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Comparative Analysis of Seismocardiogram Waves with the Ultra-Low Frequency Ballistocardiogram

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Abstract—**Simultaneous seismocardiogram (SCG) and ultra-low frequency ballistocardiogram (BCG) signals are recorded. Preliminary results from the BCG helped tag which waves on the SCG are related to the rapid systolic ejection and aortic valve closure events. These results agreed with and further confirmed previous findings using the echocardiogram. This is the first reported work on comparisons of SCG and BCG signals and provides a setup to study the effects of arterial circulation on the morphology of the SCG signal.**

Keywords—ultra-low frequency ballistocardiography, seismocardiography, cardiac events, cardiac vibration, atrial circulation

I. INTRODUCTION

The seismocardiogram (SCG, seismocardiography) and ballistocardiogram (BCG, ballistocardiography) are generally thought to be variations of the same class of infrasonic cardiac signals. Obtained noninvasively, they complement the electrocardiogram (ECG) with valuable information on the mechanical functionality of the heart and hemodynamics. Specifically, cardiac vibration is comprised of two factors: myocardial vibration, which results from heart muscle contraction, and arterial circulation, which results from blood flow. Different modalities, such as SCG and BCG, may indicate one or both factors, as described in Fig. 1.

The BCG traces the movement of the body as an effect of the blood mass ejected by the heart with each contraction to show arterial circulation [1]—[2]. Changes and abnormalities in the BCG have been correlated to various cardiac diseases and they are well documented [3]—[5]. Different types of BCG have been proposed and investigated but most of them involve some sort of floating platform that can move with the internal cardiac forces generated by a supine subject. By adjusting the binding of the platform to its surroundings, its natural frequency and its measured parameter are modified.

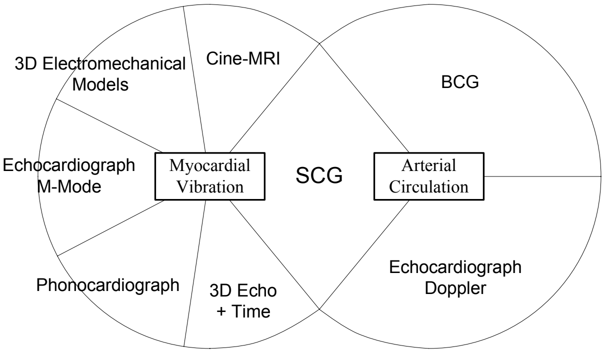

Fig. 1. Two main factors contribute to cardiac vibration and certain modalities may detect one or both. SCG morphology results from both. In this paper, we report its arterial circulation component. Its myocardial vibration component is described elsewhere [15].

Sometimes referred to as sternal acceleration BCG, SCG is more recent than BCG and also well documented. This technique involves the use of an accelerometer to determine heart activity from the surface of the chest at the sternum. Russian researchers Bayevski, Egerov, and Kasarjan described SCG in 1964 [6] and two decades later, American cardiologist Salerno and seismologist Zanetti popularized the same technique for clinical use [7]—[8]. Later groups have shown the medical relevance of SCG [6], [9]—[10].

Because of technological limitations and competing methods, neither BCG nor SCG has gained widespread clinical use so far. Modern technology has renewed interest in the area, especially SCG. Compared to some current methods in cardiology, SCG may be a less expensive solution with the extra advantage of automated analysis by computers. Some of our research has focused on recording and analysis of the SCG, including analysis of its waves [11], investigation of physiological artifacts [12], and improvement of its sensor systems [13].

One of the main challenges for SCG is to interpret its waves in terms of the underlying cardiac events creating them. Echocardiography, important itself for clinical cardiology, has provided an alternative tool to clarify the cardiac information contained within the SCG. Salerno and his group used the echocardiogram to relate SCG waves to events in the cardiac cycle, including aortic and mitral valve opening and closing, rapid systolic ejection, and rapid diastolic filling [14]. Fig. 2 shows a cycle of the SCG from our records annotated according to their findings. We have

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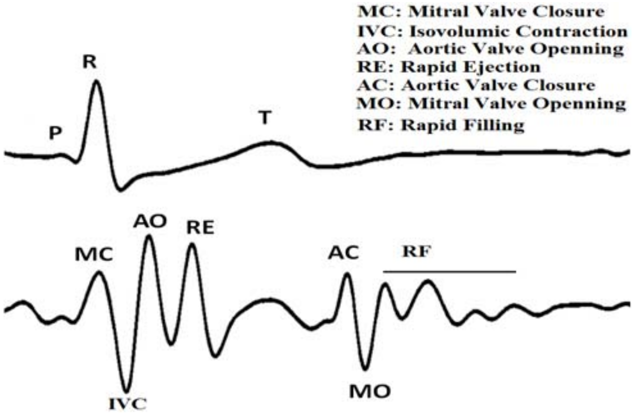

Fig. 2. A cycle of ECG (top) and SCG (bottom) recorded in our lab and annotated as proposed by the Salerno group [14].

also performed our own echocardiogram identification of synchronized SCG waves as part of our parallel study on the effects of myocardial vibration on the SCG signal morphology as shown in Fig. 3 [15]. However, at only 57 fps, the echocardiograph does not have enough temporal resolution to precisely identify cardiac events. Also, its probe does not have enough width in its field to display both the mitral and aortic valves together. These reasons have motivated us to look for other methods to characterize the SCG. The BCG provides such an alternative.

