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HRV Analysis and Blood Pressure Monitoring on Weighing Scale using BCG*

Jae Hyuk Shin and Kwang Suk Park, *Senior Member, IEEE*

Abstract— **Using the Ballistocardiogram(BCG) measured on weighing scale, heart rate variability(HRV) and blood pressure were estimated. BCG was measured while subjects were on weighing scale in resting state and under the Valsalva maneuver and static exercise condition to induce the change in cardiac autonomic rhythm. Time domain, frequency domain and nonlinear HRV parameters were estimated from the measured BCG and compared with the ones calculated from ECG measured simultaneously. For blood pressure(BP) estimation, ECG was measured additionally on the feet using dry electrodes simultaneously installed on weighing scale and R–J intervals were extracted as a BP correlated parameter at every beat cycle. HRV estimation results shows the correlation higher than 0.97, and the estimated BP was similar to the measured BP with a reliable correlations.**

I. Introduction

Ballistocardiogram(BCG) is the record of mechanical force created by the changes of centre of gravity of the body caused by heart beat and blood circulation [1]. The BCG has been reliably used to evaluate myocardial strength, functional recovery from heart attacks, and degrading cardiac health [2-4]. But, the BCG has not yet been used as a clinical tool in the hospital due to its morphological variation even in healthy populations [5].

With regard to home healthcare, the BCG has some advantages over ECG. BCG can be obtained easily without contacting electrodes, measured as a piece of daily using equipments, and used long-term monitoring of cardiovascular systems. While beds and chairs are considered as the most suitable equipments for measuring BCG with sensors installed in them, weighing scale is also introduced as useful equipment for measuring BCG and evaluating cardiovascular functions [6-10].

Weighing scale is the one of the most popular equipments easily found in ordinary home. Its nature of measuring mechanical force of gravity makes measurement of BCG more convenient without using additional sensor. Sensitive load cells can be used for measurement of BCG as well as body weight. In addition to load cells, electrodes also can be installed on weighing scale surface which can be used to measure ECG from feet of subject. Since weighing scale is the daily using equipment, if the BCG and ECG are measured from weighing scale, it is very helpful to evaluate the cardiovascular function of the subject living in home daily.

In this presentation, we summarized the HRV analysis based on BCG measured on weighing scale and blood pressure estimation based on BCG with extra electrodes installed on weighing scale.

II. Measurement System

A. BCG Measurement

The BCG was measured with a weighing scale-type load cell sensor (SPL-100L, CAS, Korea) under the feet. The cross-sectional area of the weighing scale was 300 mm by 300 mm and the height was 25 mm. It was linear in converting weight into voltage with a combined error of 0.05% in the range of 2–100 kg. When the subject was standing on the weighing scale, the BCG signal was recorded as a vital sign in the 1–25 Hz frequency range. A BIOPAC data acquisition system (BIOPAC, USA) was used to record the BCG and the signal was digitized at a sampling rate of 1 kHz with 16 bit resolution. BCG J-peaks were easily identified using a simple method to find the maximum peak of a BCG cycle, which was measured between the two sequential R-peaks of the ECG. J–J intervals, which can be calculated from the time interval between the successive BCG J peaks were collected to estimate the HRV for each subject.

B. Feet ECG Measurement

To monitor the BP without any constraint, two dry electrodes built with a copper plate were used to measure the ECG from the feet. The electrodes were placed on the weighing scale to measure the ECG from the feet and the feet-ECG(F-ECG) was measured from the plantar area of the feet. Using the high input impedance amplifier circuits, these electrodes can be used as capacitive electrodes which make the measurement of F-ECG with socks on. The measured non-constrained ECG signals were filtered by the band pass filter, which had a frequency range of 0.5–35 Hz.

C. Reference signal measurements

The standard ECG was measured from the Ag/AgCl electrodes in the Lead I configuration on the chest area. The

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K. S. Park is with the Department of Biomedical Engineering, Seoul National University, KOREA (corresponding author to provide phone: +82-2-2072-3135; fax: +82-2-3676-1175; e-mail: pks@ bmsil.snu.ac.kr).

J. H. Shin was with Interdisciplinary program of Biomedical Engineering, Seoul National University, KOREA. He is now with the Samsung Electronics Co., KOREA (e-mail: russell@bmsil.snu.ac.kr).

