35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Potential Value of Electrocardiogram and Photoplethysmogram for Non-invasive Blood Pressure Estimation during Exercise

In cheol Jeong, and Joseph Finkelstein, *Member, IEEE*

Abstract— **Blood pressure (BP) monitoring is required to ensure safety of home-based exercise in seniors. Pulse transit time (PTT) defined as the time it takes a pulse wave to travel between two arterial sites is considered to be inversely proportional to BP. Different approaches have been described to calculate PTT using photoplethysmogram (PPG) and electrocardiogram (ECG) however it is not clear which approach produces better BP estimates. The purpose of this study was to compare potential value of different approaches for calculating PTT and other derivatives of PPG and ECG described in the literature for assessing BP during exercise. Three calibration points were collected from five study participants at different levels of exertion on three different days. A high precision automated BP monitor was used to obtain reference BP. A correlation matrix between PPG/ECG derivatives and the reference BP values was analyzed. Based on the bivariate correlation analysis, PPG/ECG derivatives that demonstrated the most prominent association with reference BP were identified. The results of the study confirmed the value of individualized calibration for BP estimation using PTT and identified optimal means to derive it from PPG and ECG.**

I. Introduction

One of the main challenges in implementing an optimal home-based exercise program in older adults and individuals with cardiovascular conditions is the requirement to ensure exercise safety [1]. A crucial component to achieve this requirement is the ability to monitor blood pressure (BP) during exercise continuously and generate alert when blood pressure exceeds certain thresholds or changes abruptly [2].

Use of automated blood pressure monitors for continuous blood pressure monitoring during exercise is limited due to inherent high noise to signal ratio affecting precision of automated blood pressure monitors. The utility of photoplethysmogram (PPG) in circulatory monitoring has been widely discussed [3-4]. Various approaches based on continuous registration of PPG and electrocardiogram (ECG) have been described for non-invasive cuff-less BP estimation [5-6].

Pulse transit time (PTT) defined as the time it takes a pulse wave to travel between two arterial sites is considered to be inversely proportional to BP [4-6]. Though the use of PTT for non-invasive BP estimation has been well described, different studies derived PTT from PPG and ECG using different approaches [5-8]. Currently, it is not clear which approach produces better BP estimates. In addition, current solutions require expensive equipment [9] which makes it impractical for wide application at patient homes or they utilize equations obtained from population-based estimates [10] which may not be applicable to particular individuals with chronic cardiovascular conditions or various comorbidities in older adults.

In our previous study we introduced a practical low-cost solution for using PTT to estimate BP during exercise [11]. Our approach was based on obtaining 3 calibration points during different levels of exertion for each subject and utilizing the resulting individualized BP estimation equitation for patient-specific monitoring of BP during home-based exercise [12].

Previously, we used a single approach to calculate PTT despite the fact that different approaches have been described. The purpose of this paper was to compare potential value of different approaches for calculating PTT and other derivatives of PPG and ECG described in the literature for assessing BP during exercise.

II. Methods

A. System and Data Acquisition

Three calibration points were collected from five study participants including 3 female and 2 male adult volunteers: (1) during the rest, (2) after 5-min exercise with cycling speed of 1.5-miles/hour, and (3) after 5-min exercise with cycling speed of 2.5-miles/hour. The procedure was repeated at three separate days for each study participant.

During each visit, the subjects used a portable bicycle (Chattanooga Deluxe ExersiserTM, Chattanooga, USA) to reach two different BP levels within individual comfort zone, in addition to BP calibration during the initial resting period. Before a subject followed the experimental procedure, she/he was seated in comfortable chair, worn sensor equipment, and asked to rest for cardiovascular stabilization. Continuous monitoring of ECG and PPG was carried out at 1 kHz sampling rate with PTT being calculated in real time. Overall, the study protocol included three 45-min visits within a 2-week period. During each visit, three sequential BP calibration points were collected during different levels of exertion for each study participant.

