33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Three-Dimensional Ballistocardiography in Microgravity: a Review of Past Research

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Abstract— **This paper gives a short review of research on ballistocardiography in microgravity and indicates the benefits from this research for the use of BCG as a terrestrial cardiac monitoring system. In the past, 3-D methods required large devices to decouple the subject from the terrestrial environment and hence, BCG on Earth is usually limited to unidirectional recordings of the motion in the head-to-foot direction. However, microgravity provides a suspension-free environment where accelerations can be measured in all directions without the influence of gravity. Microgravity research indicated that along with the acceleration in the head-to-foot direction, the accelerations in the lateral and dorso-ventral direction are important in understanding the physiological forces during a cardiac cycle. Further, lung volume has a large influence on the transmission of cardiac forces to the surface of the body. To date, only the three separate components of the acceleration vector have been analyzed in 3-D BCG studies. Using the true acceleration and displacement vector (orientation and magnitude), rather than the three separate components, may permit more accurate cardiac event detection.**

I. INTRODUCTION

Ballistocardiography (BCG) is a measure of the ballistic forces acting on the entire body, due to the mechanical activity of the heart. The first BCG was recorded in 1877 by Gordon using a spring weighing machine [1]. Later, he made recordings of subjects lying supine. Subsequently, Henderson (1905) and Starr (1939) made recordings with the subject in supine position on a swinging table or bed-like support. Experiments were also conducted with the subject seated in a chair by Abramson (1933) and Trefny and Wagner (1967). Noordergraaf and many other scientists improved our understanding of the physical origin of the recordings and the physiological interpretations of the waves identified on the BCG recordings. Despite extensive study on BCG to prove its value, the technique never achieved routine use in cardiology. Interest in catheter-based invasive procedures and other methods, e.g., echocardioghraphy, rapidly increased, while there was an increasing controversy on the physiological meaning of events that were observed in a BCG signal [2]. Moreover, technical limitations encountered at that time were too challenging for routine use. Problems during the early developments included (i) the need for large and bulky equipment (ii) difficulties with the proper coupling between the body and the recording device [1] and (iii) the resonance frequencies of apparatus that were often in the range of the frequency of the BCG signal [2]. As a consequence, the BCG was nearly abandoned after the 1960s.

One of the most demanding technical requirements is the de-coupling of the subject from the terrestrial environment. However, microgravity allows for free-floating subjects and hence, enables simple direct BCG measurements, eliminating some of the technical limitations encountered on Earth. Since the early beginning of the research on BCG, it was thought that space and its microgravity environment could be very helpful.

The purpose of this paper is to give a short review of research on ballistocardiography in microgravity and to show how results from these studies can be used to improve our understanding of BCG as a method for ground based clinical and diagnostic applications on Earth.

II. VECTOR BALLISTOCARDIOGRAPHY

Although on Earth, BCG is classicaly based on unidirectional recordings of the motion of the body along the head-to-feet axis, people were already aware from the beginning that the motion in other directions may contain useful information. Starr placed subjects on a table (one degree of freedom) in various positions to obtain recordings in other directions and Nickerson and Curtis (1944) placed the subject at different angles to the direction of the motion of the bed [3]. However, rarely, planar ballistocardiograms and three-dimensional (3-D) recordings have been studied. In 1945, Hamilton and associates recorded motion simultaneously in the three principles axes [4]. Franzblau et al (1950) used a Nickerson ballistocardiograph to consecutively measure the movement in three directions [5]. Tannenbaum et al (1954) simultaneously recorded the motion of the body in the longitudinal, lateral and dorso-ventral direction and analyzed the loop display of projection of the vector on the frontal, sagittal and transverse plane [6]. In 1967, Franke and Braunstein designed a table with three degrees of freedom to record translational accelerations [7]. The research as listed above is limited to the analysis of the separate components along the three axes, or the projection (loop display) of the vector on three different planes.

In 1982, Soames and Atha obtained ballistocardiograms in supine and seated postures, using a platform which measures three mutually orthogonal forces [1]. Also measurements in the head-to-foot direction were obtained when the subjects were standing. Along with the separate components, the

Manuscript received on March 31, 2011. This research is supported by the Belgian Federal Science Policy Office (BELSPO) via the European Space Agency PRODEX program. G.K. Prisk supported by the National Space Biomedical Research Institute through NASA NCC 9-58.

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978-1-4244-4122-8/11/$26.00 ©2011 IEEE

total force vector was analyzed and results indicated a difference in both magnitude and direction of the force vector between the supine and seated postures due to a change in transmission characteristics of the body [1]. This indicates that the analysis of the 3-D vector contains information that is otherwise not visible using only the 2-D vector components.