In addition, there is no readily available study which compares the morphologies of the SCG and BCG and clarifies the cardiac information they each contain. As such, there is often uncertainty over the exact interpretation of the two signals, whether medical definitions for one can be applied indiscriminately to the other, and even which signal is which. By using the BCG to help understand the SCG, we also hope to address the confusion surrounding the two.

In this paper, we look at the contribution of arterial circulation on the SCG signal morphology with the aid of the BCG. Our results are preliminary and complement our other investigations in characterizing the SCG. Fig. 1 diagrams our overall approach.

II. PHYSICAL BASIS OF THE BALLISTOCARDIOGRAPH

As previously mentioned, most types of BCG involve a platform upon which a subject lies supinely. The physical basis of these BCG apparatuses is examined in [16].

BCG systems are categorized by their natural frequency with respect to the heart's own natural frequency of 1 Hz. Those BCG apparatuses with higher natural frequencies of 10 Hz to 15 Hz are high frequency BCG (HF-BCG). Those with natural frequencies of approximately 1 Hz are low frequency (LF-BCG) and those lower than 1 Hz are ultra-low frequency (ULF-BCG).

Binding and dampening of the BCG apparatus can be thought of as filtering its resultant signal such that frequencies below its natural frequency are removed. Thus, HF-BCG removes more of the low frequency spectrum, and so it reflects forces, whereas ULF-BCG measures displacement better. For the purpose of studying arterial circulation, we are interested in the displacement of the body center of gravity as an opposite reaction to the displacement of the blood mass center of gravity and so have opted for ULF-BCG.

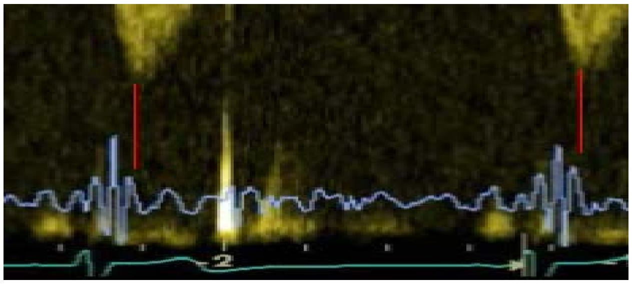

Fig. 3. Simultaneous continuous Doppler echocardiogram, SCG (blue), and ECG (green) signals. The echocardiogram was measured using a GE Vivid 7.

Fig 4. The experimental setup. The subject lies supinely on the suspended ULF-BCG bed. An LVDT is used to measure the bed's displacement. An accelerometer is used to measure the SCG.

III. METHODS

A. Seismocardiograph

The SCG signal was obtained as described by Salerno and Zanetti [7] using the same accelerometer as McKay *et al.* in their research [6]. The piezoelectric accelerometer (Brüel & Kjær model 4381, Nærum, Denmark) was taped to the subject's mid-sternum so that its circular edge is at the xiphoid process and that the sensing direction is normal to the chest. The accelerometer has a charge sensitivity of 10.07 pC/m/s^2 and frequency response of 0.1 Hz to 4800 Hz.

B. Ultra-Low Frequency Ballistocardiograph

The BCG system used in this experiment is an ultra-low frequency bed pendulum modeled after the apparatus described in [16] and is made of a piece of stretched canvas attached to the ends of a rectangular wooden frame measuring approximately 207 cm by 78 cm. The frame is suspended at four points from the ceiling with 3 m long steel wire rope of approximately 2.5 mm in diameter such that the ropes are parallel to each other. A board upon which the feet rest against is fixed to one end. A damping plate is bolted to each end and submerged into treacle to prevent and minimize oscillations after a disturbance. The bed with all fixtures weighs approximately 8 kg.

Longitudinal displacement of the frame, for displacement BCG, was measured using a noncontact linear variable displacement transformer (Macro Sensors model DC-750-050, Pennsauken, NJ, USA). The LVDT has a frequency response of 250 Hz and nonlinearity of -0.178% of its full