At each calibration point, reference BP measurements were registered by an automatic oscillometric sphygmomanometer which is routinely used in clinical care (Carescape Dinamap V100, GE Healthcare, USA). The Carescape Dinamap V100 provides high-precision automated oscillometric measurement of systolic, diastolic and mean arterial pressure and pulse rate that has been clinically proven to be more accurate than competitive models [13-14].

Research was in part supported by the Secunda Family Foundation.

I. C. Jeong is with the Chronic Disease Informatics Program, Johns Hopkins University School of Medicine, Baltimore, Maryland, 21224, USA (e-mail: ijeong1@jhmi.edu).

J. Finkelstein is with the Chronic Disease Informatics Program, Johns Hopkins University School of Medicine, Baltimore, Maryland, 21224, USA (e-mail: jfinkel9@jhmi.edu).

TABLE I. BIVARIATE CORRELATIONS BETWEEN THE PARAMETERS DERIVED FROM PPG, ECG, AND BP MONITOR

Correlations		① ECGRRI	② PEAKI	③ FOOTI	④ SYST	⑤ DIAT	⑥ PTTP	⑦ PTTM	⑧ PTTF	⑨ PTTF1	⑩ SYSA	⑪ DIAA	⑫ SBP	⑬ DBP	⑭ MBP	⑮ HR
PEAKI	Pearson Correlation	1.000**														
	Sig. (2-tailed)															
FOOTI	Pearson Correlation	1.000**	1.000**													
	Sig. (2-tailed)															
SYST	Pearson Correlation	.863**	.862**	.864**												
	Sig. (2-tailed)															
DIAT	Pearson Correlation	.983**	.984**	.983**	.758**											
	Sig. (2-tailed)															
PTTP	Pearson Correlation	.733**	.733**	.734**	.718**	.692**										
	Sig. (2-tailed)															
PTTM	Pearson Correlation	.619**	.620**	.619**	.475**	.630**	.910**									
	Sig. (2-tailed)															
PTTF	Pearson Correlation	-.332*	-.331*	-.332*	-.539**	-.234	.199	.426**								
	Sig. (2-tailed)					.121	.191									
PTTF1	Pearson Correlation	.980**	.980**	.980**	.793**	.983**	.812**	.740**	-.138							
	Sig. (2-tailed)								.365							
SYSA	Pearson Correlation	.402**	.400**	.405**	.461**	.357*	.205	.007	-.387**	.339*						
	Sig. (2-tailed)						.177	.966								
DIAA	Pearson Correlation	.670**	.669**	.672**	.543**	.675**	.373*	.261	-.304*	.639**	.889**					
	Sig. (2-tailed)							.083								
SBP	Pearson Correlation	-.590**	-.591**	-.590**	-.478**	-.592**	-.809**	-.793**	-.303*	-.683**	.028	-.173				
	Sig. (2-tailed)										.855	.256				
DBP	Pearson Correlation	-.201	-.200	-.201	-.288	-.156	-.168	-.012	.202	-.168	.138	.167	.385**			
	Sig. (2-tailed)	.186	.187	.186	.055	.307	.269	.936	.183	.270	.367	.272				
MBP	Pearson Correlation	-.495**	-.495**	-.495**	-.467**	-.473**	-.649**	-.560**	-.126	-.546**	.128	-.001	.888**	.749**		
	Sig. (2-tailed)										.403	.996				
HR	Pearson Correlation	-.863**	-.863**	-.863**	-.714**	-.860**	-.480**	-.358*	.429**	-.816**	-.416**	-.637**	.328*	.239	.318*	
	Sig. (2-tailed)													.114		
PP ⑯	Pearson Correlation	-.545**	-.546**	-.545**	-.383**	-.568**	-.797**	-.852**	-.422**	-.661**	-.034	-.265	.903**	-.048	.612**	.244
	Sig. (2-tailed)										.826	.079		.752		.106

