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# Physiological insights from gravity-free ballistocardiography*

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***Abstract*— Terrestrial ballistocardiographic (BCG) measurements are typically performed in only one or two axes because of the coupling between the subject and the ground. An appropriate physiological interpretation of these BCG signals therefore assumes that the information in the unmeasured axis is either understood, or able to be ignored. BCG signals from measurements in microgravity can be made in all three axes and permit examination of these assumptions. Such microgravity measurements show that lung volume significantly affects the BCG signals, predominately in the head-to-foot direction. Further, the maximum accelerations recorded following systole are poorly captured by coronal plane measurements as the greatest displacements occur in the sagittal plane. These results suggest a need to carefully consider the influence of the motion in the unmeasured plane when interpreting terrestrial BCG signals.**

## I. INTRODUCTION

The relatively recent resurgence in interest in ballistocardiography (BCG) as a means of inferring physiological aspects of cardiovascular function brings with it the need to consider the relationship between the measured signals and the underlying physiology. One of the principal limitations of terrestrial BCG is the fact that there is inevitable coupling of the body to the earth as a result of gravity. As such, there are the inevitable questions that arise of how this coupling affects the resulting signals and their interpretation.

Ballistocardiographic recordings performed in a free-fall environment, be it transient microgravity (μG) in parabolic flight, or sustained μG in spaceflight offers a unique opportunity to address these questions. While it is clear that routine measurements in μG are not likely to be feasible in the near future (if ever), a few such opportunities have provided valuable insight into the underlying physiology of the BCG signals more typically measured in the terrestrial environment.

The purpose of this paper is to provide a very brief review of four potentially important insights that have been obtained from BCG measurements performed in μG. All of the studies referred to have been published in the open literature and the reader is referred to the relevant citations [1-3] for the specifics of the methods employed.

## II. LUNG VOLUME MATTERS

While not the first publication to report BCG from μG, the publication from Prisk and colleagues [1] using data obtained in sustained microgravity during SpaceLab mission D-2 clearly showed the importance of controlling for lung volume. The data were collected in a single free-floating subject who had been in μG for ~7 days. The subject was instrumented with a three-lead ECG, and wore a snuggly fitting lycra suit containing a respiratory inductance plethysmograph that provided a continuous record of respiratory motion. A high-fidelity triaxial accelerometer package was strapped tightly in the small of the back (and as such, close to the assumed center of mass of the subject). Data were obtained in single 146-second period of free-float.

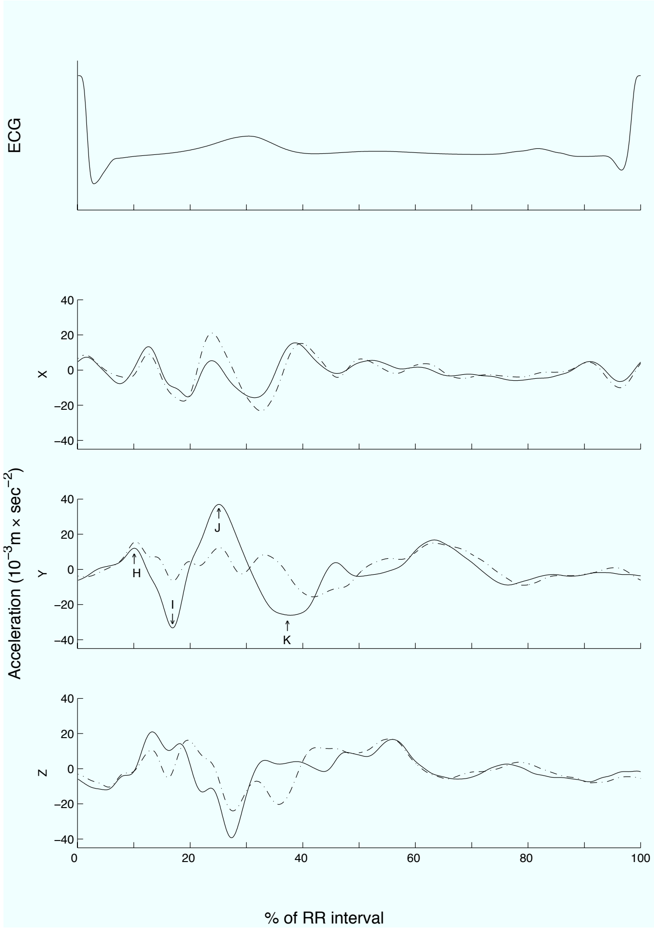

Figure 1. Ensemble averaged BCG recoding at end-inspiration (solid line) and end-expiration (dashed line) in a free-floating subject in sustained μG [1].

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When the data were analyzed, the BCG signals were ensemble averaged based on 4 distinct phases of the respiratory cycle; end expiration (close to functional residual capacity, FRC), end inspiration (FRC + resting tidal volume, TV), mid-expiration, and mid-inspiration. The results from data collected at FRC, and FRC+TV are shown in Fig. 1.

