Estimation of Hemodynamic Parameters from Seismocardiogram

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Abstract

In this paper we demonstrate that SCG can be used to estimate hemodynamic parameters such as stroke volume and the three systolic time intervals of pre-ejection period (PEP), left ventricular ejection time (LVET) and electromechanical systole (QS2).In this study, recordings of suprasternal pulsed Doppler and Impedance cardiogram (ICG) were used as the reference methods for comparison to the values estimated by SCG. Simultaneous SCG and ICG and Doppler were recorded from twenty four participants.

1. Introduction

Biosignals such as seismocardiogram (SCG), ballistocardiogram and apexcardiogram represent the mechanical vibrations of the body as the result of heart beating and have their main components in the infrasound range [1]. SCG, in particular, is recorded from the sternum and represents the acceleration generated by the heart on the surface of the body in an axis perpendicular to it in dorso-ventral direction [2].

The goal of this study was to assess the possibility that these vibrations, recorded from the sternum, could estimate four important hemodynamic parameters. This study was also conducted to identify the possibilities that this inexpensive technology could provide for monitoring of the cardiac dynamics non-invasively and as a compliment to the methods that already exist.

1.1. Stroke volume

Stroke volume (SV) is the quantity of blood ejected with every heart beat and is approximately 70 mL for a 70 kg healthy man. Different invasive and noninvasive methods have been used for the measurement of stroke volume. Doppler ultrasound is one of these many methods and has been compared to other more classical methods in order to validate its accuracy in estimation of stroke volume.

1.2. Systolic time intervals

Systolic time intervals have been shown to change with cardiac abnormalities [4]. The commonly used systolic time intervals are: total electromechanical systole (QS2); left ventricular ejection time (LVET); and, pre-ejection period (PEP).

The QS2 is measured from the start of the QRS complex to the first high frequency vibration of the aortic component of the S2. The LVET is measured from the beginning upstroke to the trough of the incisura of the carotid arterial pulse tracing. PEP is measured by subtracting LVET from QS2.

2. Methods

All the data were acquired with a National Instruments DAQ and GUI system at a sampling rate of 2.5 KHz. Suprasternal Doppler, SCG, ECG and Impedance cardiography were simultaneously recorded as shown in Figure 1. A ten minute recording, which provided more than six hundred heart beats for signal processing, was obtained from every participant.

The SCG signal was recorded as described by Salerno and Zanetti [5] with the same model piezoelectric accelerometer. The accelerometer was placed on the midline of the sternum with its lower edge at the xiphoid process. The sensor (model 393C, PCB Piezotronics) had a linear response between 0.3 and 800Hz and sensitivity of 1.0 V/g.

2.1. Participants

Signals from 24 participants (3 female, 21 male) were used for the extraction of systolic time intervals. The average of age for these participants was 36±15.9, with an average weight of 73±10.4 kg and an average height was 173±7.7 cm. Four of the participants were chosen from a patient population in Burnaby general hospital who had a history of heart attack and very low ejection fraction. The rest of the participants were healthy with no history of cardiac problems.

Eight participants, under the age of 32, were selected for the estimation of stroke volume. For these participants the signal acquisition was conducted in two separate sessions at least a day apart. The signal from the first session was used for training and the second day for testing.

Figure 1. Simultaneous, from top to bottom, ECG, suprasternal ultrasound, ICG, and SCG. The designated points on SCG were detected in order to determine the systolic time intervals as seen above. The vertical line is aligned with the R wave of ECG as a temporal landmark.

2.2. Doppler ultrasound

A 2MHz pulsed Doppler instrument (MultiFlow, DWL GmbH, Sipplingen, Germany) was used for this study. All the measurements in the present study were made with an insonation depth of 6.5 to 7.5 cm with the sample volume located 1.0 to 1.5 cm above the aortic valve. The optimum position of the probe was taken as that giving the maximum peak velocity, with minimal spectral broadening and a clearly identified upstroke on each beat. This was assessed from the spectrum analyzer display and also by listening to the audiofrequency Doppler signal. All signals were obtained by the same experienced ultrasonographer.

The ultrasound measurement relies on the physical properties of the blood ejected from the heart. The velocity of the red blood cells ejected from the heart through the aorta produces a Doppler shift in the frequency of the reflected ultrasound waves. The integration of the velocity over a single beat combined with measurement of aortic diameter is provides an established method for estimation of beat-to-beat stroke volume [3].