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

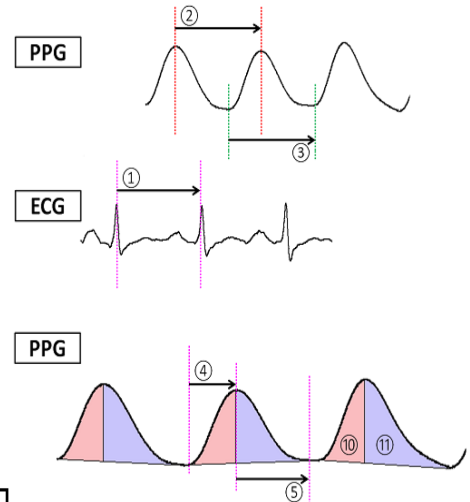

Figure 1. Parameters

① ECGRRI: Electrocardiogram (ECG) R peak to R peak Interval, ② PEAKI: Photoplethysmogram (PPG) Peak Interval, ③FOOTI: PPG Foot Interval, ④ SYST: Systolic Time of PPG, ⑤ DIAT: Diastolic Time of PPG, ⑥ PTTP: Pulse Transit Time (PTT) between ECG R peak and following PPG Peak, ⑦ PTTM: PTT between ECG R peak and following maximum acceleration point of PPG, ⑧ PTTF: Pulse Transit Time (PTT) between ECG R peak and following PPG Foot, ⑨ PTTF1: Pulse Transit Time (PTT) between ECG R peak and the second PPG Foot, ⑩ SYSA: Systolic Area of PPG, ⑪ DIAA: Diastolic Area of PPG, ⑫ SBP: Systolic Blood Pressure, ⑬ DBP: Diastolic Blood Pressure, ⑭ MBP: Mean Blood Pressure, ⑮ HR: Heart Rate, ⑯ PP: Pulse Pressure =SBP-DBP

A single lead ECG (Lead II) and PPG were simultaneously registered using two wireless physiological transmitters for ECG and PPG, and a data acquisition system (MP150, Biopac Systems, Inc., USA) connected to a laptop. ECG data were continuously acquired using Biopac Systems' wireless "BioNomadix" series ECG/Respiration transduser (BN-RSPE, BIOPAC Systems, Inc., USA). PPG data were continuously acquired using Biopac Systems' wireless "BioNomadix" PPG/EDA transducerr (BN-PPGED, BIOPAC Systems, Inc., USA). Raw data from ECG were band-limited from 0.05 Hz to 150 Hz and raw data from PPG were band-limited from DC to 10 Hz. Pre-gelled/disposable ECG electrodes (LL Electrode Series, Lead-Lok®, Inc., USA) leads were connected to the subject to obtain a Lead II trace and a pulse transducer (BN-PULSE-XDCR, BIOPAC Systems, Inc., USA) was placed on the index finger to obtain PPG.

B. *Analysis*

After subjects completed all 3 visits according to the study protocol, a total of 9 sets of reference BP values, ECG signals, and PPG signals were acquired for each participant. For each visit, a group of indices were derived from a simultaneous 30-second PPG and ECG recording following the approaches previously described in the literature [3-11]. To compare potential value of various parameters derived from PPG and ECG for BP estimation, a correlation matrix between these parameters and the reference BP values was analyzed using the bivariate correlation analysis. Data from all visits were pulled together to investigate the overall relationship among these parameters.

A PPG/ECG analysis program was developed using LabVIEW 2011 (National Instruments, USA) to extract all of these parameters from PPG and ECG as shown in Fig. 1 and Fig. 2. The parameters ① to ⑪ were based on ECG and/or PPG recordings. The parameters ⑫ to ⑯ were generated by the automated sphygmomanometer. To find ECG R peak, the lowest minimum amplitude (LMA) of ECG R peak was used to define the individual threshold value for R peak detection. To find PPG peak and PPG foot, the FIR bandpass filter that had Blackman -61dB window, 0.1 Hz low frequency cut off, and 15 Hz high frequency cut off, was used. The resulting PPG signal was analyzed based on individual threshold value defined by the LMA of PPG Peak and PPG Foot from a 30-second recording. This algorithm was applied for each subject recording separately to ensure best fit with each subject physiological response. To find the maximum acceleration point of PPG, the derivate method that had Blackman -61dB window and 15 Hz low frequency cut off was used, and then the individual threshold value based on the

