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# Cardiovascular changes in parabolic flights assessed by ballistocardiography

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*Abstract*— **This paper presents a comparison of the cardiovascular changes observed in microgravity as compared to ground based measurements. The ballistocardiogram (BCG), the electrocardiogram (ECG) and the transthoracic impedance cardiogram (ICG) were recorded on five healthy subjects during the 57th-European Space Agency (ESA) parabolic flight campaign. BCG is analyzed though its most characteristic wave, the IJ wave complex that can be identified along the longitudinal component of BCG and which has been demonstrated to be linked to cardiac ejection. The timings between the contraction of the heart and the ejection of blood in the aorta are analyzed via the time delay between the R-wave of the ECG and the I and J-waves of BCG (RI and RJ intervals respectively). Our results show that the IJ complex presents a larger amplitude in weightlessness and suggest that stroke volume (SV) increases in microgravity. We assume that ballistocardiography is an efficient method to assess the ventricular performance.**

## I. INTRODUCTION

THE effects of microgravity ($\mu$G) on the human body are well-known [4], [13], but their physiological basis are not yet completely understood. Parabolic flights (PF) are an efficient method to approach and investigate the subject more frequently than spaceflights.

Ballistocardiography is the study of the ballistic forces, and resulting motion of the body, that are due to the mechanical activity of the heart and the circulation of blood in the human body. In previous studies [3], [9], [10], [12], 3D-ballistocardiograms were obtained during a space mission and PF, in order to characterize the BCG signal in $\mu$G. The present study inscribes in the continuation of those studies, to further investigate the ballistocardiogram (BCG) in the $\mu$G environment, where no other forces than those of cardiac contractions are acting on the body. Impedance cardiogram (ICG) was used as a reference method for comparison. Indeed, ICG was proved as an efficient noninvasive method to investigate the preejection period (PEP), left ventricular ejection time (LVET), stroke volume (SV) and cardiac output (CO) [7], [11]. Fig.1 presents the classical waves and their nomenclatures, that will be used in the present study.

Data were obtained during the 57th-ESA parabolic flight campaign performed by NOVESPACE in Bordeaux, France. ECG, ICG and BCG were recorded in weightlessness and during two baseline measurements (standing and supine postures). The BCG curves were analyzed through an ensemble averaging method [9], [12] and the I and J peaks of the BCG (Fig.1) were identified. In addition, characteristic peaks of the ECG, ICG and BCG (Fig.1) were localized and used to compute the following systolic time intervals: RI interval (from the R-peak of the ECG to the I-peak of the BCG), LVET and PEP, which were defined as the BX interval and the RB interval (Fig.1), respectively.

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Our hypothesis was that ballistocardiography can be used as a method for the noninvasive assessment of left ventricular performance. We hypothesized that as a result of the expected increase in SV in $\mu$G [1], [2], [7], the IJ wave amplitude would be larger in $\mu$G compared to the standing posture on the ground. Furthermore, as suggested by a previous study [5], we presumed that the RI interval and the RJ interval would be correlated to the PEP.

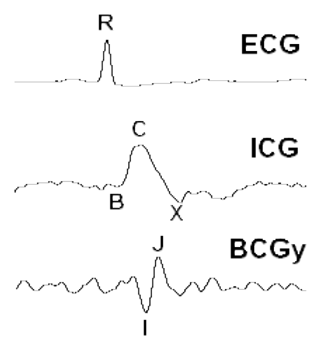


Fig. 1. Illustration of the characteristic peaks defined in the ECG, ICG and BCGy signals. The R-peak in the ECG was used as reference point to measure the time intervals. The C-peak is the maximum of the first derivative over time of the ICG. B and X points represent the opening and closure of the aortic valve, respectively. I and J peaks are two extrema of the BCG.

## II. PROTOCOLS AND EXPERIMENTAL PROCEDURES

### A. Parabolic flights maneuvers

The parabolic flights maneuvers were realized with the Airbus A300-ZéroG of NOVESPACE during the 57th-ESA campaign. One campaign consist in three days of flight with 31 parabolas per flight. A parabola is divided into the following parts (Fig.2): the ”Pull-Up”, the ”Injection”, the $\mu$G phase and the ”Pull-Out”. For the ”Pull-Up”, the pilot raises the pitch angle up to 45 degrees, which increase the perceived gravity along the vertical axis of the airplane (Gz which correspond to the body longitudinal axis for a subject standing in the airplane) to about 1.8g. The ”Injection” is the rapid transition between hyper-G phase and $\mu$G. Weightlessness lasts ∼20s until the aircraft tilts down to -45 degrees at which time starts the ”Pull-Out”, where the pilot exits the parabola trajectory to return to a stabilized level. During the ”Pull-Out”, Gz rises also to about 1.8g.

