Estimating Cardiac Stroke Volume from the Seismocardiogram Signal

Kouhyar Tavakolian*, Andrew P Blaber**, Alireza Akhbardeh***,
Brandon Ngai*, Bozena Kaminska*
*The School of Engineering Science, Simon Fraser University, BC, Canada
**Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Canada
***School of Medicine, Johns Hopkins University, Baltimore, MD, USA

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INTRODUCTION

Recent studies have shown that analysis of stroke volume variability can provide information about the inotropic state of the myocardium while the older method of heart rate variability, HRV, provides us with knowledge of the chronotropic state of myocardium and ventricular performance [1]. In this study it is shown that Seismocardiography, SCG, has the potential to provide an estimate of beat by beat stroke volume. SCG signals are mechanical vibrations created by heart beating, and is recorded noninvasively from the surface of the body [2 and 3].

In this study, recordings of suprasternal pulsed Doppler was used as the reference method for comparison to the stroke volume estimated by SCG. The Doppler method is a known methodology for estimation of stroke volume and its accuracy has been confirmed through comparison to invasive standard methods such as thermodilution [4].

The purpose of this research was to investigate whether features of the SCG related to ventricular ejection [5, 6, 7, and 8] could be reliably used to estimate cardiac stroke volume.

METHODS

Data acquisition

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 to process, was obtained for every participant. Eight healthy males (25-33 years of age) volunteered to participate in this project.

SCG recording

The SCG signal was recorded as described by Salerno and Zanetti [3] with the same piezoelectric

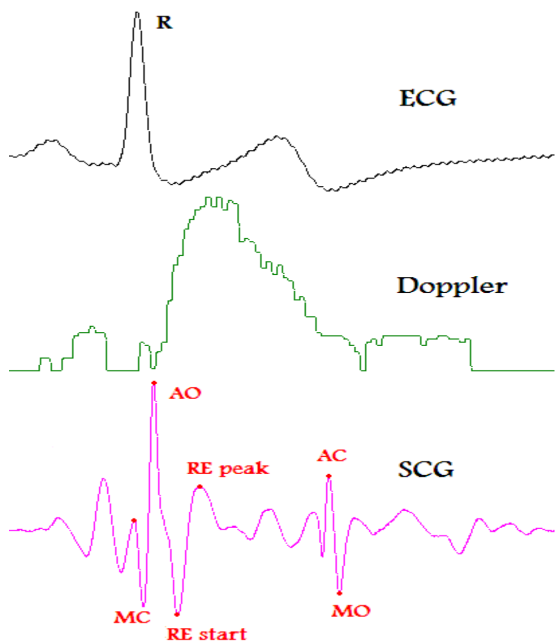

Figure 1: Simultaneous SCG, Doppler and ECG signals. MC: Mitral valve close, AO: Aortic valve open, RE: Rapid systolic ejection, AC: Aortic valve closure MO: Mitral valve open [5 and 8].

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.

Suprasternal Doppler

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 [4].

DATA ANALYSIS

Feature Extraction

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 [5, 6 and 7] in our laboratory and based on the work of Crow et al. [8].

Based on the previous studies on the morphology of SCG signal [5] (Figure 1), the following features were extracted: Isovolumic contraction time (MC-AO) and its slope, 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.

SCG Stroke volume Estimator

Initially a linear multiple regression was used in order to estimate the stroke volume; however, and very poor results were achieved and the use of a nonlinear estimator was pursued. The beat-by-beat extracted features were input into a supervised neural network which provided the preliminary SCG estimates of SV. A feed forward neural network trained by back propagation was finally chosen for this study. We used twenty neurons in the hidden layer and one linear neuron in the output. The inputs contained 14 component vectors extracted from every individual heart beat.

A Cross validation method was used to divide the extracted feature vectors into training, testing and validation sets. In each neural network session, one hundred vectors were selected for testing and one hundred for validation. The remainding vectors were used for neural network training. This was repeated until every single vector was given an equal chance to be tested against the neural network and to avoid any randomness.