2.3. Impedance cardiogram

Impedance cardiography (ICG) can be considered to belong to the more general category of impedance plethysmography that refers to estimation of volume changes in the body by measurement of changes in electrical impedance. ICG has been particularly used in the past for the estimation of stroke volume and systolic time intervals [6].

The temporal landmarks on ICG which are of special interest to us are B and X points as in Figure 1. Based on the echocardiographic studies the B point on ICG corresponds to the start of systolic ejection (aortic valve opening) and the X point corresponds to the aortic valve closure. In this study the impedance cardiogram was measured using the BoMed NCCOM3.

3. Data analysis

3.1. Stroke volume

Features were extracted from SCG signal based on current knowledge of the correspondence of SCG waves to cardiac events. This knowledge was acquired through previous research [1] in our laboratory and based also on the work of Crow et al. [7].

Based on the previous studies on the morphology of SCG signal [5] and as in Figure 1, the following features were extracted: Isovolumic contraction time (MC-AO) and its slope, systolic ejection time (AO-AC), isovolumic relaxation time (AC-MO), the area under curve during rapid systolic ejection (RE), the maximum of rapid ejection and the slope of its increase, the time between the ECG R wave and the opening of mitral valve.

For each beat the Doppler stroke volume was determined by calculation of the area under the curve on the Doppler signal (stroke distance) and multiplication by the area of aortic ring. For the first two participants the diameter, identified as LVOT, was measured with a GE Vivid 7 echocardiograph machine. For the remaining participants the aortic ring diameters were not available and were assumed to be 20 mm, the average for men.

It should be noted that the lack of exact values for aortic ring would not undermine our estimation method since it could be evaluated by stroke distance. However, a scaling that could bring the values into the range of stroke volume (70 mL) was preferred to be able to correctly assess the accuracy of our estimation [3].

Initially, nonlinear methods such neural network and nonlinear regression were used for estimation of stroke volume but our further analysis showed that the linear regression gave equally good results. In our previous study a cross validation method was used to divide the extracted feature vectors into training, testing and validation sets. This division was performed on the vectors of the same data acquisition session.

In each regression or neural network session, one hundred vectors were selected for testing and one hundred for validation. The remaining vectors were used for neural network training. This was repeated until every single vector was given an equal chance to be tested against the regressor or the neural network, and to avoid any randomness. The Bland and Altman method [7] was used to test the results; over eight subjects the average of

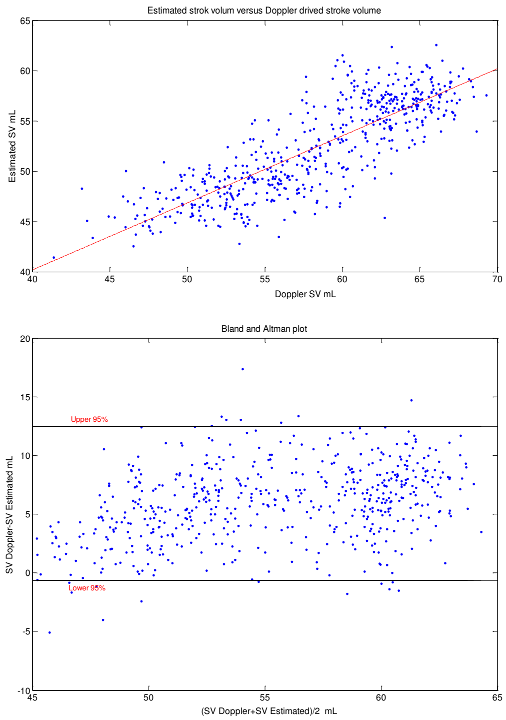

Figure 2. Top: the estimated stroke volume versus Doppler ultrasound values in mL for 601 cardiac cycles for the first participant. Bottom: Bland and Altman plot of the differences of the two methods versus their average together with the higher and lower 95% confidence intervals.

the differences was 0.07 mL with higher and lower 95% confidence intervals of 7.4 mL and -7.6 mL were obtained.

