Analysis of Seismocardiogram Capability for Trending Stroke Volume Changes: A Lower Body Negative Pressure Study

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Abstract

Features were extracted from seismocardiogram (SCG) data to correlate with stroke volume changes, estimated from arterial pressure recorded from the finger. Stroke volume was gradually reduced in twenty nine human subjects using lower body negative pressure. Twenty three features were extracted from SCG amplitudes and timings. There was at least one feature in every subject with correlation coefficient of 0.87or greater (P-value <0.01). The ratio of left ventricular pre-ejection interval to left ventricular ejection time (LVPEI/LVET) proved to correlate the most with stroke volume (r=-0.92±0.06) compared to the other features. The second most correlated SCG feature, with stroke volume, was LVPEI with (r=-0.90±0.12). The findings of this paper suggest that with simple processing of SCG it should be possible to detect a sudden drop in stroke volume that could result from a variety of different cardiac abnormalities.

1. Introduction

Stroke volume (SV) is the quantity of blood ejected with every from many possible causes. Some of these conditions may coexist and a non-invasive trending of stroke volume, as an index of cardiac contractility, could help improve such situations. As such, different methodologies have been proposed to estimate stroke volume, including the Portapres™ (Finapres Medical Systems, Amsterdam, Netherlands) device which estimates stroke volume from the signal obtained by recording continuous finger arterial pressure [1].

A seismocardiogram (SCG) is a low frequency signal (less than 30 Hz and mostly in infrasound range) recorded from the chest using accelerometers. SCG has also been used for the estimation of stroke volume [2][3][4]. This paper revisits the idea of estimating stroke volume from SCG but unlike previous attempts the goal has not been to derive a regression equation for calculation of the absolute value of stroke volume [2] or to use machine learning approach [4], which was categorized with patient specific approaches. Rather, the goal of this study was to determine those SCG features most sensitive to changes in stroke volume, over a wide range of subjects, and to track changes of stroke volume rather than to determine the absolute value of SV.

For this purpose an orthostatic stress test of graded lower body negative pressure (LBNP) was used to reduce the stroke volume (up to 40% in some subjects) and to study the corresponding changes of the SCG signal. We used a photoplethysmography technique, instead of Doppler ultrasound, for estimation of the reference stroke volume [4].

2. Method

2.1. Subjects

A total of 29 participants took part in this study including thirteen female (age: 26.5±4.3 years, weight: 62.9±9.9 kg, height: 166± 5.6 cm) and sixteen male subjects (age: 29.4±4.8 years, weight: 81±9.8 kg, height: 179.2± 4 cm). The youngest subject was 20 years old and the oldest was 44 years old. None of the subjects had any documented cardiac abnormalities. Signal recording was performed at the Aerospace Physiology Laboratory under an ethics approval from Simon Fraser University, British Columbia, Canada.

The SCG signal was measured with a high sensitivity accelerometer (Brüel & Kjær model 4381, Nærum, Denmark) as used in [4]. The participants were in the supine position and the signals were recorded in the back to front direction, perpendicular to the body surface. ECG 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). The measurement setup can be seen in Figure 1.

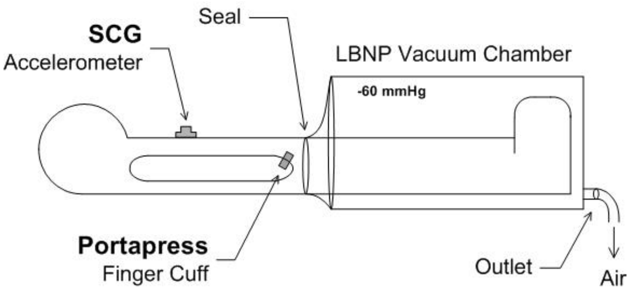

Figure1. The data recording setup for synchronous acquisition of SCG and arterial blood pressure signals.

2.2. Stroke volume changes

The finger cuff was applied to the mid-phalanx of the middle finger of the left hand. Stroke volume was estimated from the recorded finger arterial pressure with the Beatscope™ software which uses the Modelflow technique [1]. This technique has been validated against thermodilution [5] and Doppler ultrasound [1] for estimation of stroke volume and cardiac output.

In this paper we used the percentage changes in stroke volume, rather than the absolute values given by the Beatscope software, using the formula:

$$SV\% = \frac{SV - SVrest}{SVrest}$$

Where, SV_{rest} is the average of the stroke volume before the start of lower body negative pressure.

2.3. Lower body negative pressure

An orthostatic stress test of graded lower body negative pressure (LBNP) was used to change central blood volume and thereby reduce cardiac stroke volume. Lower body negative pressure 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 [6].

The participant's lower body was placed in a negative pressure chamber and sealed at the iliac crest as in Figure 1. Vacuum was applied to the chamber to drop the pressure by 10 mmHg decrements every minute, over 6 minutes through to -60 mmHg. The pressure was then increased in the reverse fashion in 6 minutes back to normal pressure. Negative pressure was terminated if participants exhibited a sudden decrease in heart rate or blood pressure or if they expressed any discomfort. One subject was excluded from the study because of the expressed discomfort.

2.4. Feature extraction

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 using an algorithm developed in Matlab. There was an average of over 1100 cardiac cycles per subject. Stroke volume was calculated by the Beatscope™ software from the Portapres waveform. A moving average of one minute was used to smooth the SCG and stroke volume values.

Twenty three features were extracted from the SCG signal in four categories, including timings (Q-MC, Q-AO, Q-IM, Q-AC, and AO-AC), amplitudes (MC, AO, IM, IM-AO), slopes (IM to AO, MC to MI, MA to RE) and root mean square values (RMS1: rms 150 ms after R wave, RMS2: rms during isovolumic contraction time).

