Seismocardiograms return Valid Heart Rate Variability Indices

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Abstract

HRV indices have traditionally been acquired using interbeat intervals obtained from the electrocardiogram (ECG) R-wave. Preliminary studies have recently shown, however, that interbeat intervals obtained from seismocardiogram (SCG) isovolumic moment point return some valid HRV measurements. This presents an interesting discovery due to the recent ubiquity of affordable accelerometers of satisfactory sensitivity in mobile phones.

For this purpose an orthostatic stress test of graded lower body negative pressure (LBNP) was used to compare HRV indices obtained from ECG and SCG during periods of different orthostatic stress.

We conclude that estimates of interbeat intervals obtained using SCG markers are valid measurements of interbeat interval when compared with ECG and lend themselves validly to time-domain and frequency-domain HRV analysis. It is our recommendation that aortic opening SCG markers be used to obtain interbeat intervals as they represent well defined events and are obtainable without the use of ECG markers.

1. Introduction

Low HRV is a risk factor for angina pectoris, myocardial infarction, as well as death following coronary heart disease and congestive heart failure [1], [2], [3], [4]. It is also correlated with depression and insomnia [5], [6]. HRV indices have traditionally been acquired using interbeat intervals obtained from the ECG R-wave. We propose to use low the seismocardiogram (SCG); frequency vibration signals recorded from the sternum using accelerometers instead. SCG is a low frequency signal which is recorded from the chest using accelerometers [7], [8], [9]. From its features, cardiac mechanical events can be identified that include (but are not limited to) aortic opening (AO), mitral closure (MC), and isovolumic moment (IM) (Figure 1.).

The validity of HRV indices using such measurements would present an interesting discovery due the recent ubiquity of very affordable accelerometers of satisfactory sensitivity in mobile phones.

Whereas preliminary data exist with respect to obtaining HRV indices from mobile device SCG recordings, no study has yet been made to establish their validity in relation to HRV analysis as obtained from top-of-the-line clinical instruments [10]. However, the validity of interbeat interval obtained from ballistocardiograms has already been established [11].

In this study, interbeat intervals and subsequent derived HRV from SCG and ECG were compared over a wide interbeat interval range induced by the use of an orthostatic challenge.

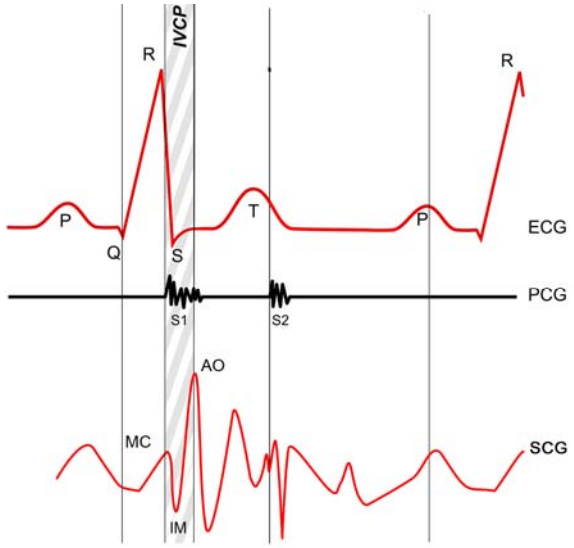

Figure 1. Single heartbeat represented by corresponding ECG, phonocardiogram (PCG), and SCG signals. Whereas ECG signals give us information about the electrical activity of the heart, SCG signals represent its mechanical activity.

2. Methods

An orthostatic stress test of graded LBNP was used to change central blood volume and thereby affect heart

dynamics. LBNP simulates reduction in central blood volume similar to hemorrhage; however, the blood volume is not lost but is instead trans-located to the lower portions of the body [12].

The participant's lower body was placed in a negative pressure chamber and sealed at the iliac. Vacuum was applied to the chamber to drop the pressure at 10 mmHg decrements every 5 minutes, to -50 mmHg and then returned to ambient pressure. Negative pressure was terminated if participants exhibited a sudden decrease in heart rate or blood pressure or if they expressed any discomfort.

