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Seismocardiography: Past, Present and Future

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***Abstract*— this paper presents an overview of seismocardiography (SCG) as a noninvasive cardiology method. The paper represents a brief historical background to the SCG, an assessment of the technology at present, and an evaluation of the challenges we must address. These challenges include the development and clarification of definitions, standards, and annotations.**

I. INTRODUCTION

The last decade has seen the development of a plethora of high quality, sensitive, inexpensive accelerometers. This, combined with the availability of ample low cost computational power, has provided us with the tools to begin to realize the clinical potential of recording and analyzing the hearts vibrational output. This was clearly the goal of our predecessors in this field. Unfortunately, at that time, clinical applicability was limited. Instrumentation was cumbersome and not very robust. Data interpretation took considerable time and skill. Despite that, the numerous clinical applications identified in that early work provide the foundation from which we now proceed. There is a clear and growing awareness of the need to reduce health care costs while providing equal or better quality of care. As an example, home health care has made the remote monitoring of physiological parameters a necessity.

The potential exists for SCG to add clinically valuable parameters in these settings. While ECG provides us with information about the *electrical* aspects of the heart; cardiac vibration signals, such as SCG, provide a window to its *mechanical* aspects. For SCG to be accepted as a new tool for assessment of cardiac performance there needs to be a consensus on the basics of the technology. This begins with the development and codifying of standards and definitions.

II. ORIGINAL WORKS

The first use of the word seismocardiogram is traced back to research work by R. Baevski in the 1960s. He was inspired by the technology used in seismology for the measurement of acceleration, and used it to measure precordial movements. Baevski's intent was to measure the fluctuations caused by heart, similar to a seismologist registering underground vibrations to predict earthquakes [1]. In the beginning, SCG was mainly used in the Russian aerospace program. The first SCG in astronauts during space flight was recorded onboard Vostok 5 in 1963. SCG was used for crew health monitoring onboard the spacecraft "Sojus" in the early seventies and has been used onboard the International Space Station (ISS) since March 2007 as part of the Pneumocard and Sonocard experiments [2].

Twenty five years later, seismocardiography was first introduced into clinical medicine, and commercialized by SeisMed Instruments, USA [3]. Simultaneous ECHO and SCG recordings were analyzed and a wave nomenclature developed for events in the cardiac cycle [4]. SCG demonstrated quantitative changes associated with obstruction of coronary blood flow during Ballon Angioplasty [5], [6]. This study gave impetus for two large clinical trials which demonstrated that SCG was more sensitive and specific than ECG in detecting coronary artery disease during ECG stress exercise testing. Additionally, it was shown that when the ECG and SCG results were combined, the sensitivity and specificity of the combined test was comparable to radionuclide and ECHO imaging techniques [7]. A later study of SCG recorded during MRI imaging demonstrated SCG as magnetic-field-compatible [8]. Simultaneous ECHO and SCG recordings made during bi-ventricular pacemaker optimization indicated that SCG may be useful to assess immediate efficacy of biventricular pacing during device implantation and optimize programmable time intervals such as AV and interventricular (VV) delays [9].

New sensor technologies have provided possibilities for portable and wireless sensors that can be worn under clothing to record the SCG signal during daily activities. A new line of research has emerged aiming to re-introduce SCG as a clinical instrument that can be used to non-invasively, and inexpensively, diagnose cardiac abnormalities [10–14].

III. APPLICATIONS AND POTENTIALS

The clinical information can be extracted from SCG through measurement of cardiac timings and SCG amplitudes.

Myocardial contractility is affected and reduced in a variety of cardiac abnormalities. 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}). SCG has been proposed for trending dP/dt_{max} [15–17]. Stroke volume is also an indicator of myocardial contractility and a close correlate of dP/dt_{max}. The seismocardiogram (SCG) has also been proposed for the estimation of stroke volume [11], [18].

