to the "notch" or point of inflection in pulse wave downslope, as it has been proven to be a sensitive index of nitrate bioavailability (Takazawa et al. 1998; Chowienczyk et al. 1999).

There are no previous studies that show the variation of individual photoplethysmography waves when repeated at different time intervals. More extensive research in this field has been carried out to determine the accuracy with which pulse transit times (PTTs) can be measured. Measurements of PTT between the ECG Q-wave and various peripheral sites was conducted in 10 normal subjects on 10 separate days. The day-to-day repeatability sigma (the square root of the within-subject mean square variance) of individual PPT measurements in a subject was 9 – 12 ms (Jago, Murray 1988). These results indicate individual repeatability of the PPG signal.

In our research, repeated measurements for each individual in the resting condition

showed almost the same arterial pressure and heart rate values (average variation in pressure was 5 %). In the resting condition, finger and artery plethysmogram curves for each subject in repeated measurements showed no significant differences for $h_i$ and $h_d$. However, other PPG wave shape parameters ($t_i$ and $t_d$) within a subject in different $PPG_{fing}$ and $PPG_{art}$ recordings might be similar or in some cases they might show a statistically significant difference.

The forearm blood flow was the only single hemodynamic parameter whose value varied throughout the study in different measurement periods. However, blood flow and PPG data analysis did not show any relationship between these two variables. We therefore propose another hypothesis for the explanation of this variability. From previous studies it is known that systemic and regional hemodynamic parameters are usually subjected to periodic fluctuation. PPG signal amplitude changes over time and has a low frequency of fluctuation, while the cardiac cycle length has a higher frequency and approximately corresponds to the respiratory rate (Nitzan et al. 1998; Avnon et al. 2004). Therefore individual variability of PPG parameters might be caused indirectly by temporal and spatial summation of fluctuations of heart cycle length and changes of peripheral resistance in magistral artery and in each microcirculatory vessels in the tissue region (Nilsson et al. 2003; Munir et al. 2008).

## References

Allen J. 2007. Photoplethysmography and its application in clinical physiological measurement. *Physiol. Meas.* 28: R1–R39.

Allen J., Murray A. 2002. Age-related changes in peripheral pulse timing characteristics at the ears, fingers and toes. *J. Human Hypertension* 16: 711–717.

Allen J., Murray A. 2004. Effects of filtering on multisite photoplethysmography pulse waveform characteristics. *Comput. Cardiol.* 31: 485–488.

Allen J., Oates C.P., Lees T.A., Murray A. 2005. Photoplethysmography detection of lower limb peripheral arterial occlusive disease: a comparison of pulse timing, amplitude and shape characteristics. *Physiol. Meas.* 26: 811–821.

Alnaeb M.E., Alobaid N., Seifalin A., Mikhalidis D.P. and Hamilton G. 2007. Optical techniques in the assesment of peripheral arterial disease. *Curr. Vasc. Pharmacol.* 5: 53–59.

Avnon Y., Nitzan M., Sprecher E., Rogowski Z., Yarnitsky D. 2004. Autonomic asymetry in migraine: augumented parasympathetic activation in left unilateral migraineurs. *Brain* 127: 2099–2108.

Chowienczyk P.J., Kelley R.P., Mac Callum H., Millasseau S.C., Andersson T.L., Gosling R.G., Ritter J.M., Änggård E.E. 1999. Photoplethysmographic assessment of pulse wave reflection. *J. Am. Coll. Cardiol.* 34: 2007–2014.

Crabtree V.P., Smith P.R. 2003. Physiological models of the human vasculature and photoplethysmography. Electronic Systems and Control Division Research, Department of Electronic and Electrical Engineering, Loughborough University, pp. 60–63.

Crilly M., Coch. C., Bruce M., Clark H., Williams D. 2007. Indices of cardiovascular function derived from peripheral pulse wave analysis using radial applanation tonometry: a measurement repeatability study. *Vasc. Med.* 12: 189–197.

Donald A.S., Charakida M., Cole T.J., Fribering P., Chowienczyk P.J., Millasseau S.C., Deanfield J.E., Halcox J.P. 2006. Non-invasive assessment of endothelial function. *J. Am. Coll. Cardiol.* 48: 1846–1850.

Erts R., Spigulis J., Kukulis I., Ozols M. 2005. Bilateral photoplethysmography studies of the leg arterial stenosis. *Physiol. Meas.* 26: 865–874.

Gonzalez R., Manzo A., Delgado J., Padilla J.M., Trenor B., Saiz J. 2008. A computer based photoplethysmographic vascular analyzer through derivates. *Comput. Cardiol.* 35: 177–180.

Hamilton W.F. 1944. The patterns of the arterial pressure pulse. *Am. J. Physiol.* 141: 235–241.

Jago J.R., Murray A. 1988. Repeatability of peripheral pulse measurements on ears, fingers and toes using photoelectric plethysmography. *Clin. Phys. Physiol. Meas*. 9: 319–330

Kelly R., Hayward C., Avolio A., O'Rourke M. 1989. Noninvasive determination of age-related changes in the human arterial pulse. *Circulation* 80: 1652–1659.

Khandanpour N., Armon M.P., Jennings B., Clark A., Meyer F.J. 2009. Photoplethysmography, an easy and accurate method for measuring ankle brachial pressure index: can photoplethysmography replace doppler? *Vasc. Endovasc. Surg.* doi:10.1177/1538574409334829.

Millasseau S.C., Guigui F.G., Kelly R.P., Prasad K., Cockroft J.R., Ritter J.M., Chowienczyk P.J. 2000. Noninvasive assessment of the digital volume pulse: comparison with the peripheral pressure pulse. *Hypertension* 36: 952–956.

Millasseau S.C., Kelly R.P., Ritter J.M., Chowienczyk P.J. 2002. Determination of age-related increases in large artery stiffness by digital pulse contour analysis. *Clinical Sci.* 103: 371–377.

Munir S., Guilcher A., Kamalesh T., Clapp B., Redwood S., Marber M., Chowienczyk P. 2008. Periphera uugumentation index defines the relationship between central and peripheral pulse pressure. *Hypertension* 51: 112–118.

Nilsson L., Johansson A., Kalman S. 2003. Macrocirculation is not the sole determinant of respiratory induced variations in the reflection mode photoplethysmographic signal. *Physiol. Meas.* 24: 925–937.

Nitzan M., Babchenko A., Khanokh B., Landau D. 1998. The variability of the photoplethysmographic signal – a potential method for the evaluation of the autonomic nervous system. *Physiol. Meas.* 19: 93–102.

Ratner E., Nitzan M., Shomer Y., Gutman A., Babchenko A. 1993. Analysis of the photoplethysmographic signal. *Proceedings of the 8th Meeting on Optical Engineering in Israel: Optoelectronics and Applications in Industry and Medicine*, 1972: 410–415.

Takazawa K., Tanaka N., Fujita M., Matsuoka O., Saiki T., Aikawa M., Tamura S., Ibukiyama C. 1998. Assessment of vasoactive agents and vascular aging by the second derivate of photoplethysmogram waveform. *Hypertension* 32: 365–370.

Zheng D., Allen J., Murray A. 2008. Determination of aortic valve opening time and left ventricular peak filling rate from the peripheral pulse amplitude in patients with ectopic beats. *Physiol. Meas.* 29: 1411–1419.