Despite the widely considered unsatisfactory nature of ballistocardiography and the 2-D and 3-D studies, only the use of measurements in the head-to-foot direction prevails in current terrestrial ballistocardiography. However, the force vector may eventually prove of clinical and diagnostic value.

III. BALLISTOCARDIOGRAPHY IN MICROGRAVITY

Except for a study by Siblia [8] in which a simple 3-D direct-body ballistocardiograph is described, 3-D BCG methods required large and bulky devices to de-couple the subject from its terrestrial environment. However, microgravity provides a near perfect suspension-free system, where accelerations can be measured in all directions without the influence of gravity.

A. Parabolic Flight

During a NASA parabolic flight campaign in 1962 using the KC-135 aircraft, the first inertial triaxal ballistocardiogram (vectorballistocardiogram) ever was recorded by Hixson and Beischer [9]. Their aim was to measure the cardiac-originated, whole-body, inertial accelerations of a human placed in a suspension system allowing motion with a near perfect six degrees of freedom.

A triaxial electrocardiogram and triaxial linear and angular accelerations were measured on a free-floating subject inside a constraint platform, essentially a rigid tub to which the accelerometers were attached. During each data collection phase of the flight profile, the subject was instructed to maintain a suspended state of respiration. It was not mentioned if this apnea was either at the end of inspiration or the end of expiration. In addition to the six flights with over 50 parabolic profiles, ground-based laboratory test were performed for comparison, in which the constraint platform, containing the human flight subject, was put on a commercial 2-D air-bearing BCG bed.

First, the separate acceleration components in the three axes[1] were analyzed. For all laboratory measurements, the peak-to-peak value of the acceleration in the longitudinal direction were larger than the side-to-side accelerations. However, in the parabolic flight data, the peak-to-peak side-to-side accelerations are always greater than those occurring along either the longitudinal axis or the dorso-ventral axis, see Fig. 1. In the majority of the data, the dorso-ventral accelerations were slightly greater than the longitudinal accelerations. The maximum peak-to-peak angular acceleration always occurred about the longitudinal axis of the body and were about two times as large as the angular accelerations about the transverse axis and five times as large as those about the dorso-ventral axis.

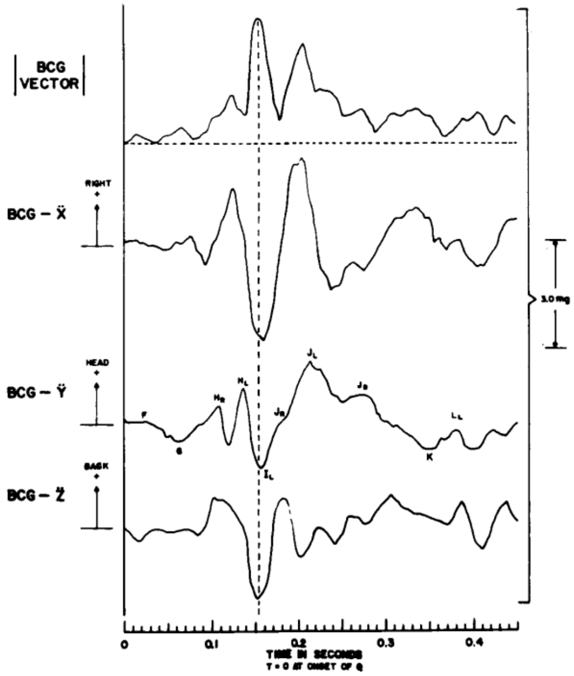

Fig. 1. BCG components and the associated vector magnitude [9]

As well as the peak-to-peak values of the individual scalar acceleration components, a loop display was used to describe the projection of the acceleration vector on the frontal, horizontal and sagittal planes. A first attempt was made to make a three-dimensional display of the evolution (magnitude and orientation) of the acceleration vector, see Fig. 2. Vectors were attached to a vertical time axis in 10 milliseconds interval, starting at the lower part of the time axis. Vectors representing the H, I and J points in the longitudinal acceleration wave are marked with tags. The change of the absolute magnitude of the BCG vector is shown in the top trace of Fig. 1. This shows that the peak BCG activity occurs in the immediate vicinity of I_L in the longitudinal accelerations and is described by a simultaneous leftward, forward and footward acceleration of the body. The waveform of the absolute magnitude of the BCG spatial vector displays events which are not fully defined, or possibly even present, in any given single axis scalar measurement [9]. The change in orientation of the acceleration vector was not further studied.