Systolic time intervals were one of the first methods in cardiology that used the term non-invasive. Several studies in the past have provided evidence supporting the use of systolic time intervals as a non-invasive estimate of left ventricular performance in patients with cardiac disease. It was particularly demonstrated that the longer PEP and shorter LVET were well correlated with the reduced stroke volume and cardiac output. In other studies on patients with various cardiac diseases, the systolic time intervals of PEP

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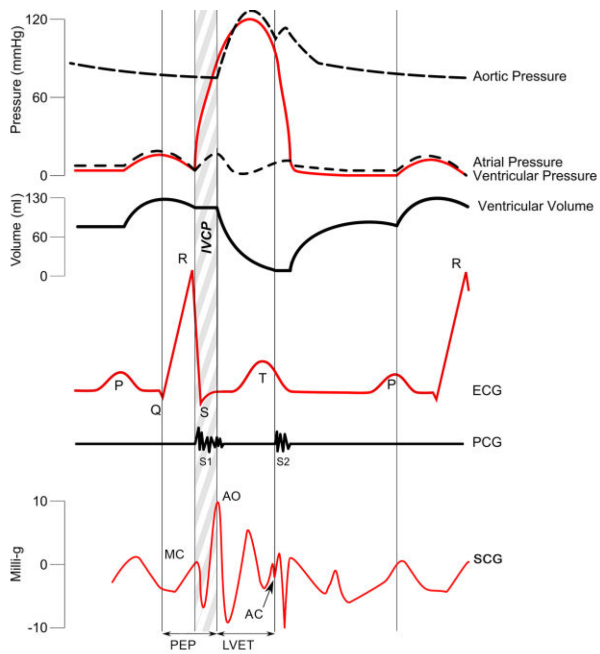

Figure 1. Wiggers diagram amended by SCG. Commonly used systolic time intervals are the left ventricular ejection time (LVET), pre-ejection period (PEP), and isovolumic contraction period (IVCP). The SCG annotations are MC (Mitral valve closure), AO and AC (aortic valve opening and closure). Systolic time intervals are shown.

and PEP/LVET ratio, each correlated significantly with ejection fraction (EF). In more recent research works it has been demonstrated that PEP decreases with increasing contractility and can be used as an index to pre-screen patients for cardiac resynchronization therapy. The utility of the SCG for measurement of systolic time intervals has been evaluated in a number of works in the past [4], [18].

All these capabilities provide application for SCG in different areas of clinical medicine and kinesiology:

- Triage and prioritization of referrals for cardiac investigations such as echocardiography
- Monitoring response to cardiac interventions
- Diagnosis and monitoring of coronary artery disease and ischemia [5], [6]
- Optimization of cardiac resynchronization therapy (CRT) [13], [15–17]
- Emergency treatment of myocardial infarct [19]
- Management of post-concussion in athletics [12]
- To be embedded in cardiac imaging modalities [14]
- Heart rate variability through measurement of heart period and pre-ejection period (PEP) [20].

IV. CHALLENGES AND SOLUTIONS

A. Definitions and Terminologies

In the past SCG has also been called by other names such as sternal acceleration ballistocardiography [21], sternal ballistocardiography [22], digital ballistocardiography [12] and cardiac micro-acceleration signals [13]. This creates a particular issue when seismocardiography is associated to ballistocardiography, which is another technique to record cardiac generated vibration signals.

Ballistocardiography has been an independent field of research. Although the source vibration is the beating heart, but the genesis of waves on BCG is different than SCG, for the most part. The bigger issue arises when the wave annotations approved for BCG (such as H, I and J) are used for the annotation of SCG waveform. The BCG annotations have different cardiovascular interpretation than the ones proposed for SCG.

In order to clarify this issue, a study was conducted to compare the morphology of SCG with classical ultra-low frequency BCG [23]. In particular it was shown that the isovolumic contraction complex on SCG (MC to AO as in Figure 1) occurs before the BCG's H wave. In other words when there are significant changes on dorso-ventral SCG, not much change can be seen on simultaneously recorded BCG.

The authors of this paper believe that *dorsal-ventral* SCG is primarily created by the local myocardial vibrations, while BCG is traditionally defined to have been caused by blood circulation [24]. Considering this, the second author of this paper proposed a classification of mechanocardiographic signals in two categories of precordial vibration and circulatory reactions [25].

However, some other workers in the field believe that there are BCG components in *tri-axial* SCG, and vice versa. To obtain clarity on this issue, simultaneous recordings of SCG and BCG were obtained on ten subjects in the first international workshop on Ballistocardiography and Seismocardiography in Vancouver, December 2012. As the results of the signals acquired in this workshop, we hope to reach consensus regarding the relation of SCG and BCG.

