J Med Syst (2009) 33:261–266
DOI 10.1007/s10916-008-9186-0

ORIGINAL PAPER

Non-constrained Blood Pressure Monitoring Using ECG and PPG for Personal Healthcare

Youngzoon Yoon · Jung H. Cho · Gilwon Yoon

Received: 20 April 2008 / Accepted: 18 June 2008 / Published online: 8 July 2008

Abstract Blood pressure (BP) is one of the important vital signs that need to be monitored for personal healthcare. Arterial blood pressure (BP) was estimated from pulse transit time (PTT) and PPG waveform. PTT is a time interval between an R-wave of electrocardiography (ECG) and a photoplethysmography (PPG) signal. This method does not require an aircuff and only a minimal inconvenience of attaching electrodes and LED/photo detector sensors on a subject. PTT computed between the ECG R-wave and the maximum first derivative PPG was strongly correlated with systolic blood pressure (SBP) (R=−0.712) compared with other PTT values, and the diastolic time proved to be appropriate for estimation diastolic blood pressure (DBP) (R=−0.764). The percent errors of SBP using the individual regression line (4–11%) were lower than those using the regression line obtained from all five subjects (9–14%). On the other hand, the DBP estimation did not show much difference between the individual regression (4–10%) and total regression line (6–10%). Our developed device had a total size of 7×13.5 cm and was operated by single 3-V battery. Biosignals can be measured for 72 h continuously without external interruptions. Through a serial network communication, an external personal computer can monitor measured waveforms in real time. Our proposed method can be used for non-constrained, thus continuous BP monitoring for the purpose of personal healthcare.

Keywords Blood pressure · Pulse transit time · Health monitor · Personal healthcare

Y. Yoon · J. H. Cho · G. Yoon
Institute for Biomedical Electronics,
Seoul National University of Technology,
Seoul, South Korea

G. Yoon (✉)
Department of Electronics & Information,
Seoul National University of Technology,
172 Kongneung-dong Nowon-gu,
Seoul 139-743, South Korea
e-mail: gyoon@snut.ac.kr

Introduction

Non-constrained and continuous blood pressure (BP) measurement is preferred for ubiquitous healthcare application or remote diagnosis. There are several noninvasive methods to measure BP such as cuff sphygmomanometer, arterial tonometer [1–3]. Cuff sphygmomanometer is not continuous beat–beat measurement of BP since it requires periodic cuff inflation and deflation. Sleep of a subject is disturbed by pressure on the arm or noise generated when the cuff is operated [4]. Arterial tonometry has the possibility of monitoring BP continuously. However, due to wrist motion and high sensitivity to sensor position, the arterial tonometer is not convenient for use in rough environment [5]. A portable hand-held health monitor was developed for measuring vital signs where an aircuff on finger was installed to measure BP [6]. Though the device was small enough to carry, nevertheless non-constrained BP measurement was not possible. It was reported that noninvasive, cuffless and continuous measurement of BP can be done by R-wave-gated infrared photoplethysmography (PPG) [7–9]. This method can be applied for continuous portable BP monitoring system.

The volumetric elasticity of blood vessel increases when BP increases. This makes vessel wall stiff and the pulse wave propagation velocity is increased. Conversely, a fall in BP causes the velocity to decrease. The pulse wave

propagation velocity is represented as the pulse wave propagation distance divided by time. Pulse transit time (PTT), which is the time for pulse wave to travel between two arterial sites, is inversely proportional to BP [10, 11]. Other parameters that are related with BP are systolic and diastolic time. Therefore, pulse waveform analysis has been applied for BP measurement [5, 12]. However, several researchers have reported that R-wave-gated PPG methods are poor to estimate BP [8, 13, 14]. This inconsistency may have been induced by several factors such as age, sex, BP difference, day-to-day variations and environmental conditions including temperature and experimental errors during measurement.

To investigate the reliability and repeatability of a proposed medical measurement method, it is important to validate obtained physiological data under various experimental conditions. Since cardiovascular features are different from a subject to a subject and day-to-day [15–17], there are individual differences and day-to-day variations in predicting BP using R-wave-gated PPG signals. It is very important to find out how much the BP estimation varies depending on a subject or in terms of time.

