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# Seismocardiographic Adjustment of Diastolic Timed Vibrations

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***Abstract*— a seismocardiography based methodology is introduced for predicting the start and the end of diastole to be used in diastolic timed vibrations. An accelerometer was placed on the sternum of 142 participants (120 healthy and 22 ischemic heart patients) to record Seismocardiogram (SCG). It is claimed that SCG, in combination with electrocardiogram (ECG), provides a mechanism for predicting diastole. It is demonstrated that prediction of the aortic valve closure point in the SCG signal helps start the vibrator in time to cover most of the isovolumic relaxation period. Also, through prediction of the mitral valve closure point, safety of the technique can be assessed by estimation of the amount of unwanted vibrations applied during the isovolumic contraction period.**

**Keywords: diastolic timed vibrations, seismocardiogram**

## I. Introduction

Diastolic timed vibrations (DTV) is a methodology consisting of applying low frequency mechanical vibrations to the chest of myocardial infarct patients during the diastole of the heart cycle, so as to help in rupturing and/or dissolving thrombus as well as improving coronary blood flow [1] . In recent years, studies have been conducted to find the optimum frequency range, location to vibrate, and pattern of vibrations for best clinical results [2, 3].

The proper timing of mechanical vibrations is of critical importance as the safety and efficacy of DTV is directly related to the timing of vibrations with respect to the cardiac cycle [4]. Vibrations must be avoided during systole where they could interfere with the contractile apparatus of the heart muscle. On the other hand, clinical trials have indicated that vibrations timed exclusively to the diastole of the cardiac cycle can advantageously facilitate heart muscle relaxation, improving the strength of heart contractions [1]. Thus, it is essential to predict the start and the end of diastole for safe and effective application of DTV, as shown in Figure 1.

So far, in DTV application, the diastole has been solely predicted by using algorithms based on ECG processing [3, 4]. The stop of vibrations is to be initiated by earlier detection of ECG R wave and the start of DTV is proposed to be initiated by detection of the peak or middle point of the T wave [4].

The method proposed in this paper still uses ECG, but it amends it with extra information provided by a simple few seconds of SCG recorded from the sternum, as long as including 15 heartbeats [5]. The use of SCG, for diastole detection, ensures that a DTV device does not overspill vibrations into systole and enables optimal application of diastolic vibrations. Furthermore, it is important to include the isovolumic relaxation period (IVRP) in the vibrations and to substantially cease vibrations prior to the start of isovolumic contraction period (IVCP). In this paper we demonstrate that the SCG signal is a viable method for predicting the start and the end of diastole, hence the proposition of a SCG-based prediction algorithm.

## II. Methods

According to our observations, the locations of aortic valve closure (AC) and mitral valve closure (MC) do not change significantly from one heartbeat to another. As shown later herein, the average of Q-MC and Q-AC timings from consecutive cycles can be used to predict valves closure times in future cycles with an acceptable error margin.

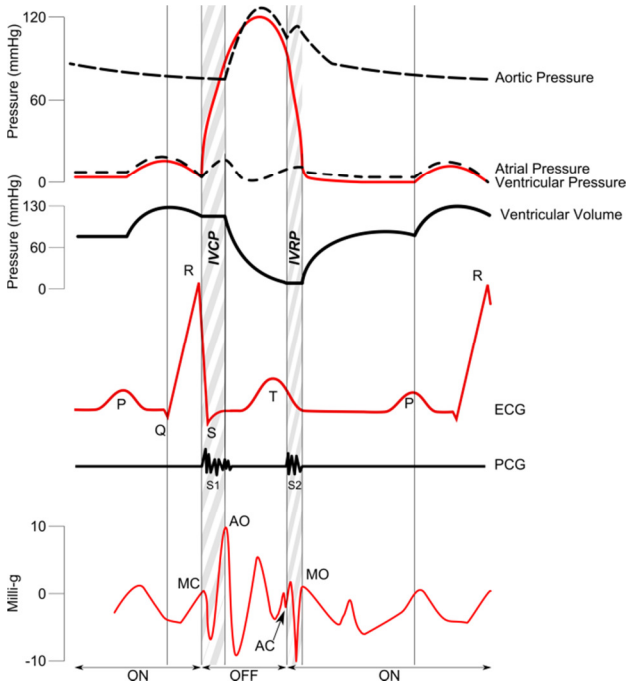


**Figure 1. A modified Wiggers diagram: a set of events in cardiac cycle for the left ventricle. AC and AO are aortic valve closure and opening, MC and MO are mitral valve closure and opening. The**

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**ideal timings of the DTV are shown as ON and OFF.**

This mechanism allows DTV to use SCG to predict the start and the end of diastole with an acceptable precision. As discussed previously, this prediction contributes to performance and safety of DTV.

