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Infrasonic Cardiac Signals: Complementary Windows to Cardiovascular Dynamics

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Abstract—**New approaches to fairly old noninvasive cardiology tools, based on studying low frequency vibrations created by the heart on the body, were reviewed. These signals were divided and studied in two categories and compared in their capability for estimation of hemodynamic parameters. In particular one representative signal of each category, seismocardiogram and ultra-low frequency ballistocardiogram, were selected and compared to each other in their correspondence to physiological events behind their waves.**

I. Introduction

Infrasonic cardiac signals have their main components in frequencies below 20 Hz and represent a displacement, velocity, or acceleration in response to the beating heart. These signals provide information regarding the mechanical functioning of the pumping heart by quantifying the pulses appearing on the body with every beat. The act of recording is noninvasive and causes neither danger nor pain.

Over the past century, extensive research has been conducted on interpreting infrasonic cardiac vibration signals, in terms of their relationship to cardiovascular dynamics and their possible use in diagnostic cardiology. Modern microelectronics and signal processing technologies have provided unprecedented opportunities to reintroduce some of these relatively old techniques as useful noninvasive cardiac diagnostic and monitoring tools [1].

In this paper a unifying view of these signals is proposed. The signals are classified into two categories based on their genesis and, their strengths and weaknesses are compared. The proposed categorization can clarify some ambiguities through the development of a common terminology, and will help researchers better comprehend the literature and locate their own work within the scope.

II. Classification

Figure 1 shows the "family tree" of infrasonic cardiac signals and each category is described as follows.

A. Circulatory Reaction Recordings

This category of signals is recorded from a free-moving platform on which the subject can lie, sit or stand. The circulation of blood in the main arteries with each heart beat changes the center of mass of the subject's body and the entire system of body and platform moves accordingly. As blood rushes upward in the ascending aorta and pulmonary artery, the system is moved footward. When blood rushes down the descending aorta, the platform moves headward. The ballistocardiogram (BCG) is the most studied signal from this category to which dynamocardiogram (DCG) [2], quantitative seismocardiogram and ballistocardiogram (Q-SCG and Q-BCG, respectively) [3], EMFiT BCG [4] and weight scale BCG [5] also belong.

B. Precordial Vibration Recordings

With every heartbeat, positional and shape changes of the heart as well as intracardiac events create vibrations that may be felt as pulsations on the surface of the chest in regions localized near the heart. These vibrations can be high in frequency (20-2000 Hz) such as audible heart sounds, or low in frequency (0-30 Hz) of which includes the infrasonic range of signals. It is hypothesized that myocardial contraction is the primary cause of these vibrations.

Techniques used to measure these signals quantify such surface pulsations in terms of acceleration or displacement at specific points on the chest. Infrasonic precordial vibration signals include the seismocardiogram (SCG) [6, 7], apexcardiogram (ACG) [1], sternal acceleration ballistocardiogram (SAB) [8], kinetocardiogram (KCG), cardiac micro-acceleration (CMA) [9] and precordial ballistocardiogram [1].

III. Comparative Study

It is valuable to consider both categories of infrasonic cardiac signals in the same context because of the following reasons.

a. Signals from both categories reflect the same cardiovascular events noninvasively, in a similar frequency range, and are utilized to extract similar hemodynamic parameters.
b. Similar terminology is used in both categories which at times creates confusion over the nature of the observed signals. For example, as in Figure 1, SCG is a precordial vibration recording while Q-SCG is a circulatory reaction recording, and BCG is a circulatory reaction signal but precordial BCG is not. As well, conventional annotations introduced for BCG have been widely used to annotate precordial