There were clear differences between the two lung volumes, with very much greater amplitudes of the principal acceleration waves seen in the BCG, the HIJK complex corresponding to the systolic phase. This was greatest in the longitudinal body axis (head to foot) with only relatively minor changes being observed in the other two orthogonal axes. The implication is that there is better coupling between the heart and the body in the longitudinal axis at higher lung volumes, although the actual mechanism for this is unclear. When the data from mid-inspiration and mid-expiration were compared, they were intermediate to those seen at end-expiration and end-inspiration, but largely similar to each other. Thus it seems that respiratory motion itself (which is opposite in these two conditions) is not an important factor in the BCG recording.

## III. DATA FROM PARABOLIC FLIGHT IS EQUIVALENT TO SUSTAINED MICROGRAVITY

The only alternative means of obtaining data in µG to spaceflight (at least in humans) is parabolic flight. However, while the transient µG (~20 seconds in each period of µG) is a period of very low residual acceleration (at least in the context of human physiology studies), it is sandwiched between two periods of hypergravity (~1.8G) necessary for the aircraft to successfully fly the maneuver [4]. This raises the question of whether the period of hypergravity preceding the µG period adversely influences the recordings made during the µG period.

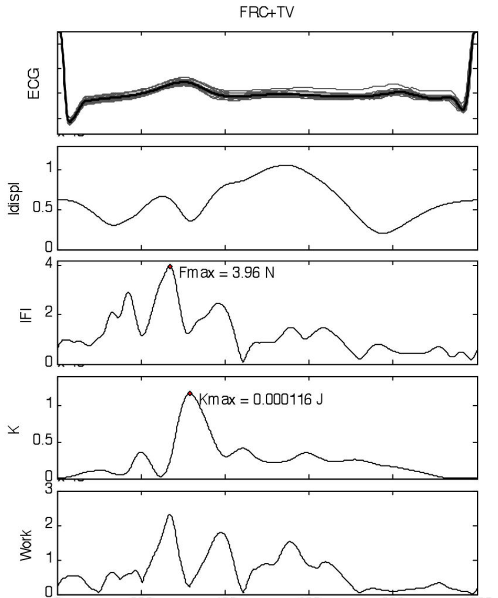

Figure 2. The BCG and derived variables from a recording in sustained µG (spaceflight). From [3].

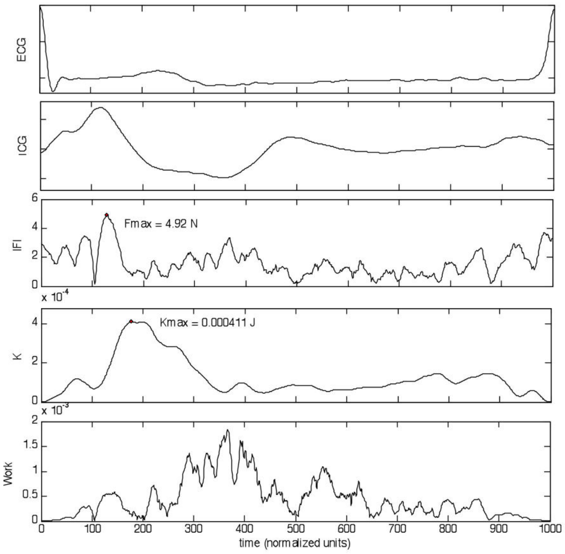

Figure 3. The BCG and derived variables from a recording in transient µG (parabolic flight). Note the overall similarity to data in Fig. 2. [3].

Fig. 2 and Fig. 3 show recordings made during sustained µG (Fig. 2, the same data are in section II) and from a subject in transient µG recorded during parabolic flight (Fig. 3) [3]. Although the data from parabolic flight are somewhat noisier, there is generally good agreement providing considerable confidence in the data obtained in that environment. This is important in that future questions that arise in the interpretation of the terrestrial BCG can potentially be answered in the comparatively accessible environment of parabolic flight without resorting to spaceflight.

## IV. THE BCG EXHIBITS A PLANE OF SYMMETRY THAT IS PRIMARILY SAGITTAL

While the typical terrestrial BCG recording is one dimensional, even the more sophisticated suspension systems employed for a 2D BCG recording have focused on a frontal (i.e. coronal) plane. However calculation of the physical displacement of the body in data collected in sustained µG (see section II) show that most of the displacement in an unrestrained subject is in the sagittal plane (Fig. 4) [2].

The implication of this result is that 2D recordings performed in a supine subject (thus performed in the coronal plane) fail to capture a significant portion of the effect of the blood ejection on the body. While this does not necessarily invalidate 2D coronal plane studies, it serves to complicate their interpretation.