TABLE II. Maximum and Minimum Bivariate Correlations for Individual Participants

Correlations		ECGRRI	PEAKRRI	FOOTRRI	SYST	DIAT	PTTP	PTTM	PTTF	PTTF1	SYSA	DIAA	SBP	DBP	MBP	HR
PEAKRRI	MAX	1.000														
	MIN	1.000														
FOOTRRI	MAX	1.000	1.000													
	MIN	1.000	1.000													
SYST	MAX	0.969	0.969	0.968												
	MIN	0.681	0.678	0.687												
DIAT	MAX	0.995	0.996	0.995	0.938											
	MIN	0.983	0.984	0.982	0.537											
PTTP	MAX	0.980	0.981	0.979	0.974	0.980										
	MIN	0.694	0.694	0.699	0.702	0.643										
PTTM	MAX	0.980	0.981	0.980	0.964	0.982	0.995									
	MIN	0.668	0.668	0.667	0.342	0.622	0.789									
PTTF	MAX	0.085	0.091	0.082	-0.018	0.175	0.584	0.579								
	MIN	-0.798	-0.799	-0.800	-0.911	-0.723	-0.793	-0.792								
PTTF1	MAX	0.997	0.997	0.997	0.957	0.999	0.987	0.987	0.180							
	MIN	0.986	0.986	0.986	0.599	0.980	0.750	0.754	-0.748							
SYSA	MAX	0.791	0.790	0.791	0.738	0.835	0.655	0.556	-0.147	0.797						
	MIN	-0.281	-0.286	-0.279	-0.349	-0.335	-0.403	-0.371	-0.727	-0.348						
DIAA	MAX	0.846	0.845	0.846	0.775	0.886	0.723	0.632	-0.167	0.853	0.992					
	MIN	0.439	0.436	0.441	0.119	0.391	-0.014	0.012	-0.587	0.377	0.732					
SBP	MAX	-0.710	-0.710	-0.710	-0.628	-0.713	-0.653	-0.548	0.646	-0.776	0.366	-0.297				
	MIN	-0.924	-0.925	-0.924	-0.797	-0.920	-0.959	-0.966	-0.353	-0.938	-0.840	-0.844				
DBP	MAX	0.612	0.614	0.617	0.607	0.605	0.589	0.549	0.251	0.607	0.562	0.599	0.875			
	MIN	-0.721	-0.722	-0.720	-0.584	-0.740	-0.888	-0.826	-0.684	-0.745	-0.222	-0.555	-0.545			
MBP	MAX	-0.515	-0.515	-0.514	-0.423	-0.545	-0.361	-0.268	0.459	-0.503	0.335	-0.201	0.990	0.924		
	MIN	-0.911	-0.912	-0.911	-0.787	-0.919	-0.946	-0.957	-0.478	-0.927	-0.618	-0.591	0.823	0.012		
HR	MAX	-0.881	-0.881	-0.878	-0.506	-0.854	-0.543	-0.677	0.830	-0.921	0.211	-0.284	0.968	0.853	0.957	
	MIN	-0.970	-0.970	-0.971	-0.952	-0.953	-0.943	-0.942	-0.327	-0.960	-0.777	-0.806	0.699	-0.643	0.519	
PP	MAX	-0.731	-0.732	-0.731	-0.548	-0.729	-0.704	-0.609	0.683	-0.792	0.404	-0.275	0.981	0.724	0.927	0.930
	MIN	-0.926	-0.928	-0.926	-0.837	-0.924	-0.972	-0.966	-0.231	-0.936	-0.842	-0.858	0.946	-0.752	0.644	0.684

MAX: Maximum correlation in 5 participants, MIN: Minimum correlation in 5 participants

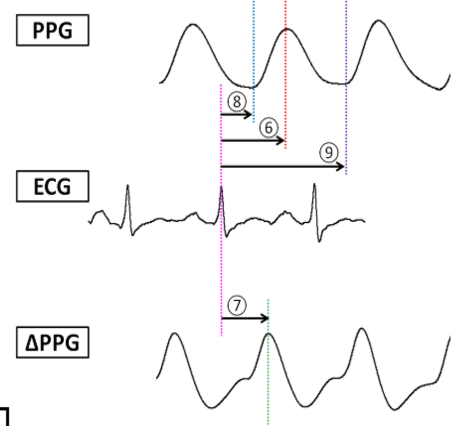

Figure 2. Parameters

TABLE III. Mean and Median Bivariate Correlations for All Individual Participants