The SCG signal was measured with a high sensitivity accelerometer (Brüel & Kjær model 4381, Nærum, Denmark) as used in [13]. The participants were in the supine position and the signals were recorded in back to front direction, perpendicular to the body surface. The ECG signal was also acquired and used to segment the cardiac cycles. All signals were recorded using an NI 9205 analog input module (National Instruments, Austin, TX). Continuous non-invasive finger arterial pressure was measured with Portapres device (Finapres Medical Systems, Amsterdam, Netherlands

2.1. Participants

Eighteen participants took part in this study including three females (age: 27.3 ± 4.9 years, weight: 53.3 ± 7. kg and height: 167.3 ± 9.0 cm) and fifteen male participants (age: 27.7 ± 3.7 years, weight: 74.8 ± 9.5 kg and height: 175.7 ± 6.3 cm). The youngest participant was 24 years old and the oldest was 38 years old. None of the participants had any documented cardiac abnormality. Signal recording was performed at Aerospace Physiology Laboratory under an ethics approval from Simon Fraser University Office of Research Ethics (British Columbia, Canada).

2.2. Signal analysis

A one minute moving average was used to smooth the SCG values. The QRS wave of the ECG was detected and used to segment heartbeats. After segmentation, morphological features were extracted from the SCG of every heartbeat with an algorithm developed in Matlab. On average there were over 1100 cardiac cycles per participant.

These SCG annotations are presented in Figure 1 and were based on physiological interpretations of chest vibrations proposed by Zanetti [7].

From the ECG and SCG signals, R, AO, MC, and IM interval time series were computed. The obtained time series were then resampled at 2 Hz and divided in 3 segments corresponding to -50 mmHg plus initial and final supine rest. We removed the first 2 minutes of each segment, considering them adaptive, effectively making calculations only on the last 3 minutes of every 5 minute segment.

We computed all 12 indices in the Task Force paper that required less than 5 minutes of recording from interbeat intervals obtained from all 4 markers [14].

3. Results

To ensure that interbeat interval time series calculated from all 4 markers were equivalent for all participants, Bland-Altman statistics were computed comparing the 3 SCG interbeat intervals to ECG R interbeat intervals [15].

The absolute mean difference between 2 measurements of an individual interval was smaller than 0.00015% of the R interbeat interval and the largest radius of 95% confidence interval was smaller than 0.07% of the mean R interbeat interval.

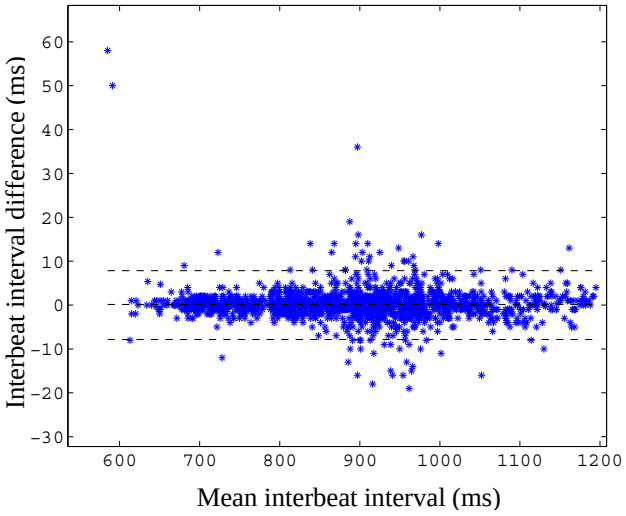

Figure 2. Bland-Altman plot comparing interbeat interval measurements obtained from R-wave and IM markers for an example subject.Bland-Altman statistics were obtained to compare AO, MC, and IM interbeat intervals to R interbeat intervals for each participant. Mean was smaller than 0.13 ms. 95% confidence radius was smaller than 7.84 ms and a maximum of 4.1% of the differences lied outside of it.

Table 1. Bland-Altman Statistics comparing all markers to R, using all participants.

	AO	MC	IM
Confidence interval (ms)	0.03 ± 6.38	0.02 ± 8.39	0.02 ± 8.63
Sample percentage beyond confidence interval (%)	4.5	2.6	2.4

For reasons of clarity, tables and figures include only SSDN, RMSSD, HF norm, and LFHF. All other reported results include all 12 computed indices.

We computed the difference between ECG R and SCG indices for each participant at baseline and -50 mmHg. The maximum absolute difference was 2.9% of the R value and the mean absolute difference was 0.50% of the R value. Percent difference for NN50 was not treated in this way as the index is discrete, and the % difference between 0 and 1 is infinite. The percent error on pNN50 can then be used as indicative of NN50 exactitude.

We then considered indices for rest and -50 mmHg conditions.