### *A. Data Acquisition*

There are two separate datasets used in this research, one was recorded at Simon Fraser University from athletes and healthy young adults (under the age of 30) and the other one recorded at the Burnaby General Hospital on patients with ischemic heart diseases and also elderly participants. The experiment included total of 142 subjects (91 males and 51 females) aged between 18 and 90 years old with the average of 39±20 years. Ages of thirty one of these subjects was greater than 60 years from which 22 had ischemic heart disease.

In the ischemic heart disease patients 15 of them had myocardial infarct less than five years prior to the recording. The average age of the patient group was 67±8.5 with maximum of 84 years, average height of 172 cm and average weight of 83 Kg.

The SCG signal was measured either with a high sensitivity accelerometer (1000 milivolts/g, factory calibrated, mass of 54 grams) [6] or the accelerometer of the study presented in [5]. The subjects were in supine position and the signals were recorded in back to front direction, perpendicular to the body surface. ECG signal was also acquired and used to segment the cardiac cycles.

### *B. Annotations*

The SCG and phonocardiogram from 142 participants, totaling 16607 heartbeats, were annotated by two trained individuals. Every single cycle was observed by both annotators and the results were verified by a third individual for inconsistencies. Software was developed in Matlab to facilitate the manual annotations by proposing MC and AC points as in Figure 1.

## III. RESULTS

The proposed algorithm used a window of 15 heartbeats and for the cycles in this window, it calculated the length of the interval from the Q-wave of ECG to the MC and AC points of SCG; denoting them respectively as Q-AC and Q-MC. The average of Q-AC and Q-MC of the particular window was used to predict the same indexes of all other heartbeats of that individual. The accuracy of these predictions is presented in the next two subsections.

### *A. Prediction of the Start of Diastole*

As stated previously, using the annotated dataset for every individual subject, the first 15 cycles were selected and the average of their Q-AC values was used as the prediction. This predicted value was subtracted from the actual values of Q-AC for all the remaining heartbeats of the selected subject to derive prediction errors. The next window was chosen by sliding the previous window five cycles forward so that the new window had an overlap of 10 cycles with the previous window. The same procedure, as in the previous window, was repeated and prediction errors were calculated. the process continued in the same way until the predicting window reached the end of the dataset, giving all the cycles a chance to be present in the predicting window. The procedure for predicting the start of diastole was applied to the annotated dataset of all the 142 participants including both healthy and patient categories.

As stated before, the difference between the predicted value (obtained from the predicting window) and the actual values (obtained from annotations) were used to derive the error series corresponding to Q-AC for every individual subject. The Bland and Altman indexes [7] for all subjects are presented in the top part of Figure 2 and their averages (separated for patients and normal) are presented in the shaded region of Table 1.

The histograms of the estimation errors for the Q-AC detection (accumulation of all prediction errors of all subjects together) are shown on top part of Figure 3 and the values derived from these accumulated prediction errors are listed in the third and fourth rows of Table 1.

The initiation of DTV just before aortic valve closure would be of no harm and would still guarantee the coverage of IVRP. Considering this, the results of Table 1 for the start of diastole are presented for both the *absolute* and *actual* values of the prediction error. The *absolute* value of the estimation error, and also the Bland and Altman values, quantify the *accuracy* of the proposed methods in prediction of the aortic valve closure event. On the other hand, the 95 percentiles on the *actual* prediction errors quantify the number of times the predictions of aortic valve closure have *gone beyond* the actual aortic valve closure event detected by SCG; thus, they are more relevant to the requirements of DTV.

As an example, for SCG acquired on the patient group, the average of 95 percentile for the absolute value of differences was 14.9 ms while the same 95 percentile over the actual value of the differences was only 10.7 ms. The 14.9 ms interval represents the limit where the absolute difference resides 95% of the time. On the other hand, the 10.7 ms interval represents the limit where the estimation can go further than the aortic valve closure point, and into the IVRP 95% of times. As stated before, considering the DTV application, the 10.7 ms interval is a more relevant index quantifying the performance of DTV during its onset.