Statistical analysis

The Bland and Altman method [9] was used to compare SCG and Doppler estimates of SV.

RESULTS

The results of Bland and Altman comparison of the Doppler and SCG estimates for each individual subject are listed in Table 1. In the best possible cases we had an average correlation coefficient of 0.70. The average of differences shows that the estimated values are 0.07 mL less in average compared to the Doppler estimated values. Also the histogram of the differences was plotted and noticed that it is normally distributed thus, the 95% higher and lower confidence intervals were calculated as mean ± 2*Standard deviations.

Figure 2 shows the Bland and Altman plots for one of the subjects. For eight subjects the average of higher 95% confidence interval was 7.45 mL and the lower limit was -7.6 mL. It should be noticed that each estimator was particularly trained for every individual.

Table1: Comparison of Stroke Volume estimated by SCG and Doppler

Participant	Mean Correlation	Standard deviation of Correlation	Max Correlation	Mean differences	Upper 95% Confidence interval	Lower 95% Confidence Interval
1	0.64	0.04	0.74	0.06	8.90	-8.80
2	0.58	0.05	0.65	-1.00	9.80	-11.94
3	0.46	0.08	0.63	-0.72	7.40	-8.90
4	0.53	0.05	0.60	0.93	10.08	-8.21
5	0.48	0.12	0.71	0.02	5.45	-5.45
6	0.57	0.08	0.77	0.12	6.69	-6.44
7	0.68	0.08	0.79	0.00	7.02	-7.01
8	0.61	0.09	0.74	0.04	4.32	-4.41
Averages	**0.57**	**0.073**	**0.70**	**-0.07**	**7.45**	**-7.60**

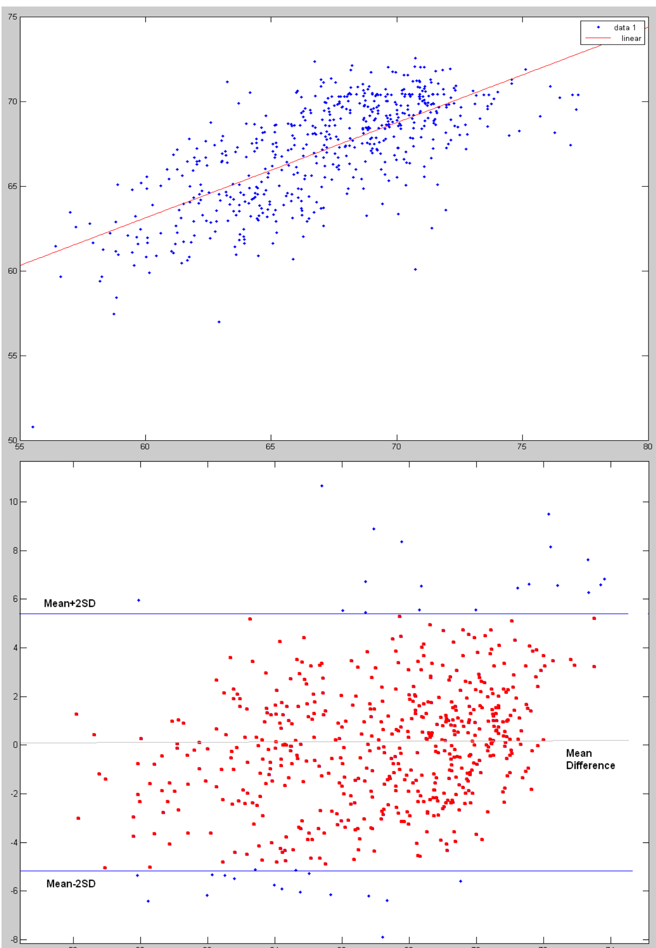

Figure 2: Plots of estimated values for the 520 heart beats of participant five. Top; the estimated stroke volume versus the Doppler values. Bottom; Bland and Altman plot of the differences versus the average of the estimated values and Doppler values. The two parallel lines indicate the 95% confidence interval boundaries.