S. H. Hwang and M.H. Chang are with Interdisciplinary program of Biomedical Engineering, Seoul National University, KOREA. (e-mail: lostzoo@bmsil.snu.ac.kr, binch007@bmsil.snu.ac.kr).

measured ECG signal was filtered using a band pass filter,

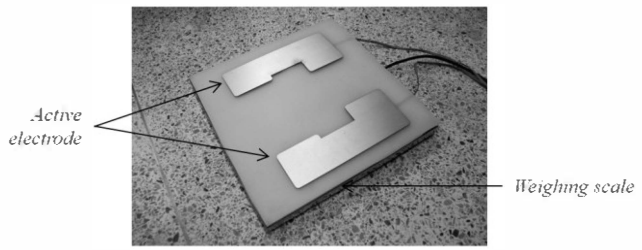

Figure 1. Weighing scale for simultaneous measurement of BCG and ECG

which had a pass band of 0.5–35 Hz. Non-invasive blood pressure (NIBP) was also recorded using the FINAPRES device (FMS, The Netherlands) to monitor cardiovascular changes under Valsalva maneuver and static exercise. A BIOPAC data acquisition system (BIOPAC, USA) was also used to record the ECG and NIBP at a sampling rate of 1 kHz with 16 bit resolution.

D. Experimental procedures

Data were collected in the afternoon for about 30 min for each subject. A total of 15 healthy male subjects aged 21 to 31 (mean and standard deviation of age: 26.7 years) participated in the experiments. Body mass indices (BMI) of the subjects were 19.6-28.7. All subjects had no history of previous cardiopulmonary diseases and were asked to abstain from caffeine and alcohol for at least 4 hours before the experiments. The ECG and BCG were simultaneously recorded on the weighing scale.

Data were collected while modulating cardiac autonomic conditions with three different sessions of resting, Valsalva, and post-exercise sessions. The heart rate (HR) and blood pressures (BP) were continuously monitored to confirm that the autonomic conditions are varying as planned upon different experimental conditions. The FINAPRES device was placed on the subject's left wrist and middle finger while standing on the weighing scale. In the Valsalva experiment, the subjects quietly rested on the weighing scale for 2min, and performed the Valsalva maneuver for 40–60s. After the maneuver was finished, subjects rested again for about 3min to stabilize the changes in the autonomic conditions. We measured all physiological signals right after the subject finished the static exercise to analyze the effect of static exercise on the cardiac autonomic functions. As a static exercise, all subjects performed squat exercises (repeat sitting-down and standing-up) more than 30 times for 1 min. Right after the exercise, subjects were standing on the weighing scale and the physiological signals, ECG, BCG and BP, were measured during the post-exercise period. The BP slowly returned to the normal state when the subject rested on the weighing scale after the exercise. During the static exercise, all of the subject's heart rates increased up to more than 85% of normal heart rate. For each experiment, 5 min sections free from artifacts were then selected for evaluation.

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III. PROCESSING AND ANALYSIS

After data were collected from the experiments, they were processed to increase SNR and extract the parameters which can be used for the evaluation of autonomic modulation and blood pressure estimation.

A. Autonomic modulation analysis using heart rate variability

The recommended HRV analysis comprises the time- and frequency-domain, and components of the nonlinear analysis. The short-term HRV analysis with 5 min segments of ECG and BCG signals was used in this study. The normal-to-normal beat (NN) intervals were collected from ECG R–R interval and BCG J–J interval for the HRV analysis. However, 5 min segments which contained either an abnormal beat or a noise-corrupted heartbeat were excluded from the interval dataset.

For the time domain analysis, we selected an average for the NN intervals (AVNN), standard deviation for the NN intervals (SDNN), RMSSD, and pNN50 as the time domain HRV parameters.

For frequency domain analysis, Cubic-spline interpolation was applied to the heartbeat intervals to resample the intervals at 2 Hz. We used the non-parametric method, the fast Fourier transformation (FFT), to calculate the HRV frequency domain parameters. The power in the very low frequency (VLF) band (~0.04 Hz), in the low frequency (LF) band (0.04-0.15 Hz), and high frequency (HF) band (0.15-0.4 Hz) was computed by summing all spectral components within each band. The total power of power spectral density was calculated by summing the three spectral bands: VLF, LF and HF. We used VLF, LF, HF, total power (TP) and a ratio of low frequency to high frequency spectral power (LF/HF) as frequency domain HRV parameters. All spectral powers of the frequency bands were measured in absolute values of power.

