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Myocardial Contractility: A Seismocardiography Approach

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***Abstract*—Features are extracted from seismocardiogram data to correlate with two indexes of myocardial contractility: dP/dt_{max} (maximum first derivative of left ventricular pressure) and stroke volume. In the first study on three pigs, it is shown that the time period between the R peak of the ECG and the first peak of the SCG (R-AO period or pre-ejection period, PEP) correlated (r= -0.86) with dP/dt_{max}. In the second study, stroke volume is gradually reduced in five human subjects using lower body negative pressure. The same feature as the pigs (R-AO) is correlated the most with stroke volume (r= -0.90).**

Keywords: dP/dt_{max}, stroke volume, lower body negative pressure (LBNP), pre-ejection period (PEP).

I. Introduction

Myocardial contractility is the intrinsic ability of the heart to contract. Different levels of contractility are achieved by the binding between myosin and actin filaments. In a variety of cardiac abnormalities, myocardial contractility is affected and reduced. The gold standard for assessment of myocardial contractility is the invasive measurement of change in pressure in the left ventricle, through the use of catheters, during the cardiac cycle and the calculation of the maximum first derivative of pressure (dP/dt_{max}) [1-3]. Stroke volume is also an indicator of myocardial contractility and a close correlate of dP/dt_{max}. The seismocardiogram (SCG) has been proposed for the estimation of stroke volume [4-6] and may also provide an estimation of dP/dt_{max}.

In this paper the estimation of myocardial contractility from the SCG was investigated with two separate parameters. Firstly, preliminary results on the association of SCG features with dP/dt_{max} are presented. To our knowledge, this is the first approach to use SCG for estimating dP/dt_{max}. A sample of signals used in this study is shown on the left side of Figure 1.

Secondly, the association of SCG features with stroke volume is evaluated. Unlike the approach in [5], which used equations for estimating stroke volume, the approach in this paper used actual measures of stroke volume recorded simultaneously with SCG (Figure 1). Furthermore, unlike [4], the stroke volume of the subjects was modified over a wide range with the use of lower body negative pressure (LBNP).

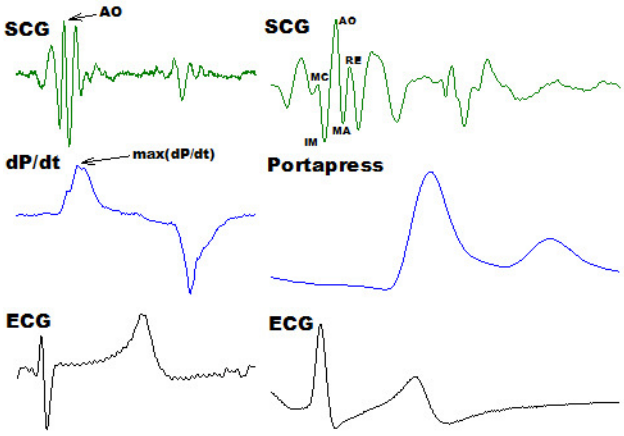

Figure 1. Left: A cycle of pig data together with dP/dt signal and ECG. Right: Annotated human SCG; MC: mitral valve closure, IM: isovolumetric moment, AO: aortic valve closure, MA: maximum acceleration of blood in aorta, RE: rapid systolic ejection point.

II. Methodology

A. SCG comparison with dP/dt_{max}

Ten, female, nonatherosclerotic swine, aged 11.3 to 12.1 weeks with body weights of 29.1 to 38.7 kg were used. This species was chosen as it has been extensively used for studies in the field of cardiology, resulting in a large volume of data generated on the cardiovascular response properties and its correlation to human cardiovascular response. The swine and human hearts have relatively similar anatomy which allows for a more direct human correlation.