In that study we decided to test the validity of the stroke volume assessment after few days using SCG. The beat-by-beat extracted features from the first session were input into a multiple linear regression. The inputs contained 17 component vectors extracted from every individual heart beat. Thus, the first session was used for training and the second session for testing.

3.2. Systolic time intervals

For systolic time intervals the ensemble average of signals was used. In order to derive this ensemble average the R wave of ECG was first calculated in order to separate different heart beats. For SCG the two points AO and AC were detected as in Figure 1 and for ICG the two points of B and X were assigned.

For the ensemble average of Doppler signal the point from which the signal rises from zero and also the dicrotic notch were identified for every one of the 24 participants. In one of the subjects the dicrotic notch was faded over averaging thus, on this single subject we could just measure the PEP value from the three targeted systolic time intervals. For two participants the Doppler was not available and for one participant the ICG was not measured as they had a pacemaker that could have been adversely affected by the current imposed by ICG device.

4. Results and discussion

4.1. Stroke volume estimation results

The results for the stroke volume estimation for the first participant, a 32 year old healthy male, can be seen in Figure 2. The results for all subjects are found in Table 1. The average of the differences over all subjects was 2.56 mL.

This was slightly worse than the results we obtained previously on single session analysis, which was close to zero [6]. Also the confidence intervals are not as narrow as our previous results.

Of the 4900 cycles analysed from all eight participants, 83 percent had an estimated value within a 10 mL range of the reference stroke volume as provided by the Doppler method. This 10 mL neighbourhood is also reported for every individual separately as in Table 1. The average correlation coefficient was 0.61.

4.2. Systolic time intervals results

Using JMP7 (SAS institute) software, a randomized incomplete block design was used on the three measured parameters of PEP, LVET and QS2 using the three methods of SCG, ICG and Doppler. The p-vales of 0.17, 0.93 and 0.81 were obtained for the parameters of PEP, LVET and QS2 respectively. These values, being more than 0.05, shows that the null hypothesis, that the mean of the three methods are equal, cannot be rejected.

5. Conclusion

This research work covered the results of analysis of SCG signal in order to extract hemodynamic parameters. In particularl, it covered two separate but related works on estimation of stroke volume and systolic time intervals.

With respect to Stroke volume, the purpose of this recent study was to improve our preliminary results of our single session evaluation [6] to double session. The goal was to show that with this simple measurement of precordial acceleration from the chest we can estimate the stroke volume on the same participant several days after the initial measurement. In other words, the aim was to

Table1: Comparison of Stroke Volume estimated by SCG and Doppler

Participant	correlation coefficient	Mean Difference mL	Upper 95% Confidence interval mL	Lower 95% Confidence Interval mL	Percentage of 10 mL Neighbors	Number of heart beats
1	0.83	5.92	12.49	-0.64	89.73	601
2	0.75	-6.6	1.12	-14.4	100	561
3	0.55	3.3	11.8	-5.2	97	685
4	0.62	7.7	23	-8.3	60.5	607
5	0.52	4	10	-0.6	96.3	513
6	0.6	2.5	10.3	-5.3	98.8	529
7	0.46	-1.5	3.7	-6.8	98	676
8	0.55	5.2	29	-19.1	40	728
Averages	**0.61**	**2.56**	**12.67**	**-7.54**	**85.1%**	**613**

prove the reproducibility of SCG for such an estimation.

Although the absolute value of stroke volume is important to cardiologist, what may be a more important benefit to patients clinically is the detection of sudden drops in stroke volume. We did not evaluate such an experimental condition; however, in future through implementation of a lower body negative pressure we will be able to change the stroke volume in a short amount of time and assess the capability of SCG in detection of such a sudden drop. An important problem we encountered during stroke volume measurement was the difficulty to reproduce the same reference Doppler estimation between days that could be changed by a slight change of angle or depth of measurement. With respect to systolic time intervals, we showed that SCG can give accurate measurements for the three most important systolic time intervals when compared to two other methods. The obtained results proved the consistency of SCG for such measurements. A limited number of subjects were used in this research and we will continue to acquire data from more participants.

Acknowledgements

We would like to thank Burnaby General Hospital for allowing us access to their patients and Dr Alireza Akhbardeh, Dr. Peter Pretorius, Amanmeet Garg and Bahman Yari Saeed-Khanloo for their helps in data acquisition and analysis.

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