The weightlessness periods during a parabolic flight only last for a short period of time (20 - 30 seconds). Hence, it was only possible to study the BCG at the onset of microgravity, and not under steady-state conditions. For that, measurements during space flight are required.

B. Space Flight

To date, the rare recordings that have been performed in microgravity were mainly done in the framework of the russian space program and were often only 1-D recordings or of an indirect nature. In 1982, Baevsky and Funtova

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[1] X-axis = transverse axis or side-to-side direction; Y-axis = longitudinal axis or head-to-foot direction; Z-axis = ventro-dorsal axis

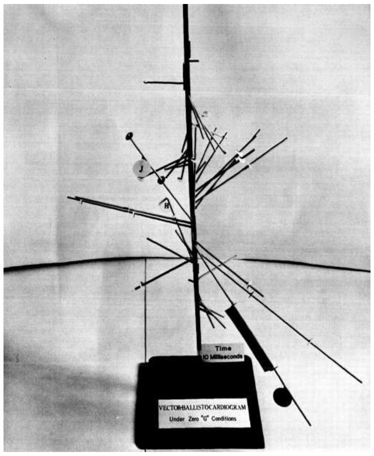

Fig. 2. Three-dimensional display of vectorballistocardiogram [9]

reported the results of ballistocardiographic examinations on the Salyut-6 spaceflight [10]. They recorded the accelerations only in the head-to-foot direction and noted an increase in systolic wave amplitude during breathold at end-inspiration late in flight.

In 1983, during the Spacelab flight D-1, Scano et al [11] found an increase in the amplitude of the BCG in the dorso-ventral axis compared with that of subjects suspended in 1G. Experimental difficulties precluded measurements in other axes.

During the STS 55 - Spacelab D-2 mission in 1993, an experiment of opportunity permitted recording of 3-D BCG on a single free-floating subject breathing normally. The goal was to determine the feasibility of making high-quality measurements of the BCG in sustained microgravity [12]. The study investigated the effect of changes in lung volume on the BCG and the motion of the body due to the respiration. The BCG was recorded along three orthogonal axes, along with the respiratory movements of the ribcage and the abdomen (using respiratory inductance plethysmography), as well as the electrocardiogram, in one subject in sustained microgravity, over a period of 15 min. For the BCG measurements, a single triaxial accelerometer was used, which was tightly taped in the lumbar region of the subject. The data from a continuous 146 s period, during which no contact with the Spacelab structure or with other astronauts occurred, was selected for analysis. The selected BCG data was ensemble averaged over the normalized cardiac cycle (R-R interval) in four distinct conditions related to the respiratory phase (end of expiration, end of inspiration, middle of inspiration and middle of expiration) [12]. Fig. 3 shows the average tracing of ECG and BCG at different lung volumes. The measured accelerations were greatest along the head-to-foot direction (Y-axis). These accelerations in the longitudinal direction, recorded at the end of inspiration, closely matched the head-to-foot accelerations as recorded in ground-based measurements. However, the data also showed significant accelerations along the dorso-ventral axis (Z-axis), accelerations that are classically not measured in 2-D recordings in a terrestrial setting. Also, the data indicated that the BCG was strongly modulated by the lung volume with much higher accelerations recorded at higher lung volumes than at low lung volumes, especially in the longitudinal axis. The accelerations are reduced by 50 to 70 % between end-inspiration and end-expiration [12]. The effect was less pronounced in the transverse and dorso-ventral directions, likely due to the presence of rigid body structures such as the chest wall and spine [12]. The direction of the respiration itself (i.e. comparing mid-inspiration with mid-expiration) had no influence on the modulation of the transmission of the forces from the heart and the measured accelerations.

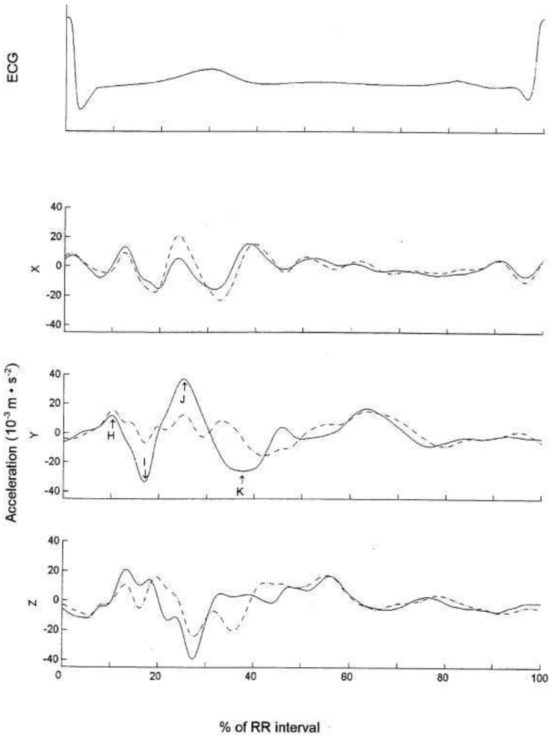

Fig. 3. Average tracing of ECG and BCG at different lung volumes (dashed: end of expiration; solid: end of inspiration) [12]