In this study, we developed a compact device that can measure ECG and PPG simultaneously. From PTTs computed from the intervals between ECG and PPG and PPG waveforms, we found the best way to estimate arterial blood pressure. Not only BP, this device provides ECG waveforms and pulse rate, it can be a useful device for monitoring cardiovascular activities for the purpose of personal health care.

Methods

The device should be compact and be operated at single DC battery. We developed a system based on an 8-bit single chip microcontroller (ADuc812, Analog Devices™, USA) as the main controller and its block diagram is illustrated in Fig. 1. Signals at the electrode sensors were put to a high CMRR differential DC amplifier (Instrumentation amplifier) and ECG waveforms were obtained after notch filtering (60 Hz power noise), high pass (HP) filtering and low pass (LP) filtering. PPG waveforms were measured by measuring light that was backscattered from a finger. In order to be operated by a 3-V battery, signal ground was set at about 1.2 V. Low voltage operation as well as minimal power-consumption designs enabled to run the unit 72 h with two AA batteries. The monitoring system is not limited to measuring blood pressure in non-constrained manner. Our device has been developed as a remote diagnostic device for the purpose of telemedicine. The monitoring system does not consist of a commercial ECG meter and PPG meter. The device had a total size of 7×13.5×1 cm. An external PC connected through a serial channel can monitor waveforms in real time. All the measured data (ECG, PPG, PTT, pulse rate) are also stored to an on-board SD memory. One can take the SD memory card and can read in a different PC. It is a versatile device for monitoring individual health status.

Experiments were conducted from 9:00 to 12:00 A.M. in a quiet environment and at a room temperature of 23°C±2°C. Five healthy male volunteers (age: 25–30 years, body mass index: 22–27 kg/m^2) were recruited. The written consent for experiment and use of measured data in clinical analysis were obtained from each subject. The subjects refrained from smoking and caffeine ingestion at least six hours prior to the experiment. ECG and PPG signals were recorded simultaneously for 60 s at a sampling rate of 227 Hz with a self-developed portable device. ECG signals were measured by the standard lead II configuration. Backscattered light from the right hand index finger were measured as PPG signal. Measured signals were transferred to a personal

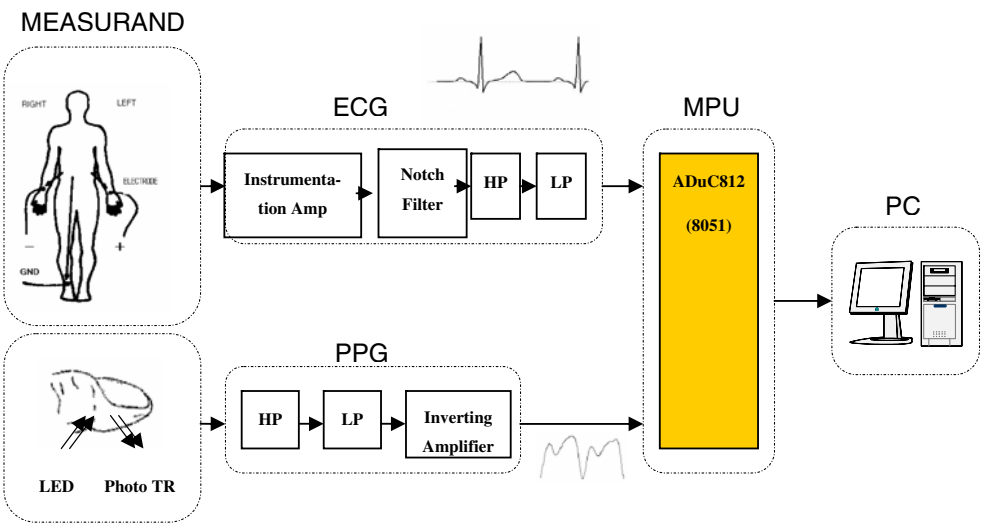

Fig. 1 R-wave gated PPG system

computer where waveforms were monitored and analyzed. Blood pressure was measured by a digital oscillometric BP meter (BP-1M, Casio^{TM}) at the left upper arm as a reference simultaneously. Eighteen seconds data of the middle of the 60-s measurement were analyzed in order to match the actual BP measurement time. PPG, ECG and BP were recorded simultaneously at a seated position after the subjects had rested for at least 5 min. Immediately after 100 step-climbing exercise (each step was 21 cm high), another measurements were recorded as post-exercise data at the same seated position. This measurement trial was repeated three times during the same day. Each trial had at least 20 min time interval to avoid the exhaustion of the subject. The experiments were repeated for 5 days with the same subjects.