B. Standard Axis

Considering the ambiguities raised by different researchers using different axial systems to identify their signals, the American Heart Association committee on ballistocardiography, made a suggestion for a unified axial system for all ballistocardiogram recordings [26], back in 50s. However, in the new approach to SCG, developed in the early 1990's, the well accepted agreement has been to take the back to front as positive axis which is opposite to the agreements on BCG as in [24], [26].

C. Frequency Range

Precordial accelerometer recordings of cardiac vibration can range from infrasonic frequencies below 25 Hz to more than 1 KHz depending on the accelerometer and the sampling frequency. Accordingly there are currently, two schools of thought regarding the range of the frequency spectrum of seismocardiogram. One school holds that SCG belongs only to the infrasonic range (mostly less than 25 Hz) [8], [9], [25] ,while the other school holds that the phonocardiogram (PCG) signals in the range (> 25 Hz) are also considered as high frequency seismocardiograms [11].

The authors of this paper belong to the first school, as mentioned above, and prefer to avoid mixing the SCG signal with PCG. One reason being that the PCG field is an established field with defined terminology and the other reason is that the genesis of the two signals is different. The SCG signal is primarily generated by the motion of the myocardial walls, whereas the audible PCG signal is primarily generated by the flow of blood through an orifice.

D. Modeling

A model of the transmission of mechanical vibrations from the heart to the sternum (point of measurement) can provide an insight to SCG derived parameters. Introduction of such models to the field of ballistocardiography significantly contributed to the understanding of the technology. However SCG modeling is more complicated as the volume of heart compared to the sensing point can't be neglected, as was the case for the ballistocardiography modeling [24] .

Several preliminary approaches to this issue were attempted in the past [27]. However, a more extensive physiological model that would include a 3D representation of the thorax cage is required in order to solve this complex inverse-engineering problem. Using the imaging modalities such as Cine-MRI or 3D echocardiography can also provide possibilities to use image processing techniques for modeling the interaction between the epicardium and the thorax, which is the prime cause of SCG from our point of view.

E. Signal Processing

Seismocardiogram is a non-stationary cardiac signal and there are morphology variations between subjects, especially those with cardiac disease. The morphology seen in Figure 1 represents a classical SCG, while in the real situations many subjects have signals with a slightly different morphology.

In particular the AO peak in many subjects can appear to have two neighboring peaks and MC tends to be smooth and not appear as a distinct peak. This is particularly an issue with cardiac patients and makes the annotation algorithms of SCG more complicated compared to the similar ones used in ECG. On the other hand, this complication also necessitates the simultaneous recording of ECG together with SCG and also, simultaneous processing of the PCG components of the recorded signals, to further assist in assessment of the MC and AC points, whenever they are difficult to find on SCG.

Having this in mind the authors are considering to make their recorded SCG signals of the past publically available, motivating the researchers with signal processing background to develop algorithms suited particularly for SCG analysis. This dataset will be released under the Ballistocardiography and Seismocardiography project of the Physionet website in 2013.

V. Conclusion

We need to identify the strengths and weaknesses of SCG and how this would apply in a clinical setting.

Strengths:

- Low-cost, off the shelf, technology available for hardware and sensors
- Ease, repeatability, and automation of data collection
- High probability of an automated analysis system developed similar to diagnostic ECG
- Could be integrated with a 12 lead ECG system to provide a much enhanced diagnostic tool for use in primary care settings, rural clinics, less developed countries
- Multi-channel SCG by recording signal from different points on the chest and to map the acceleration created by the heart on the whole surface of the chest, nearing it to a new imaging modality

Weaknesses:

- Complex waveform difficult to visually interpret
- Long history in cardiology with an unfortunate connotation of "old" technology
- Still in early stages of development with modern technology and computing power

The future of the SCG as a clinically viable tool in the cardiology community begins with us. It is most important to develop and codify standards that include and expand upon the already extensive work of the past. To gain clinical acceptance in the cardiology community, we could mirror the ECG in this respect. It is critical that this be done, in order for us to develop the clinical potential of this technology.

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