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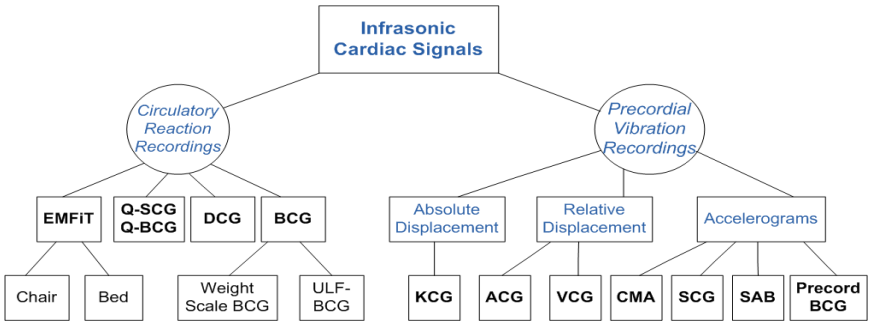

Figure 1. Two categories of infrasonic cardiac signals. EMFiT: electromechanical film transducer, Q-SCG, Q-BCG: quantitative seismocardiogram and ballistocardiogram, DCG: dynamocardiogram, ULF-BCG: ultra-low frequency ballistocardiogram. KCG: kinetocardiogram, ACG: apexcardiogram, VCG: vibrocardiogram, CMA: cardiac micro-acceleration, SAB: sternal acceleration ballistocardiogram, Precord BCG: precordial ballistocardiogram.

recordings without considering the actual physiological reasoning for the annotations.

A. Qualitative Comparison

Qualitative comparisons of representative signals from the two categories were performed; force plate recording as a representative of circulatory reaction signals and SCG as a representative of precordial vibration signal were selected and recorded simultaneously with ICG and ECG. The force plate captured the force of cardiovascular origin while a subject stood, sat, and lay supine on it as in Figure 2.

The standing position produced a signal morphology very similar to the reported weight-scale BCG [5]. The seated position produced a morphology resembling the Q-SCG [3] and the lying position produced a morphology described by dynamocardiogram (DCG) [2]. The standing position signal corresponded to almost a two-fold amplitude gain compared to the recordings obtained while the participants were seated, and approximately thrice that of lying supine. It is clearly seen from all three traces (Figure 2) that while the circulatory reaction recordings do not change much before the H point where blood rushes up the aorta, the precordial recordings demonstrate sharp waveform changes. A qualitative comparison of EMFiT BCG and ULF-BCG from the circulatory reaction group and SCG from the precordial vibration group is presented in [4].

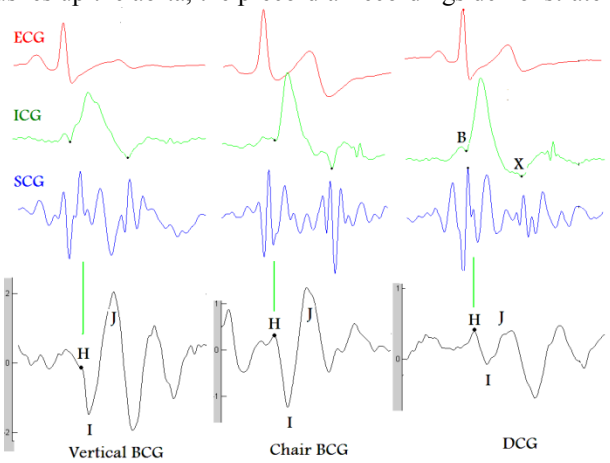

Figure 2. Left to right: standing, sitting and lying on force plate. Bottom to top: simultaneous recording of force in foot to head direction, SCG, ICG and ECG. The vertical line is in Newton. The B and X points on ICG and the H, I and J points on BCG are annotated. The vertical lines are drawn on top of the H waves.

B. Quantitative Comparison

The ultra-low frequency BCG (ULF-BCG) evolved to be the preferred method of BCG [1] and thus, it was recreated as in the original for this research [10]. The ULF-BCG bed was constructed with a piece of stretched canvas attached to the ends of a rectangular wooden frame. It was suspended at four points from the ceiling with 3 m long steel wire rope such that the ropes were parallel to each other. The bed with all fixtures had a mass of 8 kg. A small piezoelectric accelerometer (Brüel & Kjær model 4381) was fixed to the frame to measure the longitudinal acceleration such that headward movement was positive.