PPG and ECG signals were analyzed as shown in Fig. 2 to calculate five characteristic parameters. These are pulse transit time from the ECG R peak to the PPG waveform onset (PTT_foot), pulse transit time from the ECG R peak to the PPG waveform maximum derivative point (PTT_dp), systolic upstroke time (Sys_t1), diastolic time (Dia_t2) and the width of 2/3 pulse amplitude (2/3 wt). Analysis was automatically performed with the aid of Labview^{TM} (National Instrument, USA).

For all the measured data, correlation analysis was conducted on BP and each of the characteristic parameters. The parameters with the highest mean correlation coefficient were used to study the individual difference and day-to-day variation. Linear regression analysis in the form of $y=ax+b$ was set up for systolic blood pressure (SBP) and diastolic blood pressure (DBP) respectively. Regression analysis was done using total datasets of five persons (total calibration) as well as using the individual dataset of each subject (individual calibration). The absolute mean errors were computed from measured and estimated BP values. In the Total Calibration, the same regression formula obtained from all the data sets was used to calculate the estimation error for each subject. The individual calibration restricted calibration and estimation data to be data of the same individual. In the individual calibration, a regression line was obtained using the data of four days as leaving one day dataset. The remaining 1 day data set was predicted and errors were computed, which is so called 'leave-one-out' method [18, 19]. Estimation of BP for each day was done in the same manner. Parameters were compared by using Student's paired t test and one-way analysis of variance. Any p value less than 0.05 were accepted as significant, and we used the Kolmogorov–Smirnov test to determine the normality and homogeneity assumptions.

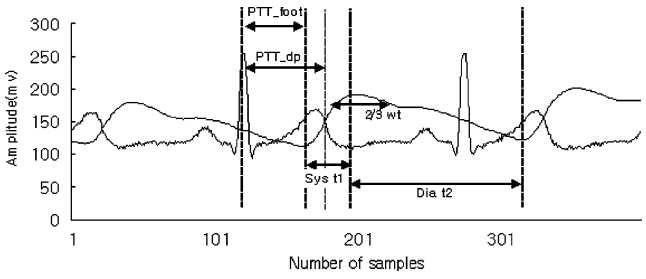

Fig. 2 Characteristic indices for PPG and ECG waveforms. *PTT_ dp* Pulse transit time from ECG R peak to the maximum first derivative PPG point; *PTT_ foot* pulse transit time from ECG R peak to PPG waveform onset; *Sys_t1* systolic upstroke time; *Dia_t2* diastolic time; *2/3 wt* width of 2/3 PPG pulse amplitude

Results

Table 1 shows the mean correlation coefficients (R) between the PPG parameters and BP. The pulse transit time to a maximum first derivative point (PTT_dp) is highly correlated with SBP. The diastolic time (Dia_t2) had the highest correlation with DBP.

Table 2 summarizes the results when PTT_dp estimated SBP and Dia_t2 estimated DBP. The PTT_dp increment of subject 2 in the regression formula was substantially higher than that of the Total Calibration. The Dia_t2 slope of the regression formula for subject 3 was much lower than that of subject 1. There were the subjects of similar regression line to the Total Calibration result (subject 3, 5) as can be seen in Table 2. The regression lines of subjects 1 and 2 were different to the regression line of the Total Calibration although they have high correlation coefficients.

The absolute mean estimation errors were given in Table 3. As expected, the Individual Calibration generally produced substantially lower SBP errors compared with the total calibration. However, DBP errors were only slightly small for the Individual Calibration. Bland–Altman plots [20] using PTT_dp and Dia_t2 for subject 2 were shown in Fig. 3. The mean of BP differences for the total calibration was not close to zero, while it was almost zero for the Individual Calibration. Figure 4 gives day-to-day variations of BP estimation error for subject 2. SBP errors from the

Table 1 The total (n=5, 5-day data) mean correlation coefficients between various PTT indices and blood pressure

R	SBP	DBP
PTT_dp	−0.712	−0.422
PTT_foot	−0.652	−0.255
Sys t1	−0.605	−0.663
Dia t2	−0.605	−0.764
2/3 wt	−0.327	−0.381

PTT_dp pulse transit time from ECG R peak to the maximum first derivative PPG point; *PTT_foot* pulse transit time from ECG R peak to PPG waveform onset; *Sys_t1* Systolic upstroke time; *Dia_t2* Diastolic time; *2/3 wt* width of 2/3 pulse amplitude.