MEAN / MEDIAN	Correlations															
	ECGRRI	PEAKI	FOOTI	SYST	DIAT	PTTP	PTTM	PTTF	PTTF1	SYSA	DIAA	SBP	DBP	MBP	HR	PP
ECGRRI		1.000	1.000	0.881	0.991	0.850	0.827	-0.265	0.992	0.280	0.639	-0.845	-0.285	-0.758	-0.931	-0.845
PEAKI	1.000		1.000	0.880	0.992	0.849	0.827	-0.263	0.992	0.278	0.637	-0.846	-0.285	-0.759	-0.931	-0.846
FOOTI	1.000	1.000		0.882	0.991	0.851	0.826	-0.265	0.992	0.283	0.641	-0.845	-0.285	-0.758	-0.930	-0.845
SYST	0.917	0.914	0.918		0.815	0.853	0.742	-0.450	0.848	0.303	0.573	-0.713	-0.213	-0.643	-0.804	-0.718
DIAT	0.992	0.992	0.992	0.873		0.816	0.812	-0.203	0.991	0.279	0.643	-0.848	-0.286	-0.759	-0.927	-0.847
PTTP	0.889	0.889	0.888	0.877	0.862		0.940	0.024	0.883	0.147	0.441	-0.823	-0.319	-0.744	-0.821	-0.817
PTTM	0.781	0.783	0.779	0.791	0.815	0.967		0.110	0.870	0.007	0.340	-0.815	-0.320	-0.729	-0.827	-0.821
PTTF	-0.096	-0.093	-0.100	-0.513	-0.015	0.209	0.202		-0.151	-0.449	-0.409	-0.050	-0.325	-0.089	0.175	-0.013
PTTF1	0.994	0.994	0.994	0.877	0.991	0.922	0.858	0.065		0.248	0.611	-0.872	-0.313	-0.784	-0.935	-0.868
SYSA	0.062	0.057	0.071	0.551	0.158	0.301	-0.213	-0.429	0.029		0.880	-0.140	0.140	-0.082	-0.222	-0.128
DIAA	0.553	0.549	0.560	0.674	0.611	0.567	0.359	-0.468	0.511	0.847		-0.471	-0.074	-0.393	-0.569	-0.461
SBP	-0.891	-0.891	-0.889	-0.692	-0.883	-0.852	-0.877	-0.203	-0.930	-0.061	-0.365		0.418	0.936	0.844	0.966
DBP	-0.569	-0.569	-0.575	-0.537	-0.549	-0.424	-0.317	-0.352	-0.668	0.226	-0.134	0.691		0.640	0.404	0.220
MBP	-0.832	-0.832	-0.833	-0.617	-0.813	-0.803	-0.856	-0.170	-0.883	-0.115	-0.319	0.955	0.883		0.797	0.828
HR	-0.929	-0.929	-0.929	-0.861	-0.941	-0.887	-0.903	0.064	-0.930	-0.014	-0.514	0.849	0.774	0.922		0.797
PP	-0.843	-0.844	-0.843	-0.740	-0.838	-0.778	-0.824	-0.176	-0.874	0.024	-0.409	0.967	0.419	0.896	0.841	

MEAN: Mean of correlations in 5 participants, MEDIAN: Median of correlations in 5 participants

LMA of the maximum acceleration point of PPG was applied. After ECG R peak, PPG peak, PPG foot, and the maximum acceleration point of PPG were identified, the parameters ① to ⑪ were calculated. The parameters ① to ⑨ were calculated as time intervals between the following points: ① - the present R peak and the next R peak; ② - the present PPG peak and the next PPG peak; ③ - the present PPG foot and the next PPG foot; ④ - the present PPG foot and the following PPG peak; ⑤ - the present PPG peak and the following PPG foot; ⑥ - the present R peak and the following PPG peak; ⑦ - the present R peak and the following maximum acceleration point of PPG; ⑧ - the present R peak and the following PPG foot; ⑨ - the present R peak and the second PPG foot. The parameters ⑩ and ⑪ were calculated as the area under the PPG curve for ④ and ⑤ respectively. All parameters were calculated on a beat-by-beat basis as it is depicted in the Fig. 1 and Fig. 2.