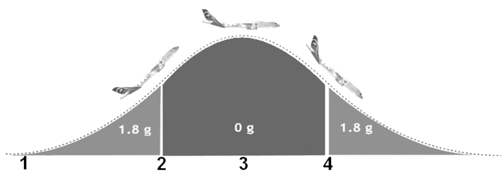


Fig. 2. Typical flight maneuver during a parabola obtained with the Airbus A300-ZéroG of NOVESPACE [15]. A parabola is divided into the following parts: 1) ”Pull-Up”, 2) ”Injection”, 3) $\mu$G and 4) ”Pull-Out”.

### B. Subjects and Protocols

Data were recorded on five healthy subjects (two women and three men; age 35±12 years; weight 70±15 kg; height 176±14 cm) who gave their written informed consent to the protocols. The protocols were non invasive, reviewed and approved by the local institutional ethical review boards and the relevant French authorities.

### C. Microgravity data

Two subjects were tested per flight during 15 parabolas each. Subjects were free-floating during the ∼20s of $\mu$G. During those maneuvers, each subject followed the same protocol: 1) During the ”Pull-Up”, the subject was generally in standing posture; 2) A few seconds before the ”Injection”, two attached operators grabbed the subject; 3) In $\mu$G, the subject was lifted by the operators to about one meter above the floor, stabilized and released after ∼4s. The subject was then in free-float with instructions to keep a rigid body posture with his arms aligned along the body and keep his eyes closed. The operators were instructed to secure the subject and prevent any sort of collision. 4) During the ”Pull-out”, the subject was assisted by operators to return safely to the floor. Note that to prevent motion sickness, each subject received about one hour before takeoff a scopolamine intradermal injection (from 125$\mu$g to 175$\mu$g).

### D. Baseline data

Before each flight, baseline data were recorded in standing (N=5) and supine (N=4) positions. The subject had to remain still during two minutes in each posture. None of the subjects was under the effect of scopolamine during measurements on the ground.

### E. Data acquisition

ECG, ICG, respiration signal (nasal thermistor) and 3D accelerations were recorded at 1 kHz using a PNEUMOCARD-Ballisto system [10]. The ECG and ICG signals were recorded with the standard eight electrodes placements [5]. The 3D-ballistocardiogram accelerometer (with six-degrees of freedom) was placed at the lower back near the center of mass (CM) of the subject.

### F. Axis System

We used the standard nomenclature for axes in ballistocardiography [14], where x is the lateral (left-to-right) axis, y is the longitudinal body (feet-to-head) axis, and z is the anterior-posterior (ventro-dorsal) axis.

## III. Methods

### A. Event Detection

QRS complexes were automatically detected on the ECG using a template correlation method. Detected events were visually inspected and, if required, manually corrected. A time series of occurrence of R peaks was then constructed to provide the RR-Intervals (RRI). The dZ/dt waveform, the derivative of the thoracic impedance signal (dICG), was used to provide the B, C and X points (Fig.1). These points were localized with an automated detection algorithm, which locate the inflection points of the ICG via the detection of extrema on the derivative.

### B. Ensemble Average

For each cardiac cycle, ECG, dICG and BCG signals were resampled to a normalized time axis [9], [12]. Shortly: the time axis corresponds to a normalization of the time between two consecutive heart beats from 0 to 1000. An ensemble average was then performed on the superimposed beat-by-beat curves to compute the average signals in the normalized cardiac cycle (Fig.3). This method allows the superposition of data from different heart beats while taking into account the physiological variations in RRI (heart rate variability).

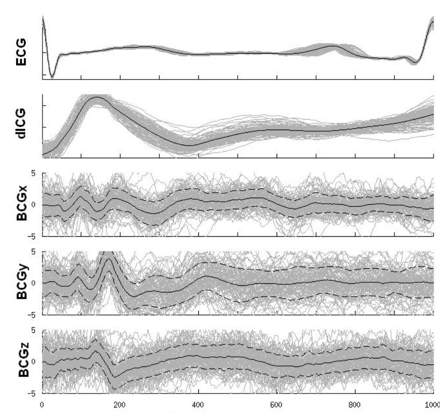


Fig. 3. Ensemble average on 99 beats in standing posture. From top to bottom: beat-by-beat ECG (a.u.); dICG (a.u.); projections of the BCG accelerations (mg) on the 3 anatomical axes: left to right (x), feet to head (y), anterior-posterior (z). Beat by beat signal is in grey, the ensemble average signal is represented by the black line with ± standard deviation (dashed line).