Table 2 Individual differences in PTT_dp versus SBP and Dia t2 vs. DBP linear regression fitting

	PTT_dp vs. SBP	*R*	Dia t2 vs. DBP	*R*
Total (n=5)	$-1.10x+402$	0.712	$-9.49x+1400$	0.764
Subject 1	$-0.92x+396$	0.740	$-14.12x+1864$	0.744
Subject 2	$-1.94x+529$	0.893	$-9.13x+1322$	0.606
Subject 3	$-1.10x+382$	0.867	$-5.77x+1053$	0.582
Subject 4	$-1.37x+423$	0.839	$-10.97x+1518$	0.438
Subject 5	$-1.03x+390$	0.817	$-10.85x+1473$	0.720

total calibration were maintained to be significantly higher than the individual calibration case. On the other hand, the differences became smaller for DBP estimation.

Discussion

In our investigation, we found that PTT_dp allowed best estimation of SBP and Dia_t2 was best used to estimate DBP. Our results were in good agreements with the previous reports [5, 10, 16, 21]. PTT_dp was more tightly correlated with BP than PTT_foot. It might be caused by a difficulty involved in computing accurate positions of the onset of PPG waveform since the PPG waveform was often distorted by motion artifact or other noise. In order to use PPG_foot as a regression parameter, distortions should be compensated by some signal processing method such as the wavelet analysis [5]. However, PPG_dp was a good substitution of the PPG_foot with additional advantages such as the easy signal processing of simply finding the first derivative maximum value. The other extracted parameters were less well correlated with SBP and DBP. PTT itself did not satisfy the standards for clinical use to estimate DBP due to a poor correlation with BP. To estimate DBP, PPG waveform analysis was better than PTT. Though the previous studies reported that the width of two-third pulse amplitude has some possibility to correlate with BP [5, 12], 2/3 wt was not adequately correlated with BP in our study. The width of some value of pulse amplitude does not seem to be appropriate for clinical use.

The regression lines of BP versus the extracted parameters showed substantial difference whether BP prediction was made using total or individual datasets. We tried to minimize the influence of other external variables by setting a room temperature of 23°C and by having the subjects of similar classifications (healthy males of 25–30 years old with a body mass index between 22–27 kg/m^2). Still, each individual has his own physical features that give different values for the regression curves of BP versus PTT related parameters. This verifies that regression estimation using many individuals is not recommended to predict BP of an individual. Especially in estimating SBP, the error ranges were contrasted between the total (9–14%) and individual calibration (4–11%).

On the other hand, the diastolic blood pressure estimation did not show much percent error difference between the individual regression (4–10%) and total regression line (6–10%). The arterial wave propagation velocity is inter-subject dependent [2, 17]. The factors affecting the velocity might be arterial length, arterial radius, or arterial stiffness. In addition, there will be sex or age difference [16, 22]. Hosaka et al. pointed out that the pulse pressure was correlated with the regression slope [4]. They found the calibration of the regression line by choosing an appropriate slope value without having a stress test. As shown in Fig. 5, the pulse pressure was strongly correlated (R=−0.712) with the PTT_dp slope for SBP estimation. But for DBP estimation the PTT_dp slope was weakly correlated (R=−0.422) with the pulse pressure. For DBP calibration, the Dia_t2 slope was better correlated than other parameters (R=−0.762) with the pulse pressure, but the same slope gave a lesser correlation (R=−0.605) with SBP. Better SBP and DBP estimations can be made by selecting appropriate PTT related parameters. The individual calibration also produced smaller day-to-day variation errors with substantially smaller for systolic pressure and with a lesser degree for diastolic pressure. In terms of day-to-day variation, the individual BP estimation using its own regression line should be used.