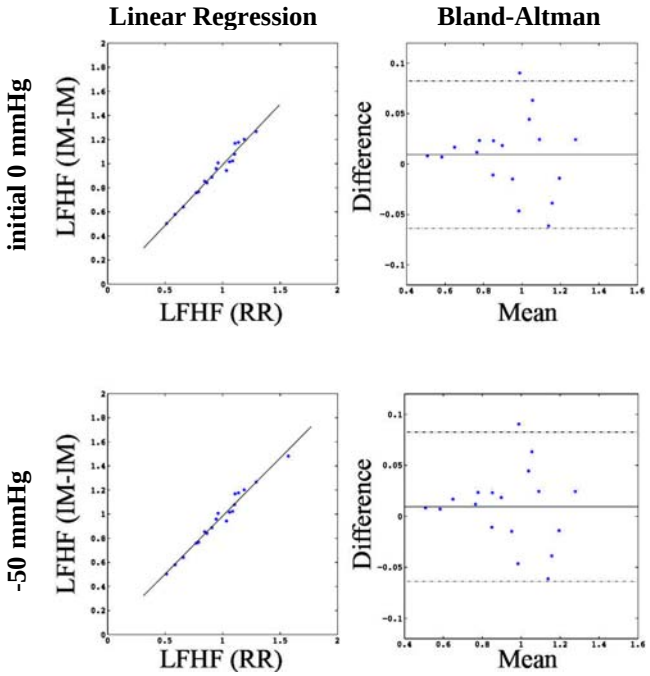

Figure 3. Correlation plots for LFHF obtained from R and from IM**.** Slope of least square linear regression at initial 0 mmHg is 0.98 with Pearson correlation coefficient r = 0.94; at -50 mmHg is 0.97 with r = 0.94. Slopes for other indices range from 0.97 to 1.02 with r > 0.93. Bland-Altman confidence interval for initial 0 mmHg is 0.017 ± 0.053; for -50 mmHg is 0.019 ± 0.055. Mean absolute difference for indices was 0.50% of the value obtained from R. Maximum single difference was 2.9% of the value obtained from R (excluding NN50).

The primary purpose of the study was to test the ability of SCG-obtained interbeat interval to detect changes in HRV. Accordingly, we compared the least square mean of the indices between initial rest and -50 mmHg conditions. In every case, whenever the ECG R-wave HRV discerned a statistically significant change, so did all 3 SCG markers.

Table 2. Least square mean of HRV indices for all participants during initial supine rest and -50 mmHg

Index	SDNN	RMSSD	HF norm	LFHF
supine				
R	44.42	35.57	51.70	0.96
AO	44.59	35.96	52.06	0.95
MC	44.65	36.05	52.08	0.94
IM	44.65	36.16	52.20	0.94
-50 mmHg				
R	38.25	24.43*	44.61*	1.30*
AO	38.56	25.04*	45.00*	1.28*
MC	38.42	24.43*	44.88*	1.29*
IM	38.60	25.43*	45.01*	1.28*
err	±4.51	±2.68	±1.53	±0.065

* denotes indices statistically different from supine indices comparing any marker with any other ($p<0.05$). SDNN denotes standard deviation of all interbeat intervals (ms), RMSSD denotes the square root of the mean of the sum of the squares of differences between adjacent interbeat intervals (ms), pNN50 is the number of pairs of adjacent interbeat intervals differing by more than 50 ms divided by the total number of interbeat intervals (%), LFHF is the ratio of power in the low frequency range (0.04-0.15 Hz) to the power in the high frequency range (0.15-0.4 Hz).

4. Discussion

HRV indices obtained with SCG markers are valid and may be used without ECG corroboration. The AO marker presents the most interesting alternative as it is obtainable without the use of another signal to identify heartbeats [13].

Previous literature focused on the use of mobile devices to compute HRV indices [10]. Admittedly, the sensitivity and sampling frequency of the device tested greatly reduced the validity of the measurements. It was our aim to establish a solid experimental basis, not only for further exploration of mobile devices, but also in clinical scientific studies. While their analysis established linear correlation between indices obtained from SCG, they did not go as far as to compare computed line regressions with the unit line passing through the origin. Their study used IM only, while we are of the opinion that AO lends itself more easily to analysis.

We used the R peak to obtain AO markers on our SCG signals because we were interested in showing that if AO is correctly identified, it is able to return valid HRV indices. Methods exist to identify AO from an SCG signal alone; however, such methods have yet to be widely used.