It should be noted that in the parabolic flight results from Hixson, the accelerations along the transverse axis were always greater than along the head-to-foot and dorso-ventral axes while in the Spacelab D-2 data, the accelerations in the heat-to-foot direction were the largest (at the end of inspiration). The reasons for this are unclear.

C. Ongoing Research

In the past studies, the three components of the BCG acceleration vectors are used. Currently, the same data from the Spacelab D-2 mission is being re-analyzed using a three-dimensional displacement vector technique. The use of the displacement curve allows for the use of new parameters such as the curvature and torsion of the curve to identify events in the cardiac dynamics. This new processing method may shed new light on the origin of cardiac forces. This method is also applied to recordings of 3-D accelerations obtained in healthy subjects lying in a dry immersion system [13].

The previous studies in parabolic flight and space flight confirm the feasibility of using BCG in microgravity. However, only a few measurements were performed on a small number of subjects, for a limited time duration, and without correlation to other (gold standard) methods. Moreover, if 3-D ballistocardiography is to be used on Earth, the influence of gravity must be evaluated, e.g., the possible difference in transmission properties between the heart and the body in microgravity compared with a 1G environment [12]. These considerations lead to the submission of a space experiment proposal entitled: '3-D ballistocardiography in microgravity (B3D)', in response to the European Space Agency Announcement of Opportunity in 2009. The goal of this study, currently in the Definition Phase, is to further investigate the potential of 3D-BCG as a non-invasive, operator independent, low cost cardiac monitoring system with potential applications for tele-monitoring as well as for clinical applications. The study will utilize measurements on multiple subjects, both in parabolic and on-board the International Space station (ISS). The 3D-BCG method will be further validated by correlation with cardiac function determined by techniques, including impedance cardiography, echocardiography, and gas rebreathing.

IV. FUTURE PERSPECTIVES

Currently, interest in ballistocardiogarphy has increased because of the new trends in home e-health systems. Ballsitocardiography may have the potential to be used to study changes in the cardiovascular system over a longer period of time, without medical staff present during the measurements.

Nowadays, the technological developments in the biomedical and electrical engineering fields has the potential to bring new developments to ballistocardiography [14]. Technological developments allow the shrinkage of the huge ballistocardiographs to such a small size that they are embedded in office chairs and wheelchairs, gathering signals from their backrest and seat [14]. Also, modified electronic bathroom scales could be used, to measure accelerations in the longitudinal axis while the patient is standing [15]. A textile-based monitoring device, the MagIC system, was developed by the Fondazione Don Gnocchi for vital signs monitoring of elderly people and cardiac patients [16]. A similar device could be developed for BCG measurements. The use of smaller and better accelerometers and of electromechanical film sensors [17] contributes considerably to the potential feasibility of BCG in the terrestrial environment.

Signal processing methods have also improved. They allow for improved control of baseline wander due to subject movement and respiration by means wavelet decomposition, independent and principal component analysis [14]. Adaptive filtering can be used to cancel floor vibrations in BCG measurements [15].

V. CONCLUSIONS

Currently, there is a resurgence of interest in ballistocardiography due to the evolution of sensors, devices and signal processing techniques. However, the origin of the BCG waves is not yet fully understood. The development of BCG for terrestrial purposes, i.e. clinical and e-monitoring applications, will benefit from research in microgravity. In a terrestrial laboratory, the BCG is dependent on the physical characteristics of the suspension system. Microgravity provides a suspension-free environment which eliminates this dependency. From the few measurements already performed during parabolic flight and space flight, it is clear that ground based BCG systems of the past miss important information. Further, respiration has a large influence on the transmission of cardiac forces and the measured accelerations at the surface of the human body. Studies in microgravity indicate that along with the accelerations in the head-to-foot direction, the accelerations in the lateral and dorso-ventral directions are important in understanding the physiological forces during a cardiac cycle. Using the true acceleration or displacement vector, rather than the separate three components, may be a big step forward in accurate cardiac event detection.

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