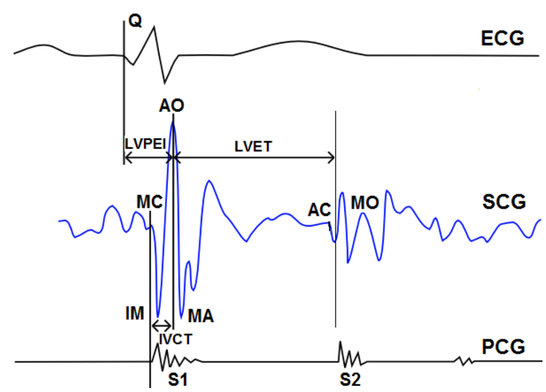

Figure 2. The SCG annotations based on cardiac cycle events: Aortic valve closure and opening (AC and AO); Mitral valve closure and opening (MC and MO); Maximum acceleration of blood in aorta (MA); Isovolumic contraction moment (IM); Left ventricular ejection time and pre-ejection interval (LVET and LVPEI); Isovolumic contraction time (IVCT). S1 and S2 are first and second sounds of the heart registered through phonocardiography (PCG) and are shown to clarify the correspondences of events on the two signals.

The SCG annotations seen in Figure 2 are based on previous literature [7][4]. The Q-AO feature corresponds to left ventricular pre-ejection period of LVPEI (also known as pre-ejection period, PEP) and the AO-AC interval corresponds to left ventricular ejection time. In our previous research we had investigated such correspondences [4].

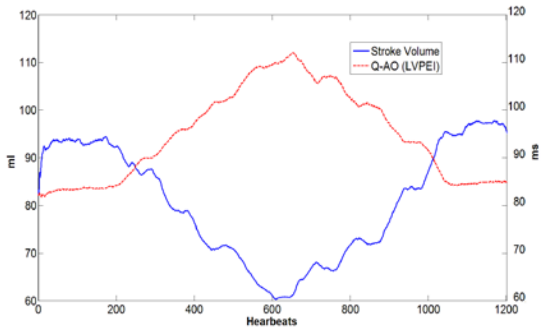

Figure 3. Simultaneous stroke volume (solid-blue in ml) and Q-AO or LVPEI in ms, (dashed-red in ms) calculated from the SCG, for a subject during lower body negative pressure.

3. Results and discussion

Before and at the peak of LBNP, over all the 29 subjects, Q-AO went from an average of 86.7 ms (SD=14.9 ms) to a maximum of 103.2 ms (SD=17.3 ms); whereas AO-AC was reduced from 321.8 ms (SD=25.2 ms) to 275.78 ms (SD=23.8 ms). A plot of stroke volume versus Q-AO can be seen for one of the subjects in Figure 3.

Of the 23 extracted features, at least one had a correlation coefficient of 0.87 or higher in each of the 29 subjects. In six subjects the best feature was from amplitude (such as AO, MC and MA amp) and in the remaining subjects the best correlated value was from timing values of SCG.

The two most dominant SCG features were Q-AO/AO-AC and Q-AO. The ratio of the Q-AO to AO-AC timing gave the highest average correlation (r=0.92±0.06) over the rest of SCG features with the next strongest correlation occurring with Q-AO (r =-0.90±0.12). As previously mentioned, AO corresponds to LVPEI and AO-AC corresponds to left ventricular ejection time to LVET.

In general it was observed that features extracted from amplitudes within the SCG signal were not as well correlated to stroke volume as the timing features. Thus for screening purposes, when only one or few features are to be selected to trend stroke volume then the results from this study suggest that the features related to cardiac timing, such as LVPEI/LVET, would provide the most reliable candidates.

Although the classical looking SCG morphology presented by [7] and represented in Figure 2 is quite common, the signal morphology can vary from person to person due to differences in the shape of the rib cage and positioning of heart within.. These can alter SCG features in certain people, and render them more sensitive to changes in cardiac contractility and stroke volume. Thus in a patient specific approach, where it may be possible to assess the more sensitive SCG features, in a calibration-like procedure, it is possible that the amplitude extracted features (such as the amplitude at the AO and MC) could be used to trend stroke volume. This could find applications in patient monitoring devices where a calibration procedure can be considered before the discharge from hospital and can improve the stroke volume trending accuracy.

In a screening application where only a single feature can be selected for trending stroke volume, the results of this paper suggest the use of Q-AO/AO-AC (LVPEI/LVET). When locating AC is problematic then LVPEI is recommended. It has also been shown that reductions in stroke volume and contractility increase LVPEI [8]. This inverse effect was also observed in this study with a very high negative correlation of more than 0.9.

4. Conclusion

In earlier studies using angiography LVPEI and LVPEI/LVET had been shown to correspond to stroke volume and ejection fraction [9][10]. In more recent work it has been demonstrated that LVPEI decreases with increasing contractility and can be used as an index to pre-screen patients for cardiac resynchronization therapy [8][11]. The results of this paper demonstrate that the systolic timing features LVPEI and LVET extracted from SCG can be used to trend stroke volume changes. Our preliminary studies on pigs also demonstrated that LVPEI derived from SCG correlates with dP/dt_{max} [12].

Motion artifacts affect mechanical signals such as SCG significantly, making it very difficult to conduct experiments such as stress tests to modify stroke volume. LBNP on the other hand, provided a stable experimental platform to change the central hemodynamics and contractility gradually and to study the corresponding SCG changes.

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