All animals were tranquilized and anesthesia was induced intravenously and, after intubation, maintained by artificial ventilation with oxygen and isoflurane. The animals were placed in dorsal recumbency. Limb-leads were placed for electrocardiographic (ECG) monitoring. Each animal's sternum area was shaved for placement of the dBG 300 SCG sensor (Heart Force Medical Inc., Vancouver, Canada). A trained operator applied the sensor on the sternum in the midline, with the lower edge of the sensor placed approximately 3 cm above the xiphoid process, the same place as advised by [7] for human studies. All procedures were approved by the Comité Institutionnel de Protection des Animaux d'Accel

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LAB and complied with the Canadian Council on Animal Care regulations.

After anesthesia induction, the left and right femoral arteries were accessed through an inguinal incision for left ventricular recordings. The right jugular vein was accessed for pacing lead placement. A 7F guiding catheter (Medtronic, Minneapolis, MN) and sensor-tipped PressureWire (St. Jude Medical Inc., St. Paul, MN) were inserted into the left femoral artery and placed in the apex of the left ventricle for the measurement of left ventricular pressure. Computation of dP/dt_{max} was completed using the RadiAnalyzer Xpress system and PhysioMon 2.02 software (St. Jude Medical Inc., St. Paul, MN).

The right atrium was paced for one minute each at 10 separate heart rate (HR) conditions: 90, 100, 110, 120, 130, 140, 150, 160, 170 and 180 bpm. All HR conditions were counter-balanced to minimize the order effect. Left ventricular pressure, aortic pressure, left atrial pressure, ECG and SCG data collection were synchronized by the use of a Biopac MP150 (Biopac Systems Inc., Goleta, CA) and sampled at 1000 Hz.

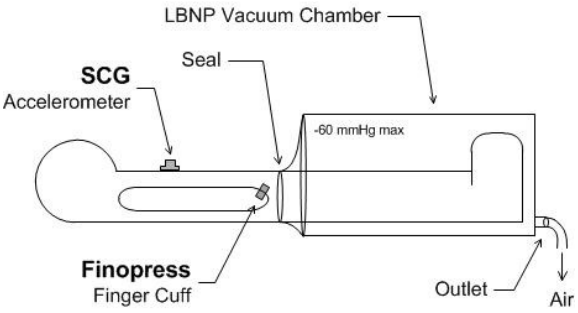

Figure 2. The lower body negative pressure setup.

B. SCG and stroke volume in humans during LBNP

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. The participant's lower body was placed in a negative pressure chamber and sealed at the iliac crest as in Figure 2. Vacuum was applied to the chamber to drop the pressure at 10 mmHg decrements every minute, over 6 minutes through to -60 mmHg. The pressure was increased in the reverse fashion in 6 minutes to reach normal pressure. The level of -40 mmHg produces similar volume shifts associated with complete upright posture.

Five young and healthy male participants took part in this study with average age 32.8 ±6.1 yrs, weight 82.2 ±11.9 kg and height 176.6 ±4.45 cm. Signal recording was performed at the Aerospace Physiology Laboratory under an ethics approval from Simon Fraser University.

The SCG signal was measured with a high sensitivity accelerometer as used in [4] (Brüel & Kjær model 4381, Nærum, Denmark). 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. Stroke volume was measured using a Portapres (Finapres Medical Systems, Amsterdam, The Netherlands).

All signals were recorded using an NI 9205 analog input module (National Instruments, Austin, TX). A snapshot of the recorded signals can be seen in Figure 1. The signal annotation as proposed in [7] is also shown.

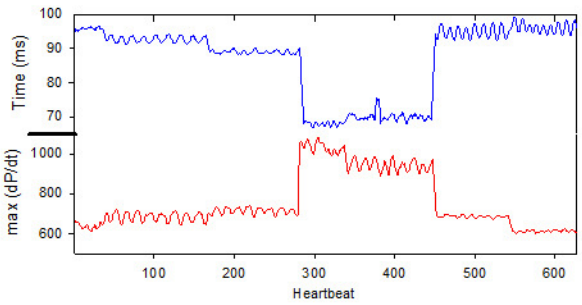

Figure 3. Bottom: dP/dt_{max} for over 600 heartbeats of one of the pigs. Top: The time period between the R peak of ECG and the peak of SCG (R-AO).