All statistical analyses were performed using IBM SPSS Statistics 21 (IBM, USA). Bivariate correlation analyses for each of 45 parameters were conducted as shown in Table I. After the bivariate correlation coefficients were calculated for the entire data set (Table I), the correlation coefficients for each of 5 participants were calculated on an individual basis to find out how much the correlation coefficients differ from participant to participant. The ranges between maximum and minimum of correlation, and correlation coefficient mean and median for each correlation pair are shown in the Table II and Table III.

III. Results

The results from bivariate correlation analysis based on entire data set are given in the Table 1. Total of 15 values for each parameter were used to analyze the “population-based” relationship between PPG and ECG derivatives and readings from an automated BP monitor. For data obtained from the BP monitor, the maximum correlation was found to be between SBP and PP (r= +0.903, p<0.01), however correlation was low between SBP and DBP (r=+0.385, p<0.01) and between DBP and PP (r=-0.048, p=0.752). Based on comparing correlation coefficients between PPG/ECG derivatives and SBP and DBP obtained from an automated sphygmomanometer, the highest correlation coefficients were found between SBP and PTTP (r=-0.809, p<0.01) and between SBP and PTTM (r=-0.793, p<0.01).

The results from the correlational analysis on an individual basis are shown in the Tables II and III. In this analysis, total of 9 values for each parameter were used. Similar to the “population-based” analysis, the relationship between SBP and PP was significant (MAX: r=+0.981, MIN: r=+0.946, MEAN: r=+0.966, MEDIAN: r=+0.967), and there was no significant correlation between DBP and PP (MAX: r=+0.724, MIN: r=-0.752, MEAN: r=+0.220, MEDIAN: r=+0.419), and between SBP and DBP (MAX: r=+0.875, MIN: r=-0.545, MEAN: r=+0.418, MEDIAN: r=+0.691). Overall correlations between PPG/ECG derivatives and SBP/DBP from automated BP monitor resembled relationships found in the “population-based” analysis. The most prominent correlations were found again between SBP and PTTP (MAX: r=-0.959, MIN: r=-0.653, MEAN: r=-0.823, MEDIAN: r=-0.852) and between SBP and PTTM (MAX: r=-0.966, MIN: r=-0.548, MEAN: r=-0.815, MEDIAN: r=-0.877). However, for some study subjects, other PPG/ECG-derived indices, such as ECGRRI, PEAKI, and FOOTI, appeared to have be better association with SBP than PTTP or PTTM (MAX: r=-0.710, MIN: r=-0.924 to -0.925, MEAN: r=-0.845 to -0.846, MEDIAN: r=-0.889 to -0.891). For some subjects DIAT demonstrated significant correlation with SBP (MAX; r=-0.713, MIN; r=-0.920, MEAN; r=-0.848, MEDIAN; r=-0.883), whereas in other subjects the best correlation with SBP was found to be with PTTF1 (MAX: r=-0.776, MIN: r=-0.938, MEAN: r=-0.872, MEDIAN: r=-0.930) in our study protocol.

IV. Discussion

In this study, analysis of bivariate correlations between the most common PPG/ECG derivatives and SBP/DBP obtained during exercise from an automated precision BP monitor has been performed. Based on the “population-based” analysis from the pulled dataset, the most prominent association was found between SBP and PTTM (r=-0.793, p<0.01). These results correspond well with previously reported data [9-11]. However, correlation analysis on a participant-by-participant basis demonstrated a wide range in the strength of association between SBP and PTTM, with other associations appearing to be more prominent. This result was confirmed by a recent study [15] that showed dependence of PTT and BP association on the underlying heath condition.

