# Three dimensional Ballistocardiogram and Seismocardiogram: what do they have in common?

P-F. Migeotte, *Member, IEEE*, L. Lejeune *Student Member, IEEE*, Q. Delière *,Student Member, IEEE*, E. Caiani, C. Casellato, J. Tank, I. Funtova, R. Baevsky, G.K. Prisk, *Senior Member, IEEE*, P. van de Borne

***Abstract*—3D-body accelerations, i.e. Ballistocardiograms (BCG) and Seismocardiograms (SCG), ECG and Impedance-cardiograms (ICG) were recorded on healthy volunteers participating to the European Space Agency (ESA) 59th parabolic flight campaign. In the present paper we document the similarities and differences that can be seen in the seismo- and ballisto-cardiogram signals in different positions (standing and supine) under normal gravity condition as well as during the weightlessness phases (0G) of a parabolic flight.**

**Our results demonstrate that SCG and BCG both present a similar three dimensional (3D) nature, with components of the BCG having lower frequency content than the SCG. The recordings performed in the 0G environment are the one with the smoothest shape and largest maximum magnitude of the Force vector. The differences seen between SCG and BCG stress further the importance for the need of using different nomenclature for the identification of peaks in both signals.**

## I. Introduction

BALLISTOCARDIOGRAMS (BCG) and seismo-cardiograms (SCG) are recordings of the vibrations of the human body that are consecutive to the cardiac contraction. They are the consequence of the recoil of the heart and the ejection and travelling of blood into the aorta and the main vessels. Both of these signals share a large number of properties. They are usually measured with similar sensors: typically accelerometer or force sensors can be used. The terminology Seismocardiogram is usually used for local recordings (e.g. the accelerometer sensor is placed close to the heart at the apex or on the sternum) and records local vibrations. Ballistocardiogram is used for overall body recordings (e.g. the accelerometer sensor is placed close to the center of mass (CoM) of the subject or records the overall body movement like when it is placed on the device supporting the body (e.g. hanging bed or weighing scale). Furthermore, while there is an inherent three dimensional nature in the force implied in the cardiac contraction, in the vast majority of cases, the research is limited to 1D or 2D analysis of the BCG and SCG components in the frontal plane. Most of the physiological interpretations are then drawn from the component along the longitudinal (foot-to-head) axis. Moreover we may suspect that the influence of gravity along one of the measurement axis implies important differences between standing and supine recordings. Early attempts to record 3D-BCG in microgravity were made [1,2,3] and in previous work [3,4] we reported 3D-BCG data recorded in space. In the present paper we focus our analysis on the similarities and differences that we can see between local (seismo-) and central (ballisto-) recordings. Simultaneous recordings of the SCG and BCG signals were performed in the supine and standing positions as well as during the transient microgravity environment obtained during parabolic flights. The present results were obtained during the European Space Agency (ESA) 59th parabolic flights campaign conducted on-board the A300-zéroG airplane of NOVESPACE. During this campaign recordings were performed in four subjects. We would like here to shed light on the intra-subject variability that can exist between those two signals and we report here only results obtained in a young healthy women. The inter-subject variability will be treated separately in a future study.

Manuscript received April 07, 2014. This work was supported by the Belgian Federal Science Policy Office (BELSPO) via the European Space Agency PRODEX program. P-F. Migeotte, L. Lejeune, Q. Delière and P. van de Borne are with the Cardiology department of the Erasmus Hospital, Université libre de Bruxelles, Belgium (email: pmigeott@ulb.ac.be). Caiani and Casellato are with Polytecnico di Milano, Italy. Tank is with the Institut für Klinische Pharmakologie, Medizinische Hochschule Hannover, Germany. R Baevsky and I. Funtova are with the Laboratory for autonomic regulation of cardiorespiratory system, Institute of Biomedical problems, Moscow, Russian Federation.

## II. Methods

The technical details of our procedure are similar to what we have done in previous studies and can be found with more details here [3, 4, 6].

### A. *Experimental procedure*

3-D accelerations (3D-BCG and 3D-SCG), ECG, Impedance cardiogram (ICG) and respiration signal (nasal thermistor) were recorded, at 1kHz using a modified PNEUMOCARD system [4]. Data were recorded on the ground (continuous 180 s recording in standing and supine) and free-floating during the ~20s of microgravity phases of the parabolic maneuvers. In order to provide 3D-SCG and 3D-BCG signals two accelerometer sensors were placed on the spine of the subject: one between the scapulae and the other close to the center of mass (CoM) of the subject. It is important to note that what we call SCG is not the traditional way of measuring it. Usually SCG is measured on the thorax of the subject rather than in its back. However, the localization between the scapulae is approximately at the same level of the sternum. The major physiological difference is certainly the presence of the spine between the

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heart and our sensor; while in the apex position, there is only the presence of a rib bone. Our motivation was to be able to use the same axis orientation without introducing confusion by inverting our axis nomenclature as it should probably have been done if we used the more traditional (apex of the heart) location for our SCG sensor.

