Relationship between arterial pressure and pulse wave velocity using photoplethysmography during the post-exercise recovery period

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Abstract

Blood pressure is an important parameter for health assessment. Noninvasive continuous beat per beat blood pressure measurement is still a complicated and expensive procedure. There is a lack of agreement on the optimal blood pressure measurement technique. Potentially the most useful indirect parameter for blood pressure monitoring could be pulse wave velocity or the inverse – pulse transit time. The objectives of the study was to determine the relationship between blood pressure and pulse wave velocity under conditions when different cardiovascular parameters change independently but simultaneously with blood pressure and to clarify whether there is a difference in relationship between blood pressure and pulse wave velocity measured by two different methods in different vascular beds. We determined the relationship between arterial blood pressure (systolic, mean) and the pulse wave velocity from 20 healthy volunteers during a post-exercise recovery period after a load cycling test. A significant correlation ($p < 0.05$) and regression ($p < 0.001$) between arterial pressure and pulse wave velocity was obtained. Pulse wave velocity measurement measured in different vascular beds showed no impact on correlation of arterial blood pressure and pulse wave velocity. The average difference between measured and calculated arterial blood pressure values did not exceed 10 mm Hg.

Key words: non-invasive continuous blood pressure; photoplethysmography; pulse transit time; pulse wave velocity.

Introduction

In recent years cardiovascular disease has become a major reason for high mortality in western countries; therefore a non-invasive and continuous system for monitoring cardiovascular parameters would be of great interest to clinicists and sport medicine physicians. One of the most important parameter's for the assessment of cardiovascular system is arterial blood pressure (BP). Chronic high blood pressure may lead to cardiovascular diseases and consequently is a risk factor for death. Currently, ambulatory blood pressure monitoring is limited to simple measurement of systolic and diastolic blood pressure at intervals. A continuous measurement of BP might provide more useful

information about a person's health condition in clinics and at home. The most logical approach for continuous cardiovascular monitoring of a large population might be a simple, non-intrusive pressure measurement.

Despite many efforts in the past concerning non-intrusive methods for continuous blood pressure measurement, there is still a lack of agreement on the optimal measurement technique.

Potentially the most useful and convenient indirect parameter for continuos, non-intrusive blood pressure monitoring are either the pulse wave velocity (PWV) or the inverse – pulse transit time (PTT). In general the PTT refers to the time it takes a pulse wave to travel between two arterial sites. There are a number of different sophisticated pulse transit time measurement techniques such as the Ultrasound Doppler, arterial tonometry, and the so called "two point" PPG method (Smith et al. 1999; Kanda et al. 2000; Lykogeorgakis 2002). However, the simplest and most convenient method is to compute PTT as a temporal difference between the R wave in an electrocardiogram (ECG) and the beginning of the following pulse wave measured by photoplethysmography (Lutter et al. 2002; Kazanavicius et al. 2003). The reported disadvantage of this described method however is that it is not possible to obtain a "true" value of the pulse transit time, because of a varying pre-ejection time (Robin et al. 1999). Moreover, research by Pollak et al. (1983) has shown that the isometric contraction time is itself time varying and can also be influenced by the blood pressure and stroke volume. The theoretical framework that outlines the relationship between PTT and blood pressure is well-known by the Moens-Korteweg equation, which connects the pulse wave velocity with dimensions of the vessel and the distensibility of the vessel wall. An acute rise in blood pressure will cause the vascular tone to increase and hence the arterial wall will become stiffer, causing PTT to shorten. Equally, a fall in blood pressure will reduce vascular stiffness and consequently the PTT will become larger (McDonald 1974).

Several studies have confirmed the application of the PTT for pressure measurement (Naschitz et al. 2004; Ahlstrom et al. 2005; Kim et al. 2006; Sharwood-Smith et al. 2006) although others still argue and consider this method to be a weak surrogate-measure (Young et al. 1995; Payne et al. 2006). The relationship between pulse transit time and arterial pressure may vary due to numerous physiological factors.

The elastic properties of the arterial wall are a major determinant of the PTT-BP relationship. This relationship can be altered by active changes to vascular tone, via for example sympathetic activity or a particular duration of the cardiac cycle (Albaladejo et al. 2001; Lantelme et al. 2002). Previous studies have also indicated that various vasoactive substances (such as NO and PGI2) can also change the tone of smooth muscles, hence, modify the compliance of the arterial wall in conduit arteries, which in turn influences PWV.