In our previous study [11], we demonstrated that an individual calibration based on different levels of exertion results in more reliable estimation of BP. The results of this study appear to indicate that the very choice of PPG/ECG derivatives used for the individual calibration should be also tailored to each particular patient based on results of bivariate correlation analysis. Whether this approach can improve estimation of BP during exercise using PPG/ECG derivatives remain to be shown.

References

[1] Meka N, Katragadda S, Cherian B, Arora RR. Endurance Exercise and Resistance Training in Cardiovascular Disease. Ther Adv Cardiovasc Dis. 2008;2(2):115-121.

[2] Finkelstein J, Wood J, Cha E. Impact of physical telerehabilitation on functional outcomes in seniors with mobility limitations. Conf Proc IEEE Eng Med Biol Soc. 2012;2012:5827-32. [PMID:23367254]

[3] Reisner A, Shaltis PA, McCombie D, Asada HH. Utility of the photoplethysmogram in circulatory monitoring. Anesthesiology. 2008;108(5):950-8.

[4] Elgendi M. Standard terminologies for photoplethysmogram signals. Curr Cardiol Rev. 2012;8(3):215-9.

[5] Lane JD, Greenstadt L, Shapiro D, Rubinstein E. Pulse transit time and blood pressure: an intensive analysis. Psychophysiology 1983;20(1):45-9. [PMID: 6828611]

[6] Allen J. Photoplethysmography and its application in clinical physiological measurement. Physiol Meas. 2007;28(3):R1-39.

[7] Naschitz JE, Bezobchuk S, Mussafia-Priselac R, Sundick S, Dreyfuss D, Khorshidi I, Karidis A, Manor H, Nagar M, Peck ER, Peck S, Storch S, Rosner I, Gaitini L. Pulse transit time by R-wave-gated infrared photoplethysmography: review of the literature and personal experience. J Clin Monit Comput. 2004;18(5-6):333-42.

[8] Wong MY, Poon CC, Zhang YT. An evaluation of the cuffless blood pressure estimation based on pulse transit time technique: a half year study on normotensive subjects. Cardiovasc Eng. 2009;9(1):32-8

[9] Idema RN, van den Meiracker AH, Imholz BP, Man in 't Veld AJ, Settels JJ, Ritsema van Eck HJ, Schalekamp MA. Comparison of Finapres non-invasive beat-to-beat finger blood pressure with intrabrachial artery pressure during and after bicycle ergometry. J Hypertens Suppl. 1989 Dec;7(6):S58-9. [PMID: 2632744]

[10] Suzuku S, Oguri K. Cuffless and non-invasive Systolic Blood Pressure estimation for aged class by using a Photoplethysmograph. Conf Proc IEEE Eng Med Biol Soc. 2008;2008:1327-30. [PMID:19162912]

[11] Jeong I C, Finkelstein J. Introducing a Practical Approach for Non-Invasive Blood Pressure Monitoring during Home-based Telerehabilitation Exercise Program. Proc. of the IEEE EMBS Special Topic Conference on Point-of Care Healthcare Technologies (POCHT2013) 2013;2013:164-167.

[12] Jeong IC, Finkelstein J. Computer-assisted upper extremity training using interactive biking exercise (iBikE) platform. Conf Proc IEEE Eng Med Biol Soc. 2012;2012:6095-9. [PMID:23367319]

[13] Lee CG, Park HM, Shin HJ, Moon JS, Hong YM, Kim NS, Ha IS, Chang MJ, Oh KW. Validation study of the Dinamap ProCare 200 upper arm blood pressure monitor in children and adolescents. Korean J Pediatr. 2011;54(11):463-9.

[14] De Greeff A, Ghosh D, Anthony J, Shennan A. Accuracy assessment of the Dinamap ProCare 400 in pregnancy and preeclampsia. Hypertens Pregnancy. 2010;29(2):198-205.

[15] Wagner DR, Roesch N, Harpes P, Körtke H, Plumer P, Saberin A, Chakoutio V, Oundjede D, Delagardelle C, Beissel J, Gilson G, Kindermann I, Böhm M. Relationship between pulse transit time and blood pressure is impaired in patients with chronic heart failure. Clin Res Cardiol. 2010;99(10):657-64.