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A Portable Measurement System for the Superior-Inferior Axis of the Seismocardiogram

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Abstract

Seismocardiography (SCG) is the measurement of vibration of the precordium due to cardiac movement. SCG is considered to be of value when cost-effective cardiac and circulatory assessment is needed. SCG is normally recorded in the dorso-ventral axis from the sternum, while it has been shown that the superior-inferior axis also has consistent waveforms and might be usable in stroke volume evaluation. Thus, it seems that a system focusing on the superior-inferior axis could be very useful. In this article, a portable measurement system for the measurement of the superior-inferior axis of the SCG is described, and its functioning is demonstrated. Four subjects were measured in the sitting position to verify the system's functioning. The measurements demonstrated the system's capability to capture accurate cardiovascular data. Future work includes the validation of the measurement of the superior-inferior of the SCG signal against an established method such as echocardiography.

Keywords: Seismocardiography; Ballistocardiography; Superior-inferior; Accelerometer

Abbreviations: BCG: Ballistocardiography; ECHO: Echocardiography; ECG: Electrocardiography; PPG: Photoplethysmography; SCG: Seismocardiography

Introduction

A large number of people suffer from heart diseases or circulatory problems [1,2]. Ballistocardiography (BCG) has been shown to be valuable in detecting relative changes of the cardiovascular function [3,4] and could be a cost-effective solution to the need of assessing the cardiac and circulatory function [5]. Seismocardiography (SCG) is also considered to be of value [6]. SCG is one of many modalities of BCG which was first reported by Gordon [7] in 1877. While BCG records circulatory reaction forces on the entire human body, SCG measures the vibration of the heart locally. This suggests that BCG would be useful in deriving cardiac output or stroke volume, whereas SCG would be most useful in detecting cardiac time intervals [6].

The first clinical application and modern nomenclature was reported in the works of Salerno and Zanetti in the early 90s [8-11]. Due to the use of validation procedures, for example, echocardiography (ECHO) the points of mitral valve closure (MC), aortic valve opening (AO), maximum acceleration of blood in the aorta (MA), onset of rapid ejection of blood into the aorta (RE), aortic valve closure (AC), and mitral valve opening (MO) have been detected [11,12]. SCG is normally recorded in the dorso-ventral axis from the sternum [10], but many groups have presented with tri-axial approaches also [13-15]. Figure 1 depicts in detail the axes used in SCG research.

Although all three axes are often measured, the focus of the analysis is on the dorso-ventral axis leaving out the possibly important superior-inferior and sinistro-dexter axes. In particular, the superior-inferior axis of the SCG has been demonstrated to have consistent waveforms [13] and can be of use in determining stroke volume [16]. While it is likely that the dorso-ventral axis and superior-inferior axis share similarities, it is also expected that there will be inherent differences between the axes. Figure 2 shows an annotated dorso-ventral SCG signal from the authors' previous study [13] compared to superior-inferior axis SCG signal. It is hypothesized that as the heart pumps the blood from the left ventricle to the aorta, more force is exerted on the superior-inferior axis instead the dorso-ventral axis. Thus superior-inferior axis could be more feasible in deriving data related to cardiac force than the dorso-ventral axis.

This article describes the latest development of the authors' previous work. The developments include the portability of the system, sensor mounting method that can be used without skin contact, refined breathing measurement, and focusing on one particular SCG axis. The measurement system is battery powered and consists of synchronized measurements of the superior-inferior axis of the SCG, electrocardiography (ECG), photoplethysmography (PPG), and respiration. The measurement data is sent wirelessly to a PC where the data is stored for further processing.

Materials and Methods

System structure

The measurement system is based on the system described by Paukkunen et al. [13]. The measurement system consists of sensors and analog gain and filtering circuits for superior-inferior SCG, electrocardiography (ECG), photoplethysmography (PPG) and respiration, and data acquisition and communication units. Figure 3 shows the block diagram of the system.