It is important to resolve the contradictions of the PTT approach for non-intrusive pressure measurement, as mentioned in the literature above. Therefore in this present work we have addressed two major questions. First, to determine the relationship between blood pressure and pulse wave velocity under conditions when different cardiovascular parameters such as heart rate and the stiffness of arterial wall change independently, and simultaneously with blood pressure, as is the case during post-exercise recovery. Second, to clarify whether there is a difference in relationship between blood pressure changes and pulse wave velocity measured by two different methods in different vascular beds – by

radial artery sphygmography in conduit artery and by finger photoplethysmography in a diffuse vascular bed consisting of small arteries and arterioles.

Materials and methods

Subjects

The study was performed on 20 healthy volunteers (10 males and 10 females) aged from 19 to 21 years. Before the experimental procedure subjects completed a questionnaire and the findings were used during a health assessment. Only those individuals with no history of cardiovascular or other serious diseases were admitted to the study. Prior to the experiment all participants were informed about the procedure and informed consent was obtained. This study was approved by the local ethics committee. To calculate PWV, a tape measure was used to measure the distances between *fossa jugularis* and sensor points (index finger tip for PPG and radial artery line for SFG). The base P was obtained non-invasively. To alter the P, the subject performed a graded bicycle exercise test. Subjects cycled at three different stages: males – 2 min at 150 W, 2 min at 180 W and 3 min at 210 W; females – 2 min at 120 W, 2 min at 150 W and 3 min at 180 W.

The exercise and measurements were carried out in a well-ventilated room at temperature 23 to 25 °C.

We began data acquisition from one minute after cycling cessation and continued until the pressure returned to baseline. While measurements were recorded the subject's sat comfortably on the veloergometer seat. Measurement sensors were attached to the subject in the following manner: the cuff of P monitor on the right hand brachial artery at elbow, PPG on left hand index finger, SFG on the left hand radial artery. ECG was recorded from III limb lead.

Measurement technique and equipment

A previously tested and approved custom-made, one channel amplifier ECG-1 was used to record ECG's. To register SFG, a pressure transducer (PFSG-064) with a discrimination of 0.1 mm Hg was placed on the right arm on skin over the radial artery in the site where the maximal mechanical pulsation was palpated. The PPG signal was recorded from the right index finger using our custom-made one channel PPG device (University of Latvia ASI) with a wavelength of 940 nm.

All sensors (outputs) were connected to a 16-bit data acquisition card (SAMP-9, Umeå, Sweden), data sampled at 800 Hz and stored for further analyses.

PM was computed using an oscillometric method (Rithalia et al 2000). We developed a special custom-made set by attaching the cuff of a portable digital blood pressure monitor (UA-767 Plus, A&D Instruments LTD®) to a laboratory pressure transducer (BP1-B, World Precision Instruments Inc®). The transducer output was sampled, and PM computed via off-line analysis using Winzoom software package. The systolic blood pressure value was obtained from a digital blood pressure monitor as a single readout from LCD display.

All measurements (PPG, SFG, ECG and P) were continuously recorded during cuff deflation (approximately 25 s). The cuff was inflated again for 15 s and the recording was stopped until the next measurement. This therefore allowed the physiological signals to be registered in separate blocks, each lasting approximately 25 s. The number of blocks for a single subject depended upon the pressure recovery rate, thus the average number of
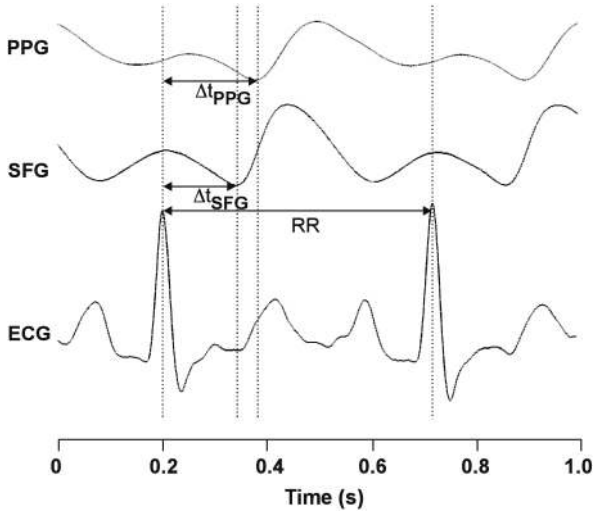
Fig. 1. ECG and simultaneously measured PPG and SFG pulse. Three different parameters were obtained for further research: the time interval between the ECG R wave and the start point of PPG pulse wave (Δt_{PPG}) and SFG pulse wave (Δt_{SFG}) and the time interval between the two ECG R waves (RR).