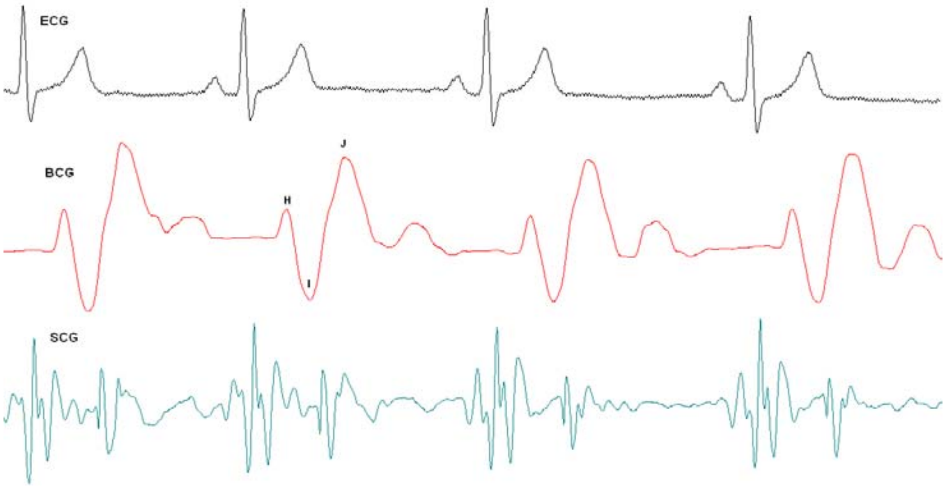

Fig. 5. Four cycles of synchronous ECG (top), displacement BCG (middle), and SCG (bottom) signals. H, I, and J waves are identified for the BCG.

range output. Measurements were recorded so that headward movements are positive and footward movements are negative according to terminology established by the American Heart Association [17].

C. *Timing Reference*

The ECG (Physio-Control Lifepak 8, Redmond, WA, USA) was also obtained to provide a timing reference for analysis purposes. The R-wave from the lead II signal marked the start of the cardiac cycle in the SCG and BCG.

D. *Data Acquisition and Analysis*

The experimental setup is shown in Fig 4. The SCG, displacement BCG, and ECG signals were synchronously sampled at 500 Hz and 16 bit resolution using National Instruments data acquisition equipment (model NI 9205, Austin, TX, USA).

The displacement BCG signal was differentiated to give the velocity BCG and their waves identified and named. Using the ECG and BCG as guides to cardiac events, corresponding fiducial points were then manually identified on the SCG.

IV. RESULTS AND DISCUSSION

A trace of synchronous ECG, displacement BCG, and SCG signals can be seen in Fig. 5. The displacement BCG is the direct displacement recording from the bed frame. A derivative of the displacement BCG signal was obtained and considered as the velocity BCG as in Fig. 6.

The point of rapid ejection on the SCG coincides with a peak on the velocity BCG signal, which confirms the previous echocardiogram assignment for this point (Fig. 2 and Fig. 3). During rapid ejection, a sudden surge of blood rushes out of the ventricles with maximum velocity and accordingly, this corresponds to a peak on the velocity BCG signal as seen in Fig. 6.

Interestingly, after rapid ejection, the next peak on the SCG signal has coincided with aortic valve closure. The most negative point of the velocity BCG recording is very close to the point of rapid diastolic filling where the blood is pushed back into the ventricles with maximum velocity. However, this point of rapid filling does not have a distinct corresponding point on the SCG signal.

According to the findings of this research we hypothesize that the W-shaped systolic complex observed in the SCG signal is a main result of the heart's vibration except for the last edge which is due to the strong ejection of blood in the aorta. The diastolic V-shaped complex, on the other hand, is mostly created during the isovolumic relaxation time. Following that, the mitral valve opens.

V. CONCLUSION

For the first time, an experimental setup was assembled to synchronously record SCG and BCG signals. The goal was to better understand the SCG morphology and its correspondence to underlying cardiac events, and to qualitatively evaluate the arterial circulation effects on the signal. Using the BCG, the points of rapid ejection, aortic valve closure, and rapid diastolic filling were identified on the SCG. The results reported in this paper are based on one subject and should be considered as preliminary. The next steps are to conduct similar tests on healthy subjects and abnormal cardiac cases. It is hoped that better understanding of the SCG signal and its morphology would enable its widespread use in clinics as a cheap diagnostic tool to assess the mechanical performance of the heart.

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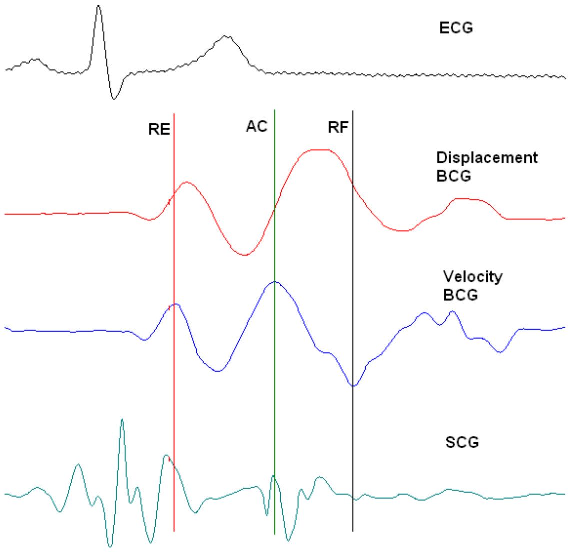

Fig. 6. Simultaneous ECG, displacement and velocity BCG, and SCG signals. From left to right, the vertical lines correspond to the point of rapid systolic ejection (RE), to aortic valve closure (AC), and to the point of rapid diastolic filling (RF).

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