In the system described in this article, the respiration signal is measured using a strain gauge. The DC-excited strain gauge is coupled in a full bridge configuration and amplified with an instrumentation amplifier (INA326, Texas Instruments, USA). The breathing sensor is attached with an inflexible band that has a piece of elastic band attached to allow breathing. To avoid mounting the acceleration sensor directly

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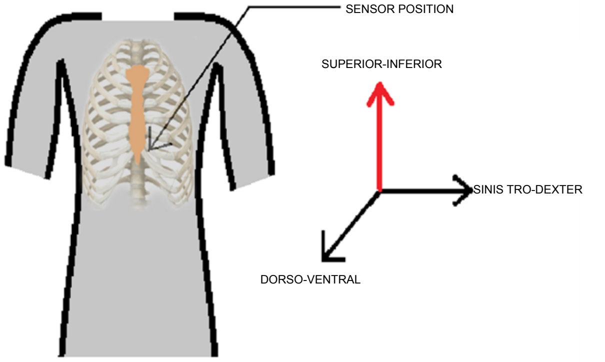

Figure 1: The axes of the SCG measurement. The arrow shows the point of attachment of the acceleration sensor.

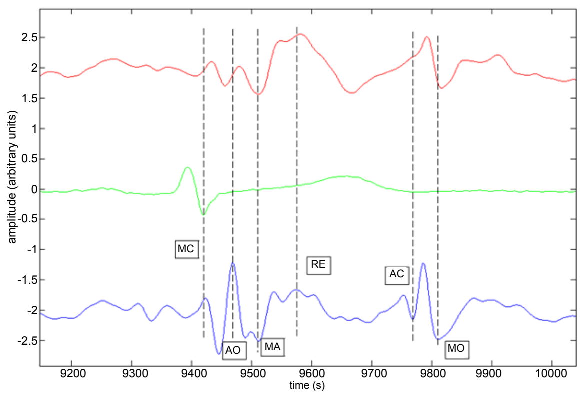

Figure 2: The superior-inferior axis SCG signal (red, on top), the ECG signal (green, in the middle), and the annotated dorso-ventral SCG signal (blue, in the bottom). Annotations: Mitral valve closure (MC), aortic valve opening (AO), maximum acceleration of blood in the aorta (MA), onset of rapid ejection of blood into the aorta (RE), aortic valve closure (AC), and mitral valve opening (MO) [13].

to skin, the accelerometer is attached between the respiration band and the chest. This configuration allows robust mounting together with less invasive instrumentation.

All signals are sampled with the microcontroller's (ATMega328P, Atmel, USA) internal ADC with 8-bit resolution at the rate of 1000 samples/second. The sampled data is sent to the host PC via a Bluetooth module (Parani-ESD200, Sena Technologies, USA). The wireless configuration of the communication subsystem decreases the overhead in setting up the measurement. While wireless communication might be more unreliable compared to wire communications, it allows more flexible setups, when the measurements are done in different environments.

In vivo measurements

Four subjects (three male and one female) aged 28-57 years with no cardiovascular medical history were measured in a sitting position in a normal office chair. Additionally, the subjects performed a phase of exaggerated breathing. Each measurement session lasted about ten minutes. The subjects were asked to sit tall and still. This was done because in developing the system, it was noticed that not sitting tall impairs the quality of the signal.

The SCG sensor was mounted on the sternum between the chest and the strain gauge belt. ECG electrodes were attached in the volar side of the wrists proximal to the hand and the medial side of the right ankle (bipolar limb lead I registration). The PPG signal was measured from the left index finger. The respiration signal was measured from the chest. In addition to the measurements done especially for this study, some data from the authors' previous work [13] was also analyzed to back up the findings in this study.