Table 3 The absolute mean estimation errors (%): |Estimated-measured|/measured×100

	Total calibration (%)		Individual calibration (%)	
	SBP error	DBP error	SBP error	DBP error
Subject 1	14±9	9±8	11±8	5±4**
Subject 2	11±9	7±5	4±2***	5±4
Subject 3	13±6	6±5*	7±7**	9±7
Subject 4	11±8	10±6	7±4*	10±6
Subject 5	9±7*	9±6	10±8	8±5

Total calibration from the regression line obtained using all the data of five subjects to estimate BP. Individual calibration used the subject's own data for calibration and estimation. The leave-one-out individual regression line formula was used to compute the estimation errors.
*p<0.05 **p<0.001, ***p<0.0001

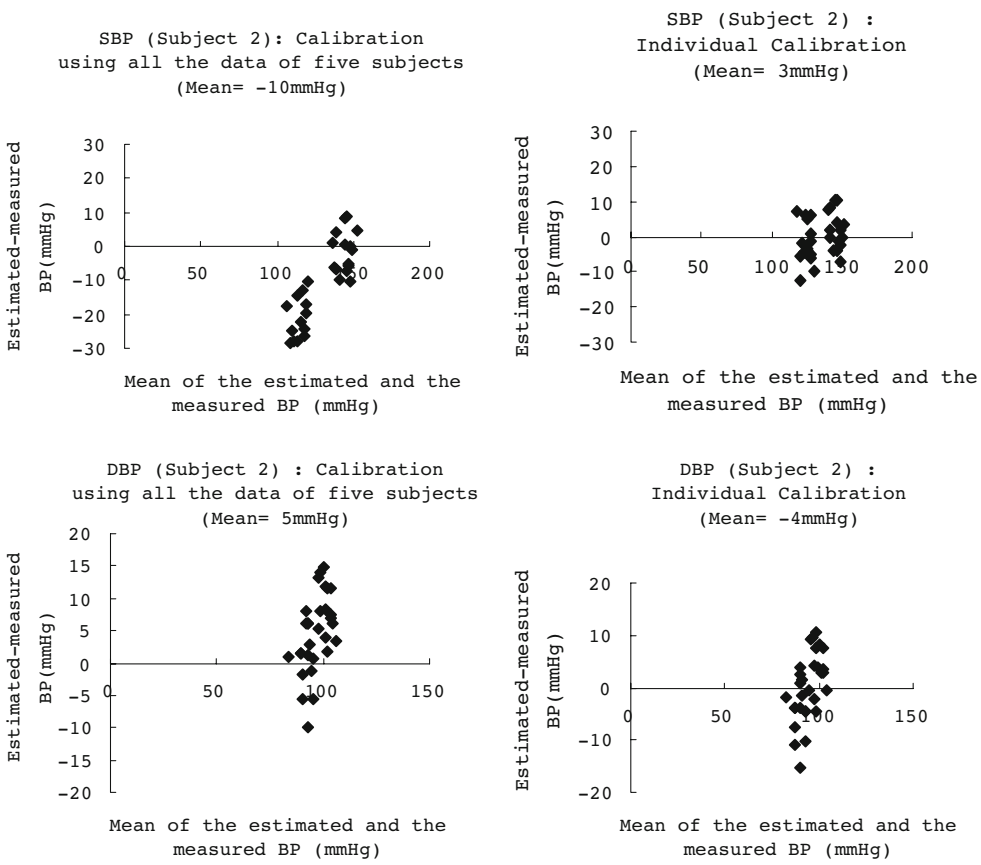

Fig. 3 Bland–Altman plot of the subject 2 BP calibrated using whole five subjects regression line formula to estimate BP and individual calibration using the leave-one-out individual regression line formula to estimate BP

In conclusion, the pulse transit time from ECG R-peak to the maximum first derivative PPG point was the best parameter for SBP estimation and the diastolic time for DBP estimation. Prediction of day to day variations was not significantly different from reference values and should be considered for experimental design. Our subject group was a young healthy male group. If we expand our subject group to include female or different-age group, lesser regression and higher percent errors are expected. It was reported that PTT decreases with aging and pulse waveform is different with aging, sex or illness [22–25].