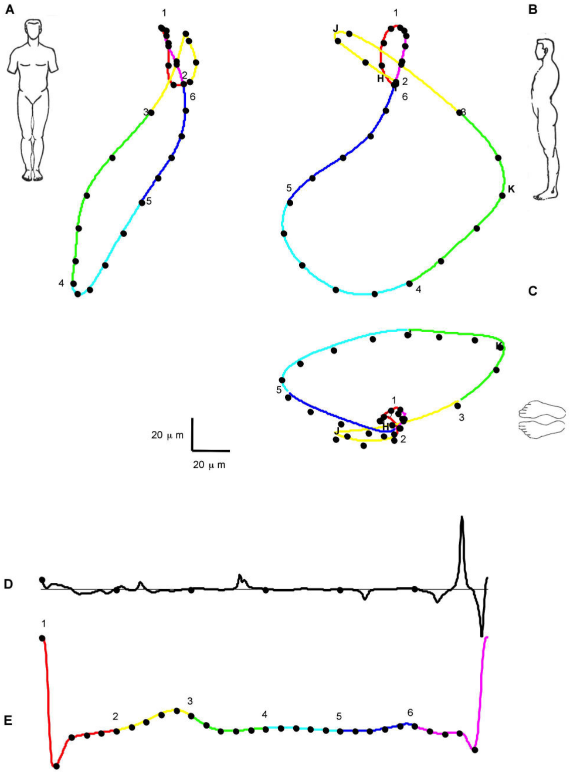

Figure 4. Projections of the displacement of a free-floating subject onto the three anatomical axes. Note that largest motion is seen in the sagittal plane. The color coding identifies the portion of the ECG activity from which the displacement arises. From [2].

## V. THE COMMONLY USED LINEAR ACCELERATIONS FAIL TO FULLY CAPTURE ACTUAL FORCES

The corollary of the lack of information from the front to back axis of the body can be appreciated in Fig. 5, which correlates the magnitude of the HI wave, with that of the overall 3D acceleration vector, and in Fig. 6 which does the same for the IJ wave. In both cases, although the correlations are significant, they are of relatively poor quality with only ~38% of the HI wave amplitude being directly attributable to the magnitude of the acceleration vector, and ~57% of the IJ wave being directly attributable [3].

The basis of these poor correlations can be seen in Fig. 4. The HIJ portion of the displacement curve is the region colored yellow. During this period the principal displacement is in the front to back direction of the body (see panels B and C) with only quite modest displacements in the longitudinal, or side-to-side directions (see panels A and C).

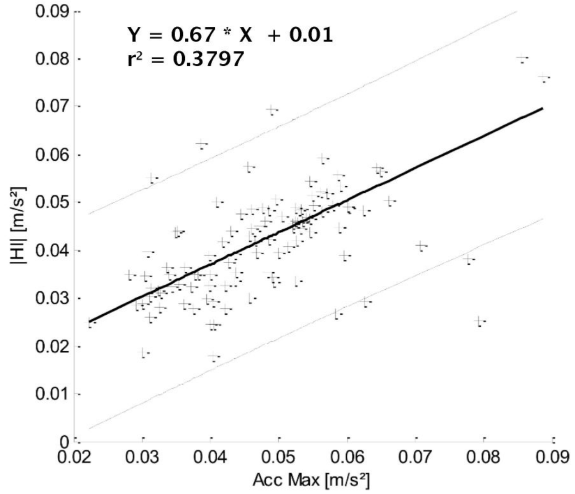

Figure 5. Correlation between the amplitude of the HI wave and the magnitude of the 3D acceleration vector recorded in a sustained μG environment. From [3].

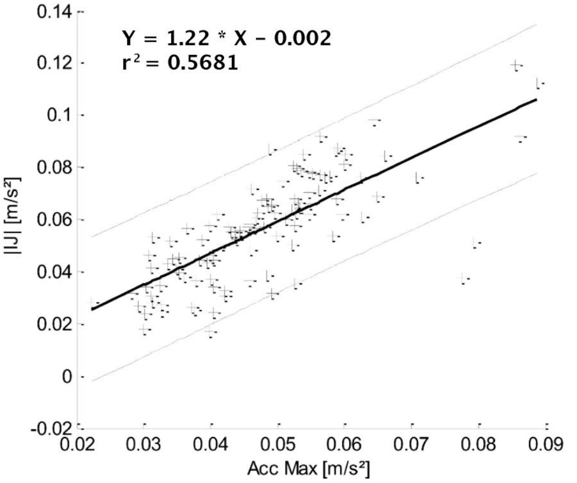

Figure 6. Correlation between the amplitude of the IJ wave and the magnitude of the 3D acceleration vector recorded in a sustained μG environment. From [3].

## VI. CONCLUSIONS

The four aspects of BCG recording described above in sections II – V highlight two important aspects to be considered when making terrestrial recordings, if there is to be a clear physiological interpretation. Lung volume at the time of recording must be standardized, and careful consideration of recording schemes that capture motion in the front to back axis of the body must be made. Appropriate consideration of both of these factors creates the potential for BCG to provide non-invasive physiologically relevant measurement measurements of cardiac function.

## VII. ACKNOWLEDGEMENTS

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