### B. *Subjects & protocols*

The protocols were noninvasive, reviewed and approved by the local institutional ethical review boards and the pertinent French authorities. Informed consent of the subjects was obtained after the inclusion visit.

### C. *Axis System*

The standard nomenclature for the axes in ballistocardiography was used: *x* is the lateral (left-to-right) axis, *y* is the longitudinal body (foot-to-head) axis, and *z* is the antero-posterior (ventro-dorsal) axis.

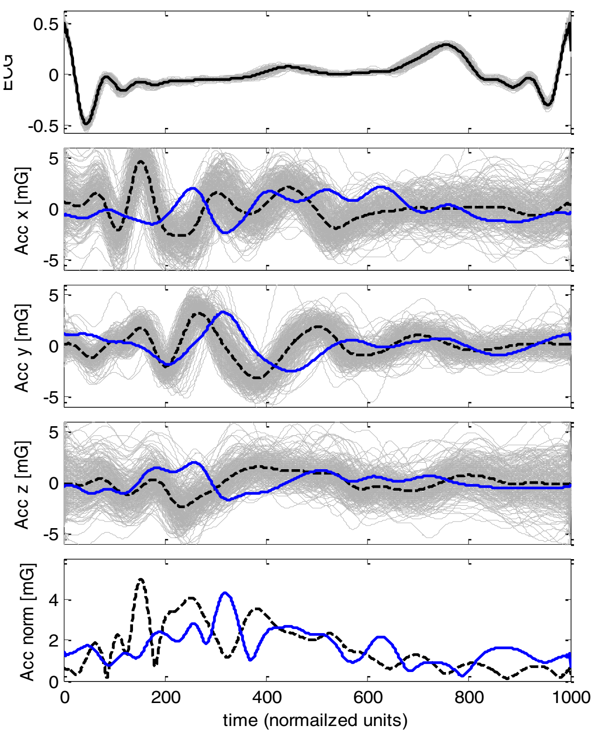


Fig. 1. Ensemble averaging of the scapulae SCG (--) recorded on the ground in the standing position. 259 individual heart beats signals (in grey) were used to compute the ensemble averaged curve (black dashed curve). Comparison with CoM BCG (blue continuous line) in the same subject in the standing position.

### D. *Ensemble averaging, Drift removal & Integration*

R waves of the ECG were automatically identified, visually inspected, and manually edited as required. For each cycle (from R to R wave), the ECG and BCG data were extracted, time aligned and resampled at a constant sampling interval: time axis was normalized so that the beginning of each cycle was set to 0 and the end to 1000. ECG and BCG curves from different heart-beats were superimposed and ensemble averaged. This allows taking into account the normal heart rate variability. The ensemble averaging procedure is equivalent to a low pass filtering procedure which removes all components of a lower frequency than the instantaneous heart rate of the subject [3, 4]. This includes removal of drifts and components due to respiration. The magnitude of the force vector is then computed as:

$$\left|\vec{F}\right| = m \cdot \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (1)$$

where m is the mass of the subject (51.2 kg).

Figure 1 present the ensemble averaging procedure applied to the standing SCG recording. A continuous stable section including 259 heart beats was selected to compute the ensemble averaging curve in the 3 axis. Results seen in figure 1 show that even in the presence of an important beat-by-beat variability, the SCG signal was stable over time.

## III. Results

As stated previously results presented here are from a single subject. This allows focusing the analysis and physiological interpretation on the intra-subject variability while a comparison between results obtained in several subjects would allow investigating the inter-subject variability. Results from the ground recordings in the standing and supine positions are from ensemble averaging of a continuous recording of about 180s while results from microgravity are from several heart beats taken from different parabolas and thus not always contiguous.

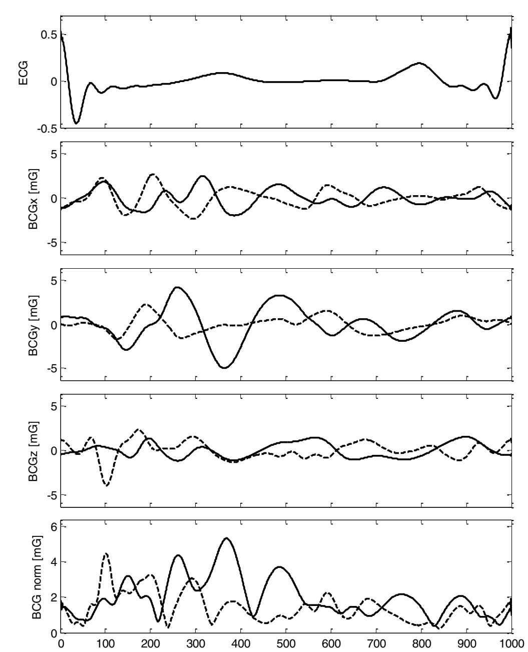


Fig. 2. Comparison between scapulae SCG (--) and CoM BCG (-) in the supine position in the same subject as in figure 1.