### C. Selection of free-floating beats

To obtain the IJ wave complex from the BCG signal during $\mu$G, all the beats occurring when subjects were not in free-float (i.e. subject held by the operators or collided with its environment) were removed. The following criteria was applied on the norm of the acceleration vector:

$$|\vec{a}| < 3[max|a_y| + 2\sigma(a_y)] \quad (1)$$

where $a_y$ is the y component of the BCG with the highest amplitude. The threshold limit in our selection criteria (1), was chosen in a way to obtain the best compromise between a large number of heart beats and heart beats in free-float exclusively (i.e. subject had no contact with its environment). The acceleration vector is defined as usual by the relation:

$$|\vec{a}| = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (2)$$

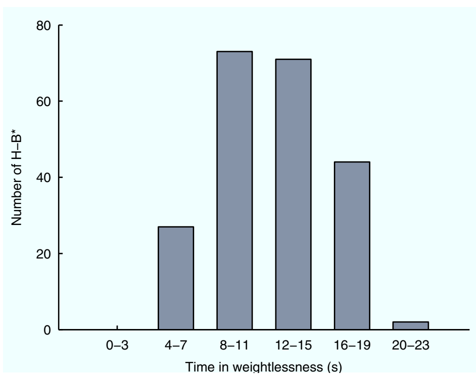


Fig. 4. Number of heart beats in free-float (*) versus the time from the start of the parabola (s).

Out of the total number of heart beats, 3967, recorded in $\mu$G, only 5.6% (224) met our selection criteria (1). The number of heart beats as a function of the time in weightlessness is presented in Fig.4. It is interesting to note that most of them (84%) are from the interval 8-19s. This is due to the threshold (1) applied on the norm of the acceleration vector, and the conditions of the PF itself where this phase is the more stable one.

### D. Statistics

Results are presented as mean values plus/minus the standard error of the mean (SEM). To account for intersubject variability, the percentage of change as $\mu$G minus baseline divided by $\mu$G, was computed. The analysis was performed on the 224 beats in free-float period. Wilcoxon signed rank tests were performed to compare $\mu$G data with baseline measures (result significant at $p<0.05$).

## IV. RESULTS

Fig.5 presents the results ($\pm$ SEM) obtained from free-floating beats (224) from all subjects. The percentage of change between $\mu$G data (N=5) and the baseline data for standing (N=5) and supine (N=4) postures was computed for the following parameters: RRI, C-wave amplitude, LVET and PEP. RRI was higher in $\mu$G compare to standing posture on the ground but lower in $\mu$G compare to supine baseline measures. C-wave amplitude and LVET were higher in $\mu$G than measurements on the ground. At the opposite, the PEP was shorter in $\mu$G phases. Note that only the percentage of change between $\mu$G and standing posture, for the C-wave and the PEP, was statistically significant ($p<0.05$).

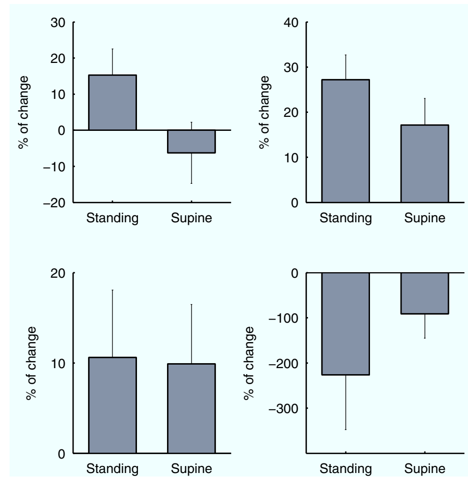


Fig. 5. Percentage of change between $\mu$G and baseline in standing and supine postures for: RRI (top-left), C-wave amplitude (top-right), LVET and PEP (respectively bottom-left and bottom-right). Values are mean $\pm$ SEM.

Results from the IJ amplitudes are presented on Fig.6. As we suspected that the BCG might have been altered in our supine measures (the accelerometer was in-between the subject and the mattress), these data will not be discussed here and we focus on the standing vs $\mu$G difference. The IJ amplitude was higher, but not significantly ($p>0.05$), in $\mu$G compare to standing posture on the ground.

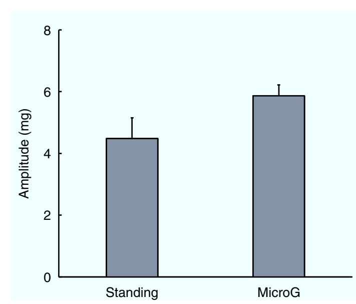


Fig. 6. Representation of the IJ amplitude in standing posture and in $\mu$G. Values are mean $\pm$ SEM.

For each subject, a linear regression was performed between the RI (or RJ) interval and the PEP. Three points corresponding to three $\mu$G phases (first-third of parabolas, two-thirds of parabolas, last-third of parabolas) were used to obtain the RI and RJ interval with an ensemble averaging method. The average correlation coefficients ($R^2$) were then computed. Low $R^2$ were obtained for both intervals: 0.457 and 0