In the nonlinear analysis, three different techniques were used to evaluate the HRV from the BCG signal; Poincare plot, detrended fluctuation analysis (DFA) and entropy analysis. We tested SD1 and SD2 in the Poincare plot analysis, $c1$ and $c2$ in DFA analysis and ApEn and SpEn parameters in entropy analysis.

B. BCG synchronized averaging for F-ECG

When the ECG was measured from the feet(F-ECG), the R-peaks were not recorded clearly because the signal was severely corrupted by the electromyogram (EMG) generated from the gastrocnemius and plantar muscles of the feet, especially when the subject was standing during the measurement. When the subject was sitting on a chair with his feet placed on the dry electrodes, the EMG noise was small and the R-peaks of the F-ECG could be identified easily. However, when the subject was standing on the weighing scale and dry electrodes, the F-ECG signal was

corrupted by an EMG signal from the leg muscles. An ensemble average technique has been widely used to reduce noise components in the desired signal. Therefore, we utilized this method to decrease the effect of the EMG noise from the F-ECG signal. F-ECG can be considered as a measurement of ECG corrupted by additional noise of N(t) which mainly came from the muscles causing EMG.

$$\text{F-ECG}(t) = \text{ECG}(t) + \text{N}(t) \qquad (1)$$

To average the data synchronized to cardiac phase, reference signals is required for the synchronization. In many cases of synchronized averaging applications, ECG R-peak is used as the synchronization reference to cardiac rhythm. But it is not possible in this case, because the ECG is severely corrupted by EMG and R-peaks cannot be detected with practical accuracy for usage. So, J-peak of simultaneously measured BCG is used for the synchronization reference. As the number of averaged cycle increases, the R-peak of the F-ECG becomes more prominent. Since the purpose of the averaging is to detect R-peak, averaging number of 5 was sufficient in most case even though it did not clearly recover total ECG waveform.

C. *Blood Pressure Estimation*

Instead of pulse arrival time(PAT) between ECG and PPG for the estimation of blood pressure, we have used R-J interval between ECG and BCG which also shows similar characteristics with the PAT. A beat-by-beat analysis of the collected data was performed for each subject and the R-J interval was compared with the systolic blood pressure(SBP), diastolic blood pressure(DBP) and mean arterial pressure (MAP) values. A linear regression method was used to estimate beat-by-beat blood pressures from the R-J interval. Relative errors between measured BP and estimated BP were calculated. To reduce the oscillatory noise caused by respiration in the R-J interval, we used a moving-window averaging technique for the R-J intervals. After averaging several sequential R-J intervals, improvements in the correlation between the R-J interval and blood pressures were calculated with different window lengths, and the similarity of blood pressures to the estimated blood pressures was analyzed.

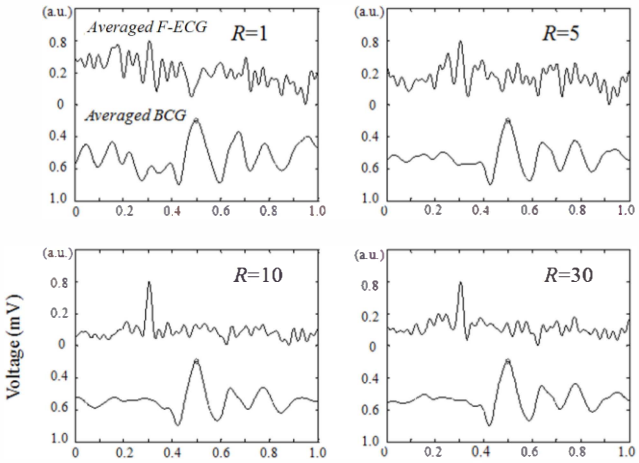

Figure 2. Synchronized averaging for ECG R-peak detection

The overall correlation results from all subject data were calculated with different lengths of averaging beats in two ways: (1) the beat-by-beat SBP was compared with the averaged R–J interval and (2) the averaged SBP was compared with the averaged R–J interval. Based on this analysis, the optimal length of averaging was determined and was used to estimate the non-constrained BP.