Among the 22 ischemic patients, the worst 95% interval was found to be 15.9 ms. In other words, in the worst case subject of the dataset, the aortic valve prediction would not have gone more than 15.9 ms after the actual value of aortic valve closure in 95% of the cycles.

Considering that IVRP lasts around 80 ms (in average), the 15.9 ms mark accounts for less than 20% overspill into

**Table 1. The results of SCG prediction of diastole: averages and standard deviations of Bland and Altman indexes values (shaded region) and the 95 percentiles for both the *absolute* value of prediction errors and the *actual* value of prediction errors. The top two rows for every index (Q-AC and Q-MC) are averages over subjects and the bottom two rows are for accumulation of all heartbeats from all participants together. Values are in milliseconds and the values after ± are standard deviations.**

| | Mean | Upper 95% | Lower 95% | 95% absolutes | 95% | |
|---|---|---|---|---|---|---|
| **Q-AC** | -0.12±0.4 | 9.4±3.8 | -9.6±4.0 | 8.8±3.5 | 7.4±3.0 | **Healthy** |
| | -0.25±0.9 | 14.6±4.4 | -15.1±4.6 | 14.9±5.4 | 10.7±3.3 | **Patient** |
| | -0.06 | 11.2 | -11.3 | 11.4 | 9 | **Healthy** |
| | -0.27 | 17.6 | -18.2 | 17.56 | 13.3 | **Patient** |
| **Q-MC** | -0.00±0.5 | 4.4±3.1 | -4.4±3.0 | 4.1±2.7 | 3.5±2.2 | **Healthy** |
| | -0.00±0.4 | 7.3±2.1 | -7.3±2.2 | 7.1±2.2 | 5.8±1.7 | **Patient** |
| | 0.00 | 4.8 | -4.8 | 4.9 | 3.7 | **Healthy** |
| | 0.00 | 8.2 | -8.2 | 8.5 | 6.4 | **Patient** |