Results

Assessment of the heart cycle events

From the results, heart cycle events were first identified and the amplitude and timing relations were studied. Averaged waveforms of a subject in supine position holding one's breath in the inhalation phase and the exhalation phase are plotted in figures 4 and 5, respectively. Corresponding waveforms appear on the superior-inferior axis approximately 45 milliseconds after the dorso-ventral axis waveforms. In figure 4, the amplitude difference between MA and RE is 0.5 arbitrary units on the dorso-ventral axis. The corresponding amplitude difference on the superior-inferior axis is 0.9 arbitrary units. In figure 5, where the subject holds one's breath in the exhalation phase, the amplitude differences are 0.58 and 0.62 for the dorso-ventral and superior-inferior axis, respectively. In figures 4 and 5, the dorso-ventral data is from the authors' previous work [13].

Properties of SCG signals in supine and sitting positions

Figure 6 shows the superior-inferior axis both in the sitting position and in the supine position from the same subject. The supine measurement is from the authors' previous work [13]. It is to be noted that the signal in the sitting position has been amplified two times more than the signal in the supine position. Both postures produce similar waveforms although the timing is different.

Noise considerations

Figures 7-9 depict different noise artefacts in the measurements. While the superior-inferior SCG trace in the figure 8 is consistent, there are high peaks during the inhalation phase of some of the breathing cycles. This same phenomenon can be seen in the figure 7 (top right) where some of the superior-inferior waveforms are distorted. In the figure 7, the superior-inferior SCG signal has some variation.

Discussion

All the measured waveforms were consistent and traceable to cardiac or lung induced artefacts. The superior-inferior SCG measurements detects the vibration of the sternum, and the onset of the major waveforms is delayed about 50 milliseconds from the ECG's QRS complex, as seen most clearly in the figure 7. The delay of major mechanical action from the electrical action is mostly due to electromechanical delay. As can be seen from the figures 4 and 5, the

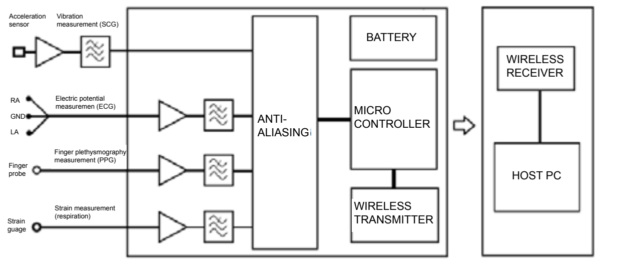

Figure 3: Block diagram of the system.

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amplitude of the MA-RE waveform is 80% higher in the inspiration and 10% higher in the expiration phase. This finding seems to support the hypothesis that quantities related to cardiac force might be more feasible to compute from the superior-inferior axis of the SCG than from the dorso-ventral axis.

The respiration signal measured with the enhanced sensor was consistent and provided information about the phase of the respiratory cycle (Figure 8). In figures 7 and 8, some abnormal artefacts are seen in the SCG signal. As the artefacts couldn't be traced to any physiological activity, the cause of the artefacts seems to be the attachment method of the acceleration sensor. It was noticed that the respiration belt might move especially during the peak of inhalation. This suggests that the mounting method used for attaching the SCG sensor might be unreliable. Thus, future implementations should avoid belts to attach the SCG sensor and use, for example, double-sided adhesive tape instead.

In figure 7, some variation is seen in the superior-inferior SCG. Although, this could be depicted as noise, the authors' suggest that it is merely a display of the modulation of heartbeats due to breathing. In fact, comparing the figures 4 and 7, it seems that the trace in the figure 7 displays two main alternative waveforms corresponding to inspiration and exhalation phases. The variation in the SCG signal has been proposed to be due to respiration induced physiological effects in the circulation in earlier studies also [15]. Figure 9, where raw and digitally filtered signals are plotted, backs up the suggestion that the variation isn't probably of due to electrical noise.

In figure 8 at the bottom right, a rather low amplitude PPG signal is seen. This is probably due to the subject's individual cardiovascular characteristics. A collaborating physician suggests that the low amplitude might be due the subjects' heart adapting to the relatively low heart rate (under 60 beats per minute).