IV. RESULTS

Five minutes data segments were selected from 15 subjects for three experimental sessions. The average number of heartbeats increased during both the Valsalva and exercise experiments and they were 369.1, 397.5, and 422.8 from resting, Valsalva, and exercise experiments, respectively. The inter-beat intervals dramatically changed during the Valsalva and post-exercise sessions while they fluctuated with small variations within a normal range during the resting. During the Valsalva session, the beat intervals gradually decreased due to an increase in internal pressure from the strain, and the beat intervals rapidly increased after release of the strain and finally returned to a normal state. During the post-exercise session, the intervals and variation of the interval were decreased due to enhanced sympathetic activity right after the exercise, and the intervals and variation of the interval gradually increased and returned to the normal state in the late part of the session.

Table 1. Comparison of BCG derived HRV parameters to ECG derived in three experimental sessions

		Rest		Valsalva		Post Exercise	
Parameter		RE(%)	ρ	RE(%)	ρ	RE(%)	ρ
Time domain	AVNN (sec)	0.00	1.00	0.00	1.00	0.01	1.00
	SDNN (sec)	2.52	1.00	2.46	1.00	2.13	1.00
	RMSSD (sec)	8.69	0.98	9.18	0.98	9.68	0.98
	pNN50 (%)	16.86	0.99	16.83	0.99	n.a.	0.98
Frequency domain	VLF (sec^2)	0.43	1.00	0.81	1.00	0.47	1.00
	LF (sec^2)	2.58	1.00	3.92	1.00	3.31	1.00
	HF (sec^2)	10.28	1.00	10.16	1.00	13.74	0.99
	nVLF (a.u.)	3.19	1.00	2.51	0.99	3.37	0.98
	nLF (a.u.)	2.86	0.99	3.26	1.00	5.50	1.00
	nHF (a.u.)	7.65	0.99	7.99	0.97	11.53	0.98
	LF/HF (a.u.)	10.64	0.98	10.30	0.96	19.07	1.00
	TP (sec^2)	3.41	1.00	2.82	1.00	3.62	1.00
Nonlinear analysis	SD1 (sec)	10.69	0.97	13.17	0.97	14.22	0.97
	SD2	1.07	1.00	1.46	1.00	0.83	1.00
	α1	5.38	0.89	5.24	0.96	7.98	0.93
	α2	0.39	1.00	0.72	1.00	0.40	1.00
	ApEn	2.38	0.86	8.58	0.81	9.74	0.91
	SpEn (a.u.)	1.24	0.85	2.12	0.96	2.08	0.94
	Average	5.01	0.97	5.64	0.98	6.33	0.98

Three domain HRV parameters were calculated using the BCG as well as ECG data and compared by relative errors and correlation. The results are summarized in Table 1. The average relative errors increased from resting state(5.01%) to Valsalva(5.64%), and exercise experiments(6.33%). The average of correlation coefficients for all the HRV parameters were 0.97, 0.98, and 0.98 during resting, Valsalva and post-exercise sessions, respectively. And they indicate that all of the correlation coefficients were highly significant with *p*-values less than 0.01. Very small differences between HRV and B-HRV were observed for most of the HRV parameters. The relative errors were also low (RE<10%) for the most of the HRV parameters except for the pNN50, LF/HF, HF, and SD1 parameters. Detailed description of analysis is reported previously [10].

SBP, DBP and MAP were estimated for ten subjects during Valsalva maneuver using R-J interval calculated from BCG and ECG measured on weighing scale. Calculated R-J intervals show the correlation of -0.768, -0.546 and -0.670 with SBP, DBP and MAP respectively. The most of the mean relative errors were lower than 10%. The calculated BP estimation equations represent the different physical characteristics among individuals. By averaging the R-J intervals and the blood pressures for multiple beats, the correlations were increased maximally up to -0.929 and 7 beats were optimal for increasing the accuracy.

V. CONCLUSION

We have suggested that BCG measured on weighing scale can be used as valuable information for the monitoring healthcare by evaluating autonomic modulation and by estimating blood pressure in everyday life. Since weighing scale is widely distributed deep into our home and simple to use without any prior knowledge, suggested method implemented on weighing scale can be applied easily in healthcare monitoring for ubiquitous healthcare.

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