The SCG signal was obtained as described by Salerno and Zanetti [7]. A piezoelectric accelerometer with integrated conditioning circuitry (PCB Piezoelectronics model 393C) was placed on the subject's mid-sternum so that the circular edge of the accelerometer was at the xiphoid process and that the sensing direction was normal to the chest in the dorsoventral direction [7].

IV. Results

Three simultaneous signals of SCG, ULF-BCG, and ECG were recorded from five participants, and they were asked to lie supine on the suspended bed as in Figure 3. All participants were healthy, male adults between 25-32 years old. A sample of recordings of four participants can be found in [4]. The ensemble average of the signal for subject five is as in Figure 3. There were a total of 288 heart cycles from the all participants taking part in the test, excluding cycles with motion artifacts. The H point on ULF-BCG corresponds to the start of blood flow in the aorta, and I point corresponds to the peak of maximum acceleration of blood in the aorta [1]. It is clear that the H point of BCG aligns with the aortic valve opening (AO) on SCG, and I point on BCG aligns with the maximum acceleration (MA) point on SCG.

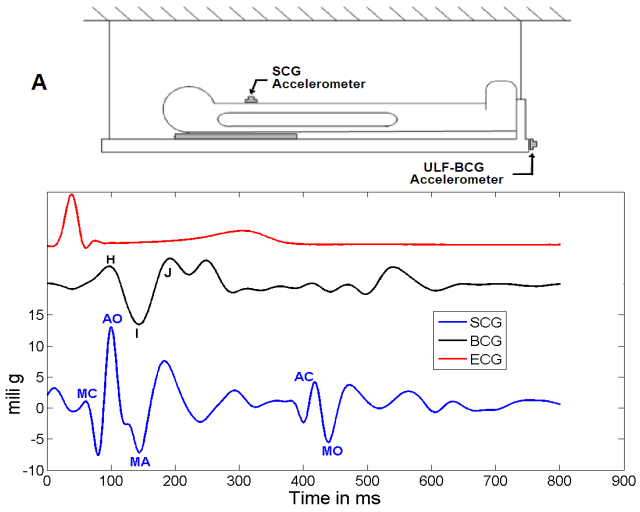

Figure 3. Top: Data acquisition setup for simultaneous recording of ULF-BCG and SCG. Bottom: Ensemble average of SCG, ULF-BCG and ECG starting from the Q-wave on ECG. MC and MO are mitral valve opening and closure points. AO and AC are: aortic valve opening and closure points. MA is the point of maximum acceleration of blood on aorta.

In a previous work, we have correlated the MA point on the SCG to maximum acceleration of blood in the aorta, obtained via Doppler ultrasound beam targeted to the aortic valve [11]. I point of ULF-BCG and the MA point on SCG were detected using an algorithm that segments the data using the QRS complex of ECG and annotates SCG and BCG separately, as in Figure 3.

The Bland and Altman analysis yields a mean bias of 0.17 and the lower and higher limit of agreement of -8.5 ms and 8.9 ms respectively, as in Figure 4. In 90% of the 288 heartbeats the absolute value of difference between the MA and I points were less that 7.2 ms. This demonstrates that these two points correspond to the same cardiovascular event of maximum acceleration of blood in the aorta, as was also confirmed with other methods mentioned previously.

V. Discussion

As it was observed from the previous section, the same cardiovascular events are at the origin of formation of some of waves in BCG and SCG. As the aortic valve opens both signals decrease leading to nadir at the same time. Nevertheless, there are also differences of morphology between the waves before aortic valve opening and later on during the diastole.

BCG, as representative of circulatory reaction category, is different from precordial recordings, such as SCG. The difference is that BCG reflects the movement of the centre of mass of the whole body and its support, while SCG reflects the local mechanical vibration of the upper part of the body as recorded from the chest. The H, I, J, K and L annotation, initially used for BCG, has their own particular defined meaning, agreed upon by researchers of BCG field in the past [2].