III. Results

A. dP/dt_{max} in pigs

The R wave of the ECG was used to segment heartbeats. Inspired by the annotation of human SCG[1] [7], eighteen morphological features were extracted from every cardiac cycle in the SCG, including amplitudes, slopes and timings of peaks and valleys. Data from three pigs were completely analyzed for this paper.

From the simultaneous dP/dt signal, dP/dt_{max} was calculated by finding the local maximum within a 200 ms window following the R wave of the ECG, as can be seen in Figure 1. A plot of dP/dt_{max} compared with one of the simultaneously extracted SCG features over all heartbeats of one of the pigs can be seen in Figure 3.

For the three pigs of this study, average dP/dt_{max} was calculated for each heart rate's entire recording session. Each of the eighteen SCG-extracted features was also averaged for each heart rate. A stepwise regression was performed over accumulation of all the features. The time period between the R peak of the ECG and the AO peak of the SCG (R-AO) was selected as the best feature. The correlation coefficient over the data of all three pigs together was -0.86 and is plotted in Figure 4. These results suggest an association between dP/dt_{max} and features extracted from the pig SCG.

[1] To our knowledge no investigation has ever been done on the physiological origins of a pig's SCG.

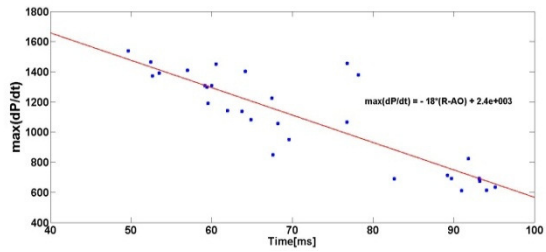

Figure 4. dP/dt_{max} plotted versus the selected feature (R-AO) for all 30 sessions of the three pigs together.

Table 1. Correlation coefficients between the dP/dt_{max} for every pig and the selected SCG feature.

Pig	1	2	3	Average
r	-0.75	-0.94	-0.91	-0.87

B. Stroke volume in humans

Similar to the pig data, the R wave of the ECG was used to segment heartbeats and morphological features were extracted from the SCG using software developed in Matlab. There were over 930 cardiac cycles per subject.

Sixteen features were extracted from the SCG signal in four categories, including timing (R-MC, R-AO, R-MI and MC-AO), amplitude (MC, AO, MI, MI-AO), slopes (MI to AO, MC to MI, MA to RE) and root mean squares (RMS1: rms 150 ms after R wave, RMS2: rms during isovolumic contraction period).

The stroke volume was calculated by the Beatscope software from the Portapres waveform as in Figure 1. A plot of the stroke volume for one of the subjects can be seen on top of Figure 5 together with one of the SCG extracted features (RMS).

The first row of Table 2 shows the r^2 value of a multivariate regression over all sixteen features. For every individual feature the r^2 value was calculated and for every subject the three features with maximum r^2 are reported in the middle of Table 2. A mixed stepwise regression was performed on the data from each subject and six features common between all of the five subjects (MC, MA, MI-AO slope, MC-MI slope, RMS1 and R-AO) were selected. A multivariate regression which included all six selected variables was then performed for each subject to provide the r^2 in the second to last column of Table 2. The selected features are from all four categories and the resulting r^2 are quite high. The final column in Table 2 represents the correlation coefficient for the SCG variable R-AO.

IV. Discussion

As explained in the second part of the previous section, a variety of extracted SCG features were compared in this study with the intent to select the best features for every subject. It was observed that the features extracted from the amplitude of the SCG signal were not as good when compared to timing features in two of the subjects (subjects one and five). It is obvious that as more features are added, the less the estimation error becomes; nevertheless, if only a few features are to be selected, then timing features may provide the better candidates.