### A. SCG vs BCG,

Figure 1 presents the comparison of the SCG and BCG signals obtained on the same 259 heart beats from a single subject in the standing recording. It is seen that all three components present a significant value and contribution to the magnitude of the force vector. Furthermore, the maximum magnitude of the vector does not show large differences between SCG and BCG signals (Fmax = 2.17 and 2.51N for SCG and BCG respectively). It the timing of various waves within the cycle that present the largest differences.

The X-axis component of SCG presents a higher variability in the signal and larger peak close to the cardiac contraction. The SCG magnitude of the Force does peak earlier than the BCG.

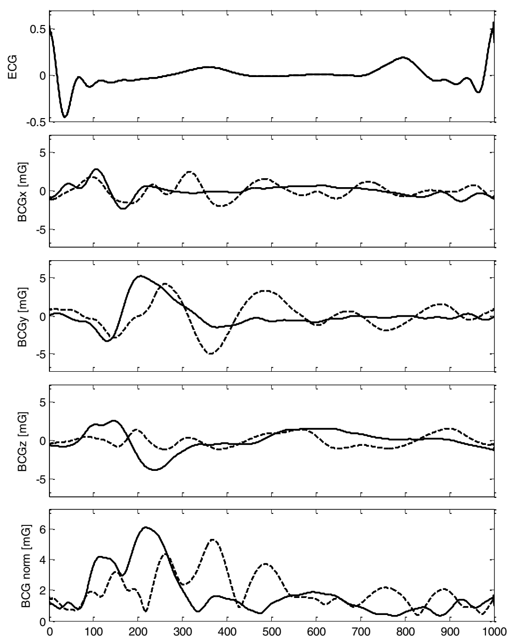


Fig. 3. Comparison between supine (--) and free-floating (-) BCG at the subject center of mass.

### B. Standing vs supine

Figure 2 presents the comparisons between the SCG and BCG signals in the supine position. It is noteworthy that the Y-axis BCG component presents a larger magnitude than the SCG component. Also one can observe an important peak in the Z-axis component of SCG that occurs probably during the ejection phase.

### C. Zero-G vs supine

Figure 3 presents the comparison between supine and 0G BCG signals. As expected, the supine position presents the largest similarities to the 0G condition and as we could expect, the supine Z-axis component (ventro-dorsal) is smaller than the Z-axis 0G component. Z-axis component was likely damped by the influence of gravity. As for the X-axis component one can identify more peaks and valley in the supine recording than in the 0G one; thus showing that there is a larger and wider frequency content in the supine data.

### D. Zero-G scapulae (SCG) vs CoM (BCG)

Figure 4 presents the differences between the SCG and BCG signals as they appear under the 0G condition. Both signals are smoother than the ground based reference. It is noteworthy that the diastolic phase looks more stable and less distorted than on the ground.

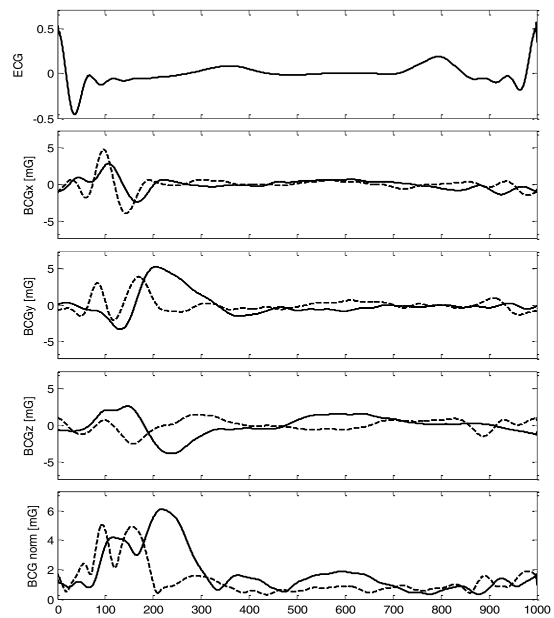


Fig. 4. Comparison between scapulae SCG (--) and CoM BCG (-) during 0G phases of a parabolic flight.