The system described in this article proved to be feasible for recording different cardiac induced events using a compact design paired with wireless data transfer. The wireless interface can be of use when monitoring and measurement cannot be done in the same room for safety reasons for example. At this point, the clinical application of the system is not feasible while providing consistent waveforms, the SCG signal's physiological meaning is still not clear. In this study, it was seen that the superior-inferior and dorso-ventral axes share similarities, but the results are still preliminary. Research on the physiological meaning of the SCG signal's waveforms deserves the same kind of attention as the waveforms from the dorso-ventral axis of the SCG [17-19]. The next step would be to perform, for example, an ECHO validation for the superior-inferior axis of the SCG also.

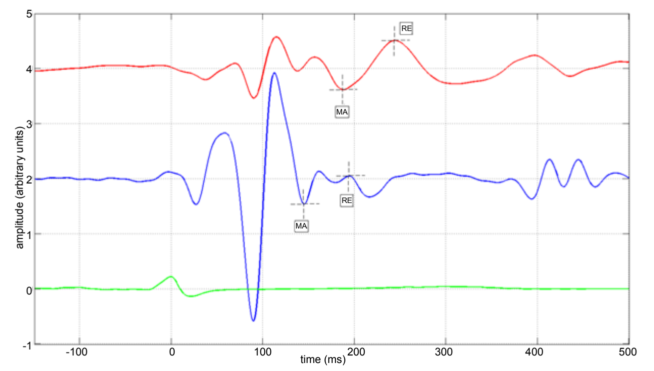

Figure 4: Measurements of the inhalation phase while the subject is supine. The annotated superior-inferior axis SCG signal (red, on top), the annotated dorso-ventral SCG signal (blue, in the middle), and the ECG signal (green, in the bottom). Annotations: maximum acceleration of blood in the aorta (MA) and onset of rapid ejection of blood into the aorta (RE).

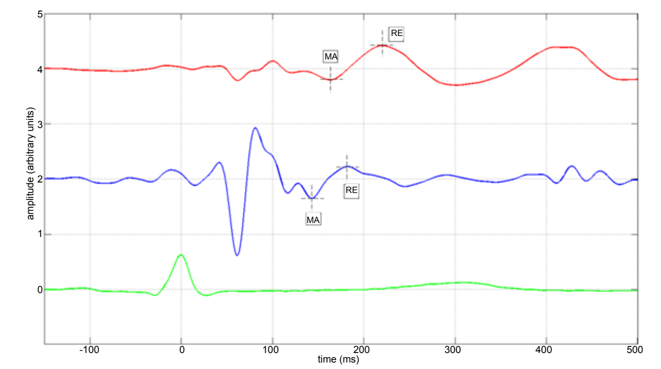

Figure 5: Measurements of the exhalation phase while the subject is supine. The annotated superior-inferior axis SCG signal (red, on top), the annotated dorso-ventral SCG signal (blue, in the middle), and the ECG signal (green, in the bottom). Annotations: Maximum acceleration of blood in the aorta (MA) and onset of rapid ejection of blood into the aorta (RE).

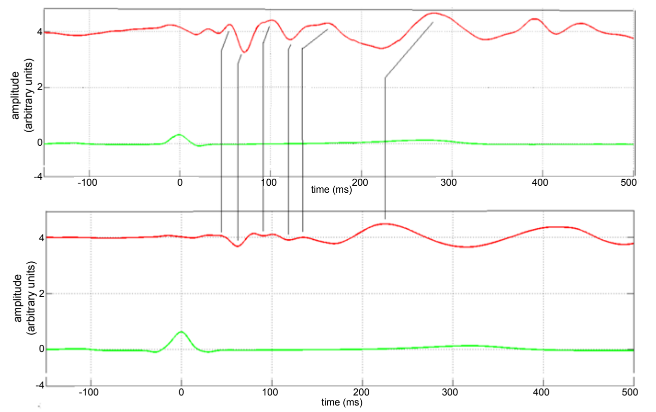

Figure 6: Measurements in the superior-inferior axis in the sitting position (topmost red curve) and in the supine position (lower red curve) from the same subject. The corresponding ECG signals are presented with green curves.