In personal healthcare, one of the important applications is cardiovascular risk monitoring [26]. Cardiovascular disease has been one of the critical factors to death. The necessity of personal monitoring can be even more important since its nature is often acute. ECG monitoring is also suitable for persons with symptoms which may be caused by arrhythmia, light-headedness, syncope and palpitations. Blood pressure is an important physiological parameter in evaluating cardiovascular system. Additional

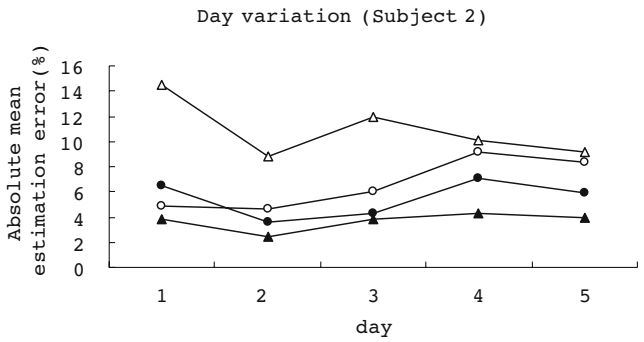

Fig. 4 Day-to-day variations of BP estimation error for the subject 2. *Empty triangle* SBP estimation errors calibrated using whole five-subject regression line formula to estimate BP, *empty circle* DBP estimation errors calibrated using whole five-subject regression line formula to estimate BP, *filled triangle* SBP estimation errors by individual calibration, *filled circle* DBP estimation errors of the individual calibration

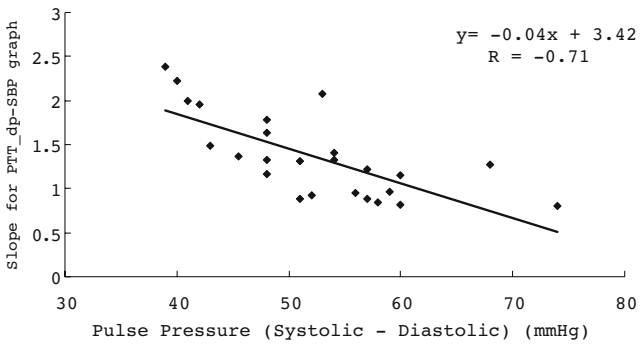

Fig. 5 Pulse pressure versus the slope for PTT_dp–SBP graph in all datasets

information of blood pressure will be more informative in terms of diagnosis. So far blood pressure monitoring along with ECG and PPG measurements based on home-use device has not been available. Furthermore, continuous monitoring capability for the period of three days will enable to perform the functions of a Holter monitor and event recorder as well. When this monitoring device is connected to a PC which is linked to the internet, a remote healthcare service center can monitor biosignal in real time. In this case our monitoring program should be installed in the remote PC. We believe that a compactness of the device and a convenient way of measuring blood pressure can be very instrumental in enhancing personal healthcare. It is expected that consumer home-use medical devices will grow every year at a rapid increase rate due to the growth diabetes, hypertension, respiratory diseases and obesity. At this time, a one-time calibration should be made before measuring blood pressure for a particular individual. This may be an inconvenience. However, the device itself is for a personal use and this merit can override the inconvenience of calibration process.

Acknowledgments This work was supported by Seoul R&BD Program, Seoul, Korea.