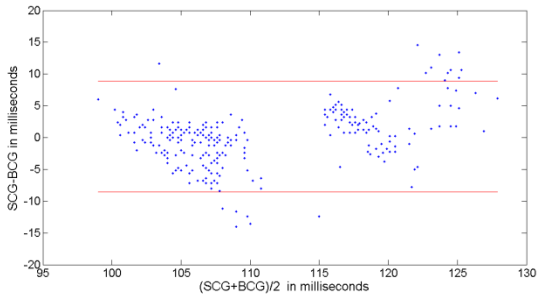

Figure 4. Bland and Altman plot for measurements of I point on ULF-BCG and MA point on SCG.

Using the same terminology in the annotation of precordial recordings [1, 8] can create unnecessary confusion on the meanings of these waves and should be avoided.

The differences, mentioned above, create different possibilities for every category in terms of their capability to reflect hemodynamic parameters.

1) Cardiac Time Intervals:

As precordial recordings such as SCG, are recorded from positions closer to the heart, there is less mechanical damping of the cardiac vibrations compared to BCG, in which the heart moves the whole body and the recording system (such as bed, chair, and weight scale). Thus, events such as valvular openings and closure demonstrate themselves on the morphology of precordial recordings. This makes them suitable for measurement of systolic time intervals [13, 14] and diastolic time intervals [15] that are of value to noninvasive cardiology.

On the other hand, these events get dampened out by centre of mass recordings such as BCG. Figure 3, clearly shows that on SCG there is a "V" shape between MC and AO points, corresponding to isovolumic contraction period, during which there is not a significant change on BCG wave. The force plate recordings on Figure 2 also confirm the same fact that, while there is a significant change on SCG morphology before aortic valve opening, the circulatory reaction recordings do not manifest noticeable changes.

Thus, in terms of the evaluation of the timing of cardiac events, precordial recordings, such as SCG, are better candidates compared to circulatory reaction recordings. The slope of this "V" shape has been claimed to be related to myocardial contractility as it corresponds to a period of time where there is no blood flow inside or outside the heart and the vibrations are solely created by myocardial contraction [6].

2) Stroke Volume and Cardiac Output:

The opening of aortic valve and rush of blood up the aorta creates the main component of circulatory reaction recordings as in Figure 2, and this information has been successfully utilized in the past to estimate stroke volume and cardiac output [2, 5]. As BCG is a record of the sum of all cardiovascular forces exerted on the body, its amplitude is a more faithful representation of the force of

the cardiac system compared to precordial recordings which reflect just a portion of this force that affects torso.

Thus, efforts on the estimation of stroke volume from precordial recordings have not been as successful as BCG [8, 14]. The shape of the rib cage and position of it with respect to the heart can modify the amplitude of waves recorded on the chest thus; estimation of stroke volume, from such partially transmitted forces, requires a more complicated estimator, and in the best case would end up with a patient specific estimation of the stroke volume [14]. On the other hand, the analysis of BCG in order to extract stroke volume is much simpler and is not dependant on the size of the patient [5].

VI. Conclusion

Infrasonic cardiac signals provide a window on the mechanical performance of the heart and the advent of new technologies has initiated a recent revival of the field. We have presented a comparative review of these signals and have divided them into two main categories as in Figure 1. In this listing of infrasonic cardiac signals the emphasize was on more recent techniques, otherwise listing all the other known signals in the literature could have lengthen the paper.

The old BCG instruments, as the most used form of the circulatory reaction recordings, were quite bulky and required patients to lie down on beds suspended from the ceiling, while new non-constraint methods, based on weight scale [5], beds and chairs [18, 3] have provided new possibilities to record these signals more efficiently.

On the other hand, unlike old methods of recording SCG [6, 7], the more recent methods of precordial recordings do not require attaching heavy and bulky measurement systems to the chest [7] and rather use MEMS accelerometers [16] that can be even used in wearable systems [17]. The same accelerometers can be used to also record higher frequency heart vibration (phonocardiogram) [17] and also be used for activity monitoring.

Contactless methods using microwave radar [19] and laser [20] have also been implemented to record such vibration from the chest. Extension of such research can provide novel tools, enabling non-constraint, noninvasive monitoring of mechanical functioning of the heart.

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