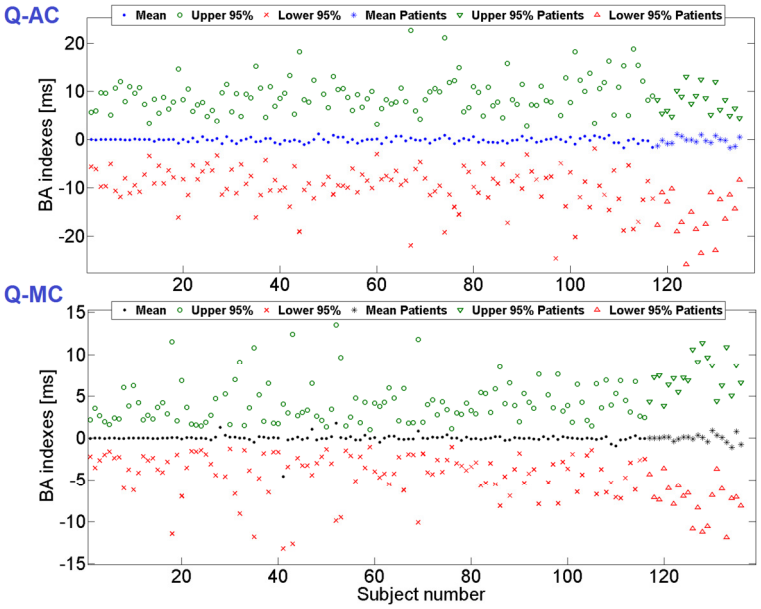


**Figure 2. Bland and Altman values for all subjects. Top: start of diastole, Bottom: end of diastole**

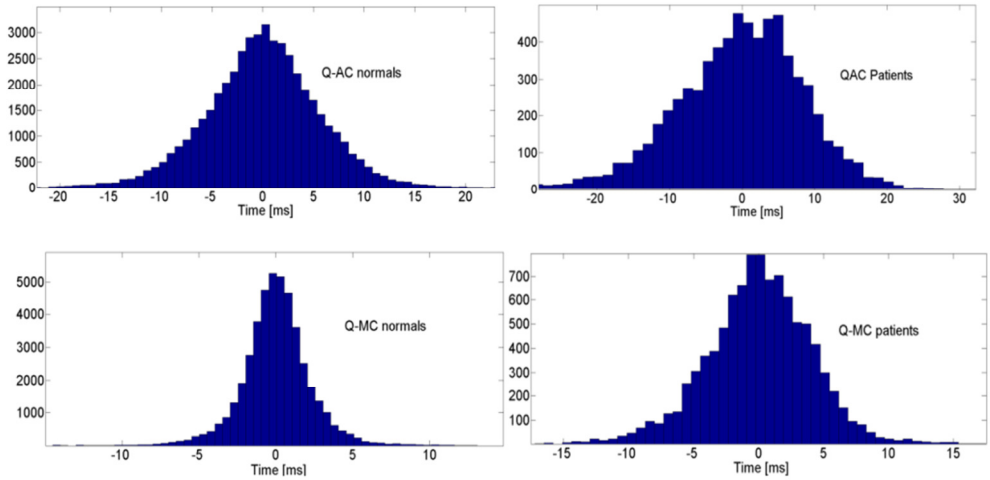


**Figure 3. The histogram of estimation errors for the start (top) and end of diastole (bottom) using SCG.**

IVRP in 95% of the cycles and in the worst case of the patient group.

The results presented in the four first rows of Table 1, corresponding to Q-AC, indicate that the population with ischemic heart disease had higher error margins compared to the healthy population, which is expected.

### *B. Prediction of the End of Diastole*

For the point of mitral valve closure, which indicates the end of diastole, the MC point of SCG was used (as in Figure 1). The same methodology, as used for prediction of start of diastole – explained in previous subsection – was used for the prediction of the end of diastole. The

prediction errors were quantified as in Table 1, using Bland and Altman indexes and 95 percentiles. The fifth and sixth rows of Table 1 present the averages of these values, separately derived for every participant. The Bland and Altman indexes for Q-MC detection are presented in the bottom section of Figure 2.

The histograms of the prediction errors (accumulation of all cycles from all subjects) for Q-MC are shown in the bottom part of Figure 3, which are derived by accumulation of prediction errors of heartbeats from all subjects together. The same data was used to derive the prediction error indexes listed in the last two rows of Table 1.

The same discussion as for the start of diastole holds for the end of diastole that the absolute value of prediction error is less important than the actual value since stopping before the mitral valve closure is not as important as stopping afterward, considering the DTV application. IVCP is a period when the heart prepares for the final push of blood out through the aorta and it may not be safe to vibrate the heart during this period. Stopping a few milliseconds before the isovolumic contraction might provide a comfortable safety margin for the patients.

## IV. Discussion and Conclusion

In this paper, we proposed a new methodology, based on SCG, for adjusting the timing of DTV in order to assure that the device would be active within the defined limits [9]. The two important criteria were to assure that DTV would stop *before* the mitral valve closure (so as not to cover the IVCP) and would start *not later than* the aortic valve closure (so as to cover as much of the IVRP as possible).

Based on averaging of Q-AC of 15 consecutive cardiac cycles, we can predict the start of diastole with error margin (95 percentile) of 10.7 ms, and worst prediction error margin of 15.9 ms in the ischemic patient population. This means that if the DTV was to start, for instance, 16 ms before the prediction of aortic valve, using SCG, chances of fully covering the IVRP is more than 95 percent in the subject with the worst prediction. The prediction of start of diastole can be used to initiate the application of vibrations in a DTV device.

Q-MC interval prediction can be used to assess the amount of overspill into IVCP. It was indicated that even in the case of ischemic heart disease group, the 95 percentile error margin was 5.8 ms in average. For the end of diastole, unlike its start, the SCG estimation cannot be used to initiate the stopping of vibrations. As soon as the Q-wave of ECG is detected, the stop command needs to be sent to the motor deriving DTV. Nevertheless, what would be useful is to assess the capability of the system to stop before the mitral valve closure point predicted by SCG or to quantify the amount of overspill into the IVCP.

It should be noted that it is also possible to extract higher frequency vibrations, corresponding to phonocardiogram as in Figure 1, from the accelerometer on the chest [8]. However, in a comprehensive study on the same dataset [9], it was demonstrated that the lower frequency vibrations (SCG) perform better than the higher frequency (PCG) in prediction of aortic valve closure and mitral valve opening.


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