DISCUSSION

In this study a novel methodology is proposed for beat to beat estimation of stroke volume. Our preliminary results show that the estimated values, as in Table 1, in 95% of the cases, were in a 7.5 mL range of the values estimated by Doppler suprasternal measurement. Considering the normal values of stroke volume, for men, this approximates a 10% range.

It should be noted that in this study the SCG method was compared to another indirect method of stroke volume measurement for which we did not have the aortic ring diameter for 8 participants. Thus, we approximated a 20 mm diameter from the literature. While we know there are inter-personal differences which could influence our reference stroke volume this would only affect the estimate by a fixed constant for each participant.

As a next step, 3D electromechanical models of the heart will be used to simulate SCG signal and will allow us to study this area from a different point of view [6]. There are also possibilities to improve our estimator and to find out the optimum initial weights for our neural network leading to better estimation results or to even use other types of estimators such as a support vector machine or supervised fuzzy adaptive resonance classifiers [10]. We will also record signals from patients with low ejection fractions and assess the accuracy of our estimator in abnormal cases.

REFERENCES

[1] S. Akselrod, Y. Amitayt, R.M. Lang, V. Mor-Avi and L. Keselbrener, "Spectral analysis of left ventricular area variability as a tool to improve the understanding of cardiac autonomic control" *Physiological Measurment Vol.* 21, pp. 319-331, 2000.

[2] W.P.S. McKay, P.H. Gregson, B.W.S. McKay, J. Militzer, " Sternal acceleration ballistocardiography and arterial pressure wave analysis to determine stroke volume" Clin Invest Med, vol. 22, no. 1, pp. 4-14, 1999.

[3] D.M. Salerno, J. Zanetti, "Seismocardiography: A new technique for recording cardiac vibrations. concept, method, and initial observations" J Cardiovasc Technol, vol. 9, no. 2, pp. 111–118, 1990.

[4] J.A. Innes, C.J. Mills, M.I.M. Nobels, K. Murphy, S. Pugh, A.C. Shore, A. Guz, "Validation of beat by beat pulsed Doppler measurement of ascending aortic aortic blood velocity in man" vol. 21, pp. 72-80, 1986.

[5] K. Tavakolian, B. Ngai, A. Akhbardeh, A. P. Blaber and B. Kaminska "Comparative analysis of infrasonic cardiac signals" Computers in Cardiology, vol. 36, pp. 757−760, 2009.

[6] A. Akhbardeh, K. Tavakolian, V. Gurev, T. Lee, W. New, B. Kaminska, N. Trayanova "Comparative analysis of three different modalities for characterization of the seismocardiogram" 31th IEEE Engineering in Medicine and Biology conference, pp. 2899:2903, 2009.

[7] B. Ngai, K. Tavakolian, A. Akhbardeh, A. P. Blaber, and B. Kaminska "Comparative analysis of seismocardiogram waves with the ultra-Low frequency ballistocardiogram" 31th IEEE Engineering in Medicine and Biology conference, pp. 2851:2854, 2009.

[8] R.S. Crow, P. Hannan, D Jacobs, L. Hedquist, D.M. Salerno "Relationship between seismocardiogram and echocardiogram for events in the cardiac cycle" American Journal of Noninvasive Cardiology, vol. 8, no. 1, pp. 39–46, 1994.

[9] J.M. Bland, D.G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement" Lancet, pp. 307-310, 1986.

[10] A. Akhbardeh, Nikhil, P.E Koskinen and O. Yli-Harja, "Towards the Experimental Evaluation of Novel Supervised Fuzzy Adaptive Resonance Theory for Pattern Classification," Pattern Recognition Letters - Elsevier, 2007.