The timing feature that stood out was the period between the R wave of the ECG to the AO point of the SCG. This corresponds to the pre-ejection period (PEP). The pig data also indicated that the pig-equivalent R-AO feature correlated well with dP/dt_{max}. It is also understood from the literature that reduction in stroke volume and contractility increases PEP [8]. This inverse effect was observed with the high negative correlation in both the pig and human data (Tables 1 and 2).

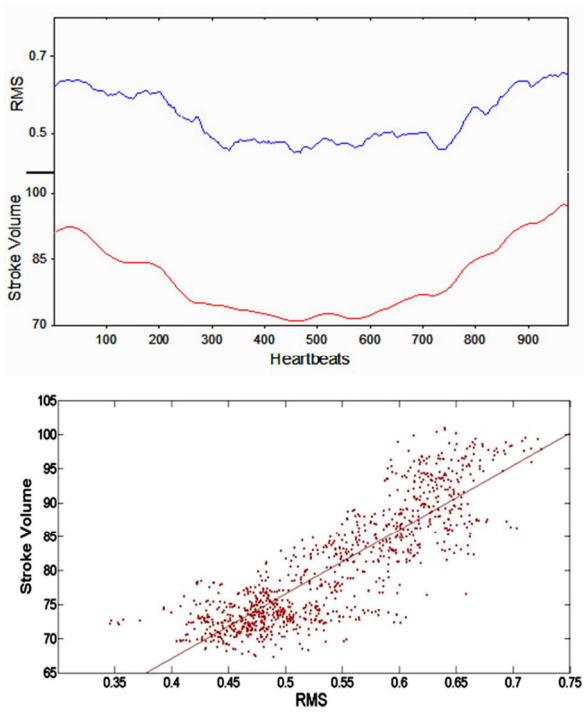

Figure 5. Top: Stroke volume (bottom trace) and RMS of the SCG signal over more than 900 heartbeats of a subject. Bottom: Stroke volume plotted versus the RMS value.

V. Conclusion

In our previous study we used general regression and nonlinear estimators to predict stroke volume, obtained through Doppler ultrasound [6]. That study presented a patient-specific solution to estimate stroke volume in which the algorithm was trained on the data of every individual subject separately. Thus, all possible morphological features were fed to the estimator to increase its accuracy. In this study we were more focused on the different effects of every individual feature on the indexes of contractility and also on a wider range of stroke volume.

As was expected, because of the inherent nature of SCG and the different ways the heart is located in the rib cages of individual persons, certain features of mechanical vibration in the SCG are more dominant in some than others. Although the classical looking SCG proposed in [7] is quite common, different morphologies

exist in some subjects with normal cardiovascular function.

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, provides a stable experimental platform to change the central hemodynamics and study the corresponding SCG changes. The preliminary results of the LBNP test are presented in this paper. More tests are planned on a greater number of subjects.

Analysis of the pig data is currently underway to examine other SCG features. We are also planning a human dP/dt_{max} study with heart failure patients undergoing cardiac resynchronization therapy.

Table 2. The r^2 values for different subjects and different combination of features.

Subjects	r^2 on all features	Three selected features	r^2 of best feature	Category	r^2 of six common features	r for R-AO feature
1	0.90	R-MC, R-MI, R-AO	0.69	Timings	0.77	-0.80
2	0.99	MC, R-AO, R-MI	0.92	Amplitude and Timings	0.94	-0.94
3	0.98	RMS2, MC, R-AO	0.98	All	0.96	-0.92
4	0.92	R-MC,R-AO,R-MI	0.81	Timings	0.98	-0.90
5	0.96	R-AO, R-MC, MC	0.93	Amplitude and Timings	0.87	-0.96
Average	**0.95±0.03**	***R-AO***	**0.87±0.10**	***Timings***	**0.90±0.07**	**-0.90±0.06**

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