Table 3. Bland-Altman 95% confidence interval for chosen indices, comparing SCG markers with R-wave.

	AO-AO		MC-MC		IM-IM	
	0 mmHg	-50 mmHg	0 mmHg	-50 mmHg	0 mmHg	-50 mmHg
SDNN (ms)	-0.27 ± 0.90	-0.32 ± 0.97	-0.32 ± 0.60	-0.34 ± 0.60	-0.33 ± 0.67	-0.35 ± 0.70
RMSSD (ms)	-0.39 ± 2.52	-0.55 ± 2.79	-0.48 ± 1.78	-0.53 ± 1.78	-0.59 ± 2.14	-0.68 ± 2.21
HF norm (%)	-0.28 ± 1.78	-0.39 ± 1.95	-0.34 ± 0.96	-0.36 ± 0.95	-0.46 ± 1.25	-0.51 ± 1.31
LFHF	0.010 ± 0.073	0.014 ± 0.080	0.013 ± 0.037	0.013 ± 0.037	0.017 ± 0.053	0.019 ± 0.055

The differences between interbeat intervals obtained from ECG and SCG markers were statistically insignificant. Although differences up to 60 ms were recorded for individual intervals, since the total number of recorded heart beats in a given period of time longer than a few heartbeats will always be the same using all markers, differences will always average to a value very close to 0. Since HRV index practices depend on recordings longer than 2 minutes, it is no surprise that SCG returns valid indices.

References

[1] Ho KKL, Moody GB, Peng C-K, Mietus JE, Larson MG, Levy D, et al. Predicting survival in heart failure case and control subjects by use of fully automated methods for deriving nonlinear and conventional indices of heart rate dynamics. Circulation 1997;96(3):842–8.

[2] Algra A, Tijssen JG, Roelandt JR, Pool J, Lubsen J. Heart rate variability from 24-hour electrocardiography and the 2-year risk for sudden death. Circulation 1993;88(1):180–5.

[3] Tsuji H, Larson MG, Venditti FJ, Manders ES, Evans JC, Feldman CL, et al. Impact of reduced heart rate variability on risk for cardiac events The Framingham Heart Study. Circulation 1996;94(11):2850–5.

[4] Tsuji H, Venditti FJ, Manders ES, Evans JC, Larson MG, Feldman CL, et al. Reduced heart rate variability and mortality risk in an elderly cohort. The Framingham Heart Study. Circulation 19941;90(2):878–83.

[5] Bonnet MH, Arand DL. Heart rate variability in insomniacs and matched normal sleepers. Psychosom Med 1998;60(5):610–5.

[6] Stein PK, Carney RM, Freedland KE, Skala JA, Jaffe AS, Kleiger RE, et al. Severe depression is associated with markedly reduced heart rate variability in patients withstable coronary heart disease. J Psychosom Res 2000;48(4-5):493–500.

[7] John M. Zanetti, K Tavakolian. Seismocardiography: Past, Present and Future. 35th Annual International Conference of the IEEE EMBS 2013;7004–7.

[8] Salerno DM, Zanetti J. Seismocardiography for monitoring changes in left ventricular function during ischemia. Chest 1991;100(4):991–3.

[9] Castiglioni P, Faini A, Parati G, Di Rienzo M. Wearable Seismocardiography. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2007 EMBS 2007: 3954-7.

[10] Ramos-Castro J, Moreno J, Miranda-Vidal H, Garcia-Gonzalez MA, Fernandez-Chimeno M, Rodas G, et al. Heart rate variability analysis using a seismocardiogram signal. 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 2012 : 5642–5.

[11] Friedrich D, Aubert XL, Fuhr H, Brauers A. Heart rate estimation on a beat-to-beat basis via ballistocardiography - a hybrid approach. 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 2010: 4048–51.

[12] Cooke WH, Ryan KL, Convertino VA. Lower body negative pressure as a model to study progression to acute hemorrhagic shock in humans. J Appl Physiol 2004;96(4):1249–61.

[13] Akhbardeh A, Kaminska B, Tavakolian K. BSeg++: A modified Blind segmentation method for ballistocardiogram cycle extraction. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS 2007: 1896–9.

[14] Malik M. Heart rate variability. Annals of Noninvasive Electrocardiology 1996;1(2):151–81.

[15] Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. Journal of Biopharmaceutical Statistics 2007;17(4):571–82.

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