References

1. Chen, Y., Li, L., Hershler, C., and Dill, R. P., Continuous non-invasive blood pressure monitoring method and apparatus. *US patent*. 6,893,401 B2, 2005.
2. Nichols, W., and O'Rourke, M., *Mcdonald's blood flow in arteries*. Arnold, London, 1998.
3. Webster, J. G., Medical *instrumentation: Application of design*. Wiley, New York, 1998.
4. Hosaka, H., Sakata, H., Sugo, Y., Sohma, T., and Kasuya, H., Pulse-wave propagation time basis blood pressure monitor. *US patent*, 5, 649,543, 1998.
5. Teng, X. F., and Zhang, Y. T., Continuous and noninvasive estimation of arterial blood pressure using a photoplethysmographic approach. *Pro. 25 Ann. IEEE EMBS*, 3153–3156, 2003.
6. Yoon, G., Lee, J. Y., Jeon, K. J., Park, K. K., and Kim, H. S., Development of a compact home health monitor for telemedicine. *Telemedicine and e-Health*. 11(6):660–667, 2005.
7. Barschdorff, D., and Erig, M., Continuous blood pressure monitoring during stress ECG. *Biomed. Tech. (Berl.)* 43, 34–39, 1998.
8. Naschitz, J. E., Bezobchuk, S., Priselac, R., Sundick, S., Dreyfuss, D., Khorshidi, I. et al, Pulse transit time by R-wave-gated infrared photoplethysmography: review of the literature and personal experience. *J. Clin. Monit. Comput*. 18:333–342, 2004. doi:10.1007/s10877-005-4300-z.
9. Curb, J. D., Labarthe, D. R., Cooper, S. P., Cutter, G. R., and Hawkins, C. M., Training and certification of blood pressure observers. *Hypertension*. 5:610–614, 1983.
10. Geddes, L. A., Voelz, M. H., Babbs, C. F., Bourland, J. D., and Tacker, W. A., Pulse transit time as an indicator of arterial blood pressure. *Psychophysiol*. 18:71–74, 1981. doi:10.1111/j.1469-8986.1981.tb01545.x.
11. Yano, K., Kimora, T., Sato, Y., Nichiwaki, K., and Shimada, Y., Delay time between the R-wave and maximum pulse wave upstroke reflects alterations in blood pressure. *Anesthesiol*. 96: A491, 2002.
12. Awad, A. A., Ghobashy, M. A., Stout, R. G., Silverman, D. G., and Shelley, K., Blood pressure determination using the pulse oximeter waveform'. Retrieved from www.gasnet.org/interface/12.1.2abstract4.html, 2001.
13. Chen, W., Tobahashi, T., Ichikawa, S., Takeuchi, Y., and Togawa, T., Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. *Med. Biol. Eng. Comput*. 38:569–574, 2000. doi:10.1007/BF02345755.
14. Payne, R. A., Symeonides, C. N., Webb, D. J., and Maxwell, S. R., Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure. *J. Appl. Physiol*. 100:136–141, 2006. doi:10.1152/japplphysiol.00657.2005.
15. Allen, J., and Murray, A., Age-related changes in peripheral pulse timing characteristics at the ears fingers and toes. *J. Hum. Hypertens*. 16:711–717, 2006. doi:10.1038/sj.jhh.1001478.
16. Jago, J. R., and Murray, A., Repeatability of peripheral pulse measurements on ears, fingers and toes using photoelectric plethysmography. *Clin. Phys. Physiol. Meas*. 9:319–330, 1988. doi:10.1088/0143-0815/9/4/003.
17. O'Rourke, M., and Gallangher, D. E., Pulse wave analysis. *J. Hypertens*. 14:147–157, 1996. doi:10.1097/00004872-199602000-00001.
18. Martens, H. A., and Dardenne, P., Validation and verification of regression in small data sets. *Chemometr. Intell. Lab. Syst.* 44:99–122, 1998.
19. Stone, M., An asymptotic equivalence of choice of model by cross-validation and Akaike's criterion. *J. R. Stat. Soc. B*. 38:44–47, 1977.
20. Bland, J. M., and Altman, D. G., Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1:307–310, 1986.
21. Chawla, R., Kumarvel, V., Girdhar, K. K., and Sethi, A. K., Can pulse oximetery be used to measure systolic blood pressure. *Anesth. Analg*. 74:196–200, 1992.
22. Allen, J., and Murray, A., Prospective assessment of an artificial neural network for the detection of peripheral vascular disease from lower limb pulse waveforms. *Physiol. Meas*. 16:29–38, 1995. doi:10.1088/0967-3334/16/1/003.
23. Robert, A. A., John, A. S., Dennis, M. D., Mark, A. W., and Taylor, C. B., The covariation of blood pressure and pulse transit time in hypertensive patients. *Psychophysiology*. 18:301–306, 1981. doi:10.1111/j.1469-8986.1981.tb03038.x.
24. Smith, R. P., Argod, J., Peping, J. L., and Levy, P. A., Pulse transit time: an appraisal of potential clinical applications. *Thorax*. 54:452–458, 1999.
25. Wippermann, C. F., Schranz, D., and Huth, R. G., Evaluation of the pulse wave arrival time as a marker for blood pressure changes in critically ill infants and children. J. Clin. Monit. 11, 324–328, 1995. doi:10.1007/BF01616991.
26. Trzeciak, B. G., Siebert, J., Scislo, J., Jaskiewicz, M., and Babinska, Z., Telemedicine: the determination of fatal cardiovascular risk in internet users population. *Comput. Cardiol*. 32:367–370, 2005. doi:10.1109/CIC.2005.1588113.