blocks (pressure readouts) varied individually from 10 to 14. The PPG and SFG pulse wave delay times (*Pulse Transit Time*) Δt_{SFG}, Δt_{PPG} (defined as the time interval between the ECG R wave and the start point of pulse wave) were computed by Winzoom using the method previously described by many authors (Drinnan et al. 2001; Lutter et al. 2002; Nitzan et al. 2002; Kazanavicius et al. 2003) (Fig. 1).

PPG and SFG Pulse wave velocities (PWV_{PPG} and PWV_{SFG}) were calculated using the Matlab (Math Works®) software package. To reduce the influence of the respiratory system we averaged 10-15 successive cardiac cycles (overlaps at least one respiration cycle), so that each block had a single RR, Δt_{SFG}, Δt_{PPG} value (Asmar et al. 1995).

Statistics
Statistical analysis of the data was performed on SigmaStat 2.0, SPSS 10.0 (SPSS®) and Matlab 5.3 (Math Works®) software packages.

Appropriate statistical methods were selected after the Kolmogorov-Smirnov normality test prior to other statistical procedures. The correlation (Pearson or Spearman) between PWV and PS as well as PWV and PM was calculated for both PPG and SFG signals. The same data was tested on different regression models to best fit the regression curve. We used a linear regression analysis (PWV as a dependent and P_S independent) to determine the coefficients of equation for calculation of arterial pressure from PWV measured by two different methods: PPG and SFG (PWV_{PPG} and PWV_{SFG}). The preceeding analyses were performed for single subjects ($12 < n < 16$) and between subjects ($n = 20$). To examine whether regression slopes of PWV_{PPG} and PWV_{SFG} are equal, we performed analyses of covariance (ANCOVA) for individual subjects (Neter, Wasserman 1974). To test whether PWV_{PPG} and PWV_{SFG} have the same correlation, we compared correlation coefficients (using a t-Test).

Results

Almost all measured parameters followed a normal distribution, and in most cases it was possible to apply parametric tests.

Fig. 2 shows pulse wave velocity (derived from pulse wave transit time), arterial blood pressure (systolic, mean) and duration of heart cycle (as R-R interval) recorded during the post-exercise recovery period. The pulse wave velocity measured by PPG (PWV_{PPG}) was significantly higher than the pulse wave velocity measured by SFG (PWV_{SFG}) ($p < 0.001$) (Fig. 3).

We observed a significant correlation between P_S vs PWV_{PPG} ($r = 0.856 \pm 0.109$; $p < 0.05$), P_S vs PWV_{SFG} ($r=0.850 \pm 0.091$; $p<0.05$), PM vs PWV_{PPG} ($r = 0.807 \pm 0.095$; $p < 0.05$) and P_M vs PWV_{SFG} ($r = 0.815 \pm 0.071$; $p < 0.05$), and there was no significant difference between correlation coefficients when we compared PWV_{PPG} with PWV_{SFG} (Fig. 4).

All data were significantly fitted to a linear regression model ($p < 0.001$), and slopes of the regression lines were significantly equal for P~PWV_{PPG} and P~PWV_{SFG} (PWV_{SFG} vs P_S and PWV_{PPG} vs P_S; PWV_{SFG} vs P_M and PWV_{PPG} vs PM) (Fig. 5).

Finally we used the linear regression equation

$$P = \frac{PWV - a}{b} \qquad (1)$$

with individual regression coefficients (a, b) and values of PWV (PWV_{PPG}, PWV_{SFG}) to compute P_S and P_M.

The precision of calculated P_S and P_M, was assessed by subtracting computed values from those measured. On average the difference did not exceed 10 mm Hg (error was plus or minus; Fig. 6).
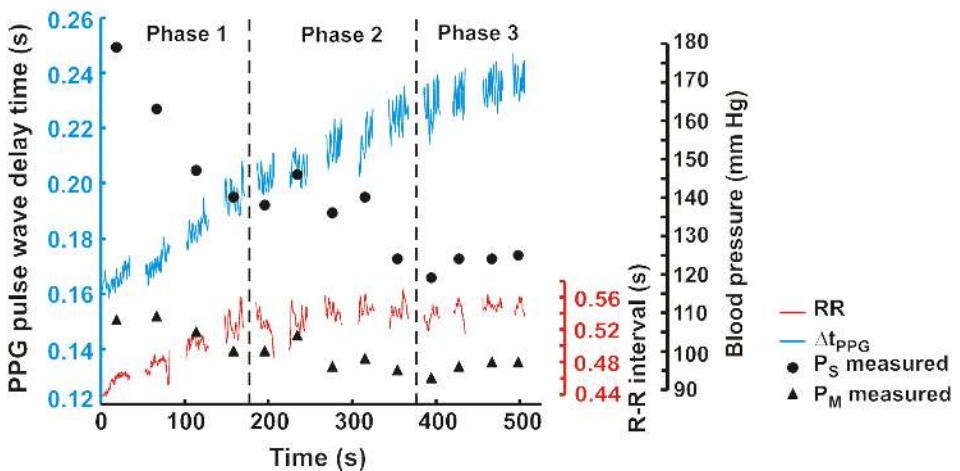

Fig. 2. Pulse wave delay time (Δt), systolic blood pressure (P_S), mean blood pressure (P_M) and duration of heart cycle (RR) – in the whole recovery period for one subject.
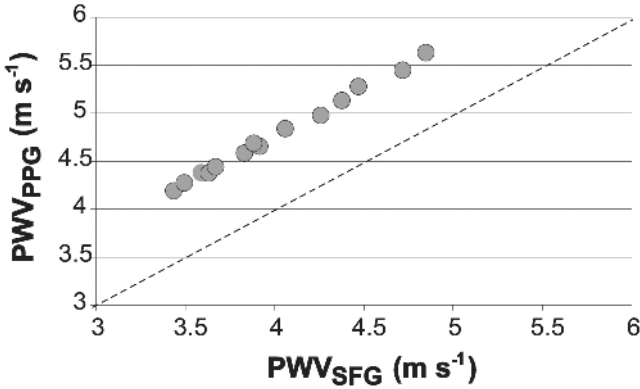
Fig. 3. Comparison of pulse wave velocity (PWV) measured by two different methods on different vascular beds – radial artery sphygmography (PWV_{SFG}) and finer photoplethysmography (PWV_{PPG}). The graph shows PWV data from one subject.
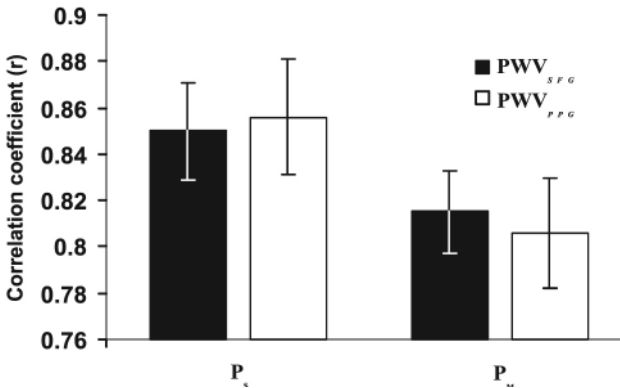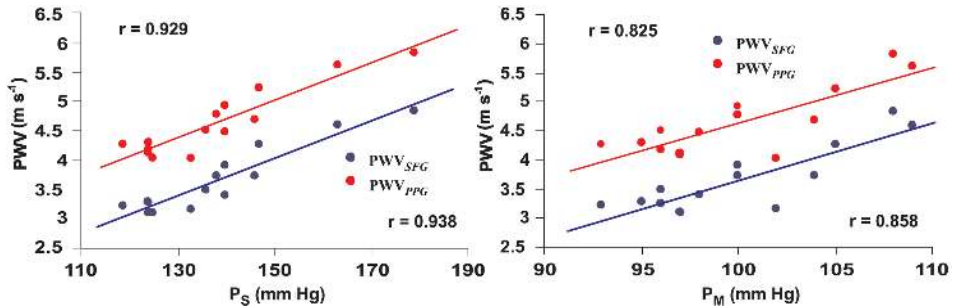

Fig. 4. Comparison of correlation coefficients (P_S vs PWV_{PPG} and PWV_{SFG}, PM vs PWV_{PPG} and PWV_{SFG}). Error bars show value of standart error.

Discussion

In this study we assessed the relationship between blood pressure and pulse wave velocity registered by PPG and SFG under conditions when different cardiovascular parameters such as heart rate and the stiffness of arterial wall change independently but simultaneously with blood pressure. As we predicted, there was a difference between PWV measured by PPG and PWV measured by SFG. The values of PWV, measured at different arterial sites, was not the same, likely due to other influencing factors, such as the reflection of pressure waves and different flow distributions within the arterial system. Differences in PWV measurement methods also should be taken into account. Both the SFG and the PPG records pulse waves, but they do so on the basis of different physical parameters – SFG measures oscillations of conduit artery diameter, while for PPG – blood volume oscillations are measured from a diffuse vascular bed.

    We assume that in our case the most important factor that leads to the PWV_{PPG}

Fig. 5. Comparison of P (P_S in A, P_M in B) and PWV regression slopes when PWV was measured by different methods in different sites: sphygmography (PWV_{SFG}) and photoplethysmography (PWV_{PPG}). Upper correlation coefficient (r) for upper regression line, lower r for lower regression line. The graph shows typical data from on subject.
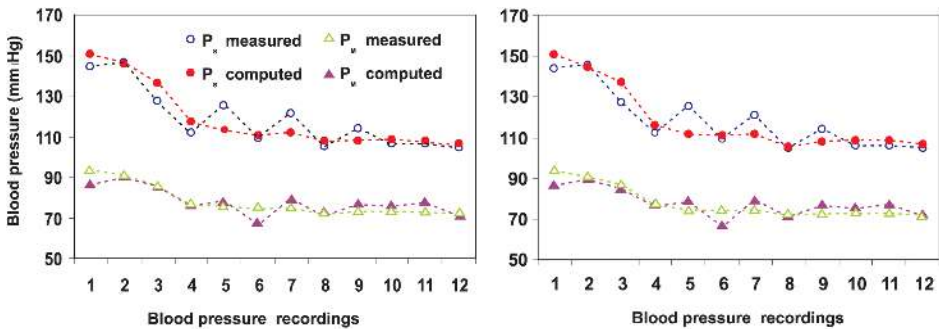
Fig. 6. Comparison of blood pressure values obtained by a conventional compression blood pressure measurement apparatus ($P_{S, M}$ measured) versus blood pressure values obtained based on the pulse wave velocity measurements ($P_{S, M}$ computed). A, PWV measured by SFG; B, PWV measured by PPG. The graph shows typical blood pressure data obtained during the recovery period after the cycling test.

recordings being higher than PWV_{SFG} is the difference in vascular beds, which is where a pulse wave travels and from which the signal is taken. Pulse waves travel from the heart to the radial artery line, but also from the heart to the fingertip. The common part of both paths (PPG and SFG) are large elastic type arteries and conduit arteries. However, 18 to 23 cm path for the PPG recording were only the small, muscular arteries and capillaries, which are located in the palm and fingers tissue. There is evidence that PWV in muscular arteries is higher than in elastic arteries (McDonald 1974; Harada et al. 2002). Thus, it seems reasonable that different vascular beds can have different influences on correlation of PWV~P.

Our study revealed that, contrary to results of other authors (Young et al. 1995, Payne et al. 2006) both PWV_{SFG}~P and PWV_{PPG}~P relationships are linear, PWV~P regression lines have the same slopes and finally the correlation coefficients for both P~PWV_{PPG} and P~PWV_{SFG} did not differ significantly.

As other authors (Barschdorff, Erig 1998; Kazanavicius et al. 2003; Lass et al. 2004; Kim et al. 2006) we also have confirmed in our study a close correlation between PWV

and arterial pressure.

Other authors confirm that PWV is not the only parameter that represents P changes, but others such as heart rate, elasticity of arterial wall and arterial vasomotions may also play a crucial role in blood pressure determination (Lu et al. 1992; Chen et al. 2000; Naka et al. 2003).

Previous studies (Mircoli et al. 1999; Drinnan et al. 2001; Lantelme et al. 2002) have proposed that the heart rate may change PWV by itself, thus there is a necessity to include this in P calculations. Others have shown that heart rate has no clear effect (Kingwell et al. 1997; Lass et al. 2004). Such controversial reports can possibly be explained by the involvement of various regulatory mechanisms that alter pressure in different ways. It is known that in many other studies, the experimental protocol was very similar to ours in that alterations of arterial pressure were induced by physical load. Recent studies showed that the application of a physical task usually leads to change of sympathetic tone, which in turn will increase heart rate (Mircoli et al. 1999). Moreover, regulatory hemodynamic mechanisms are not simple, because the sympathetic nervous system (sympathetic tone) may affect elastic-type and muscle-type arteries differently. Dynamics of the after-exercise recovery process itself may depend on various other factors such as age, type of nervous system and the individual properties of every subject whereby the physiological mechanisms involved can be very distinctive. For example, after-exercise hyperaemia itself may increase a linear velocity of the blood flow which consequently may change arterial tone by the mechanism of endothelium dependent flow mediated dilation (ref FMD). Recent research proved that flow mediated dilution has an remarkable effect on pulse wave velocity (Naka et al. 2006).

Our analyses of the recovery curves for 20 subjects showed that they involve different specific physiological mechanisms, and it was possible to split the whole process in to three consequent phases, based on changes in parameters (Fig. 2).

During the first phase (phase I) arterial pressure (P_M, P_S) and heart rate decrease rapidly and monotonously. During the second phase (phase II) the pressure continues to decrease but the heart rate remains fairly stable, because of its rapid recovery in the previous phase. During the final, third phase (phase III) the values of those three parameters do not change significantly, but the dynamics of pulse wave velocity still shows that relatively slower changes are still occurring, possibly due to normalisation of vascular tone.

We conclude that The PWV~P relationship which is unique for each individual, and that itremains stable during post-exercise restitution. Other factors that change along with P (heart rate and arterial tone) which might influence PWV did not show an impact on PWV~P relationship.

References

Ahlstrom C., Johansson A., Uhlin F., Länne T., Ask P. 2005. Noninvasive investigation of blood pressure changes using the pulse wave transit time: a novel approach in the monitoring of hemodialysis patients. *J. Artif. Organs* 8: 192–197.

Albaladejo P., Copie X., Boutouyrie P., Laloux B., Declere A.D., Smulyan H., Benetos A. 2001. Heart rate, arterial stiffness, and wave reflections in paced patients. *Hypertension* 38: 949–952.

Asmar R., Benetos A., Topouchian J., Laurent P., Pannier B., Brisac A.M., Target R., Levy B.I. 1995. Assessement of arterial distensibility by automatic pulse wave velocity measurement. Validation and clinical application studies. *Hypertension* 26: 485–490.

Barschdorff D., Erig M. 1998. Continuous blood pressure monitoring during stress ECG. *Biomed. Tech.* 43: 34–39.

Chen W., Kobayashi T., Ichikawa S., Takeuchi Y., Togawa T. 2000. Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. *Med. Biol. Eng. Comput.* 38: 569–574.

Drinnan M.J., Allen J., Murray A. 2001. Relation between heart rate and pulse transit time during paced respiration. *Physiol. Meas.* 22: 425–432.

Harada A., Okada T., Niki K., Chang D., Sugawara M. 2002. On-line noninvasive measurements of pulse wave velocity. *Heart Vessels* 17: 61–68.

Kanda T., Nakamura E., Moritani T., Yamori Y. 2000. Arterial pulse wave velocity and risk factors for peripheral vascular disease. *Eur. J. Appl. Physiol.* 82: 1–7.

Kanda T., Nakamura E., Moritani T., Yamori Y. 2000. Arterial pulse wave velocity and risk factors for peripheral vascular disease. *Eur. J. Appl. Physiol. Occup. Physiol.* 82: 1–7.

Kazanavicius E., Gircys R., Macikenas E. 2003. Determination of arterial blood pressure using the pulse transit time. *Informacines Technologijos ir Valdymas* 4: 23–29.

Kim J.S., Chee Y.J., Park J.W., Choi J.W., Park K.S. 2006. A new approach for non-intrusive monitoring of blood pressure on toilet seat. *Physiol. Meas.* 27: 203–211.

Kingwell B.A., Berry K.L., Cameron J.D., Jennings G.L., Dart A.M. 1997. Arterial compliance increases after moderate-intensity cycling. *Am. J. Physiol.* 273: H2186–H2191.

Lantelme P., Mestre C., Lievre M., Gressard A., Milon H. 2002. Heart rate: an important confounder of pulse wave velocity assessement. *Hypertension* 39: 1083–1087.

Lass J., Meigas K., Kattai R., Karai D., Kaik J., Rossmann M. 2004. Optical and electrical methods for pulse transit time measurement and its correlation with arterial blood pressure. *Proc. Estonian Acad. Sci.* 10: 123–126.

Loukogeorgakis S., Dawson R., Phillips N., Martyn C.N., Greenwald S.E. 2002. Validation of a device to measure arterial pulse wave velocity by a photoplethysmographic method. *Physiol. Meas.* 23: 581–596.

Lu W., Li H., Tao S., Zhang D., Jiang Z., Cui L., Tu J., Gou D. 1992. Research on the main elements influencing blood pressure measurement by pulse wave velocity. *Front. Med. Biol. Eng.* 4: 189–199.

Lutter N., Siebert C., Schuettler J. 2002. Continuous noninvasive blood pressure measurement: can accuracy be improved by comprising variations of the pulse waveform amplitude. *Abstracts of the Society for Technology in Anesthesia Annual Meeting:* http://www.anestech.org/media/Publications/Annual_2002/Lutter.html.

McDonald D.A. 1974. *Blood Flow in Arteries*. 2nd ed. Edward Arnold Ltd, London.

Mircoli L., Mangoni A.A., Giannattasio C., Mancia G., Ferrari A.U. 1999. Heart rate-dependent stiffening of large arteries in intact and sympathectomized rats. *Hypertension* 34: 598–602.

Naka K.K., Tweddel A.C., Doshi S.N., Goodfellow J., Henderson A.H. 2006. Flow-mediated changes in pulse wave velocity: a new clinical measure of endothelial function. *Eur. Heart J.* 27: 302–309.

Naka K.K., Tweddel A.C., Parthimos D., Henderson A., Goodfellow J., Frenneaux M.P. 2003. Arterial distensibility: acute changes following dynamic exercise in normal subjects. *Am. J. Physiol. Heart Circ. Physiol.* 284: H970–H978.

Naschitz J.E., Bezobchuk S., Mussafia-Priselac R., Sundick S., Dreyfuss D., Khorshidi I., Karidis A., Manor H., Nagar M. Peck E.R., Peck S., Storch S., Rosner I., Gaitini L. 2004. Pulse transit time by R-wave-gated infrared photoplethysmography: review of the literature and personal experience. *J. Clin. Monit. Comput.* 18: 333–342.

Neter J., Wasserman W. 1974. *Applied Linear Statistical Models: Regression, Analyses of Variance, and Experimental Design*. Richard D. Irwin, Homewood, Illinois.

Nitzan M., Khanokh B., Slovik Y. 200.2 The difference in pulse transit time to the toe and finger measured by photopletysmography. *Physiol. Meas*. 23: 85–93.

Payne R.A., Symeonides C.N., Webb D.J., Maxwell S.R.J. 2006. Pulse transit time measured from the

ECG: an unreliable marker of beat-to-beat blood pressure. *J. Appl. Physiol.* 100: 136–141.

Pollak M.H., Obrist P.A. 1983. Aortic-radial pulse transit time and ECG Q-wave to radial pulse wave interval as indices of beat-by-beat blood pressure change. *Psychophysiology* 20: 21–28.

Rithalia S., Sun M., Jones R. 2000. *Blood Pressure Measurement - The Measurement, Instrumentation, and Sensors Handook*. Webster J.G. (ed), CRC Press LLC, N.W.

Robin P.S., Jerome A., Jean L.P., Patrick A.L. 1999. Pulse transit time: an appraisal of potential clinical applications. *Thorax* 54: 452–457.

Sharwood-Smith G., Bruce J., Drummond G. 2006. Assessment of pulse transit time to indicate cardiovascular changes during obstetric spinal anaesthesia. *British J. Anaesthesia* 96: 100–105.

Smith R.P., Argod J., Pepin J.-L., Levy P.A. 1999. Pulse transit time: an appraisal of potential clinical applications. *Thorax* 54: 452–845.

Young C.C., Mark J.B., White W., DeBree A., Vender J.S., Fleming A. 1995. Clinical evaluation of continuous noninvasive blood pressure monitoring: accuracy and tracking capabilities. *J. Clin. Monit.* 11: 245–252.