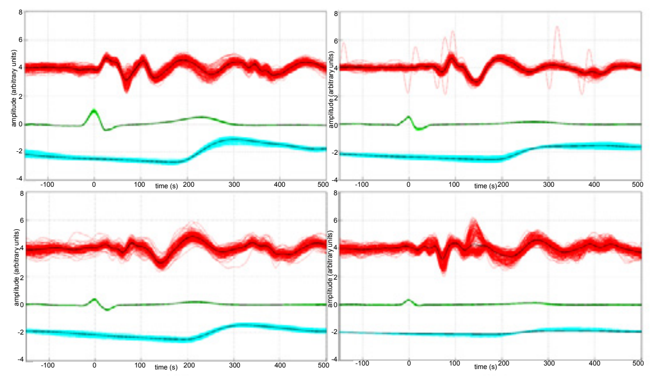

Figure 7: 246 heartbeats of all subjects are superimposed in the same figures together with their averages (black curves). The red depicts the superior-inferior SCG, the green depicts ECG and the cyan shows PPG.

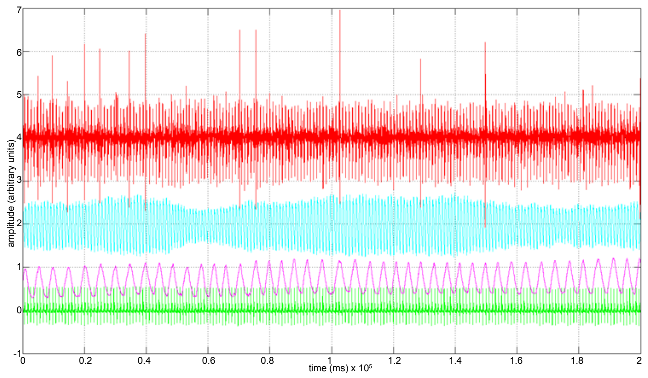

Figure 8: Time traces of the signals of a subject. The red line is the superior-inferior SCG, the cyan shows the PPG, the magenta the respiration, and the green depicts ECG.

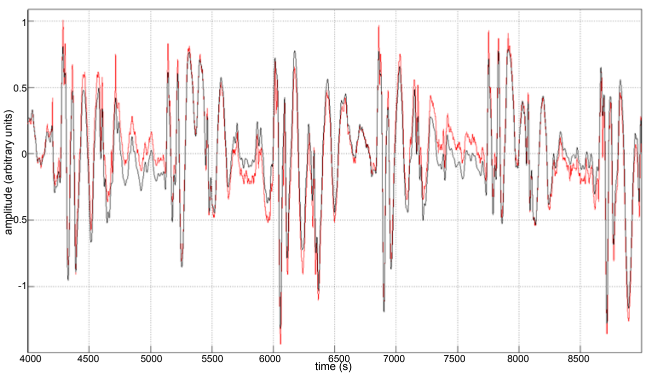

Figure 9: Raw and digitally filtered superior-inferior SCG time traces. The black curve is the filtered signal and the red is the raw signal.

Lately, there have been reports on three-dimensional SCG measurements, and it is anticipated that these will provide more accurate cardiovascular information than uniaxial approaches [16,20]. However, the benefits of using three axes instead of one have rarely been demonstrated. Some benefits were reported, for example, in Castiglioni et al. [14] but similar results might be possibly obtained using only one axis. While tri-axial approaches might yield more accurate results, uniaxial approaches still hold their place due to possibly lower overhead in the hardware and software implementation.

Conclusions

A system combining superior-inferior SCG, ECG, PPG, and breathing measurements was described. Several properties of the superior-inferior SCG were discussed and compared to earlier findings in the field. Future developments include the validation of the superior-inferior axis against an established cardiovascular monitoring method, such as ECHO.

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