### E. Frequency analysis

The frequency content of the BCG and SCG signals were analyzed in all three axes and compared to the apex SCG signal. A welch averaging periodogram spectral estimate (50% overlap with a 1.6 s hamming window) was applied to the data obtained during the longest uninterrupted (total of 11.5 s) recording obtained in free floating conditions under parabolic flight. The results (see fig. 6) show that all three components of the BCG signal have lower frequency content than the scapulae SCG components. SCG recorded at the apex of the heart presents higher frequency content than both SCG and BCG signals.

## IV. Discussion

Table 1 presents a comparison of the results obtained from the recordings in various conditions: Standing and supine baseline recorded on the ground in a normal gravity before the flight and the 0G weightlessness condition obtained during the parabolas on a free floating subject. Mean heart

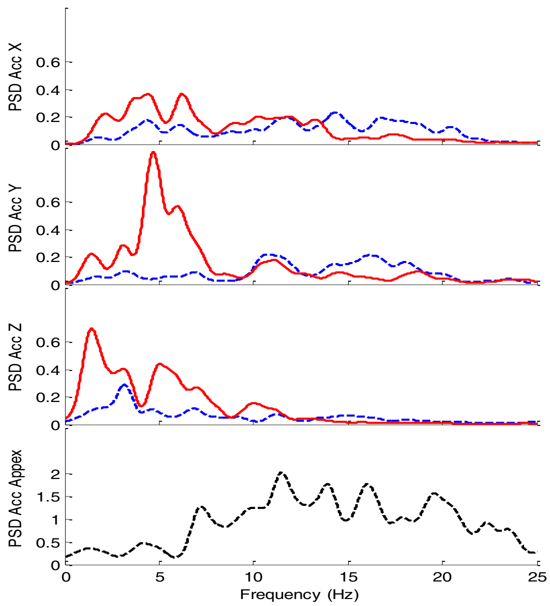

Fig. 6. Power spectrum frequency analysis of three axis scapulae SCG (blue dashed) and CoM BCG (red continuous) and single axis Appex SCG (lower panel) during 11.5 s of a free floating phase in parabolic flight.

rate (1/RRI) did not presented large differences between supine and 0G while the difference between standing and supine positions was larger and significant. It is interesting to note that the index of the maximum magnitude in the force vector (ind Max), when multiplied by RRI to be converted into a normalized time ranges from 78.2 68.4 to 61.1 ms (from standing to 0G) which values are compatible with the pre-ejection period duration. The same is not true for the ind Max in the magnitude of the BCG signals which ranges from 163 to 142 ms. However when one considers the values of the maximum magnitude of the Force verctor, they are very consistent ranging from 2.51 to 2.54 N for the SCG signal and from 2.17 to 3.07 N for the BCG signal. The higher value seen in the 0G condition is in agreement with a higher stroke volume that is often seen in the early phase of adaptation to the 0G environment of parabolic flights.

| | | | SCG | | BCG | |
|---|---|---|---|---|---|---|
| | N | RRI (s) | ind Max | F (N) | ind Max | F (N) |
| Standing | 261 | 0,511 | 153 | 2,51 | 319 | 2,17 |
| Supine | 256 | 0,670 | 102 | 2,25 | 368 | 2,68 |
| 0G | 103 | 0,650 | 94 | 2,54 | 219 | 3,07 |

Table. 1. Comparisons between values obtained on the seismo- (SCG) and ballsisto-cardiogram (BCG) on the ground in the standing and supine positions as well as during the weightlessness phases of a parabolic flight in a 0G environment. N: number of heart beats used to compute the ensemble averaged curves. RRI: RR-intervals (heart period), ind Max: index of the maximum in the magnitude of the acceleration vector. F: magnitude of the force vector at its maximum.

## V. Conclusion

Our results of 3D acceleration recordings in the same subject, close to center of mass (BCG), and close to the heart, between the scapulae (SCG), show clear differences. These differences are seen in the standing and supine positions as well as during the weightlessness (0G) phases of a parabolic flight. Recordings preformed close to the CoM (BCG) shows smoother curves with lower frequency content than those performed close to the heart (SCG). Furthermore, the recordings performed in 0G shows also lower frequency content than the supine recordings. This suggests that gravity induces higher frequency oscillations, likely through a stiffer mechanical coupling. The results presented here are important in the debate of the nomenclature that could be used to identify and name the various events seen in the SCG and BCG signals. Indeed, the simultaneous recordings that are presented here demonstrate that there are important differences in timings and amplitude of these waves. And without a concurrent recording it would be extremely difficult to identify and link them to a particular and reproducible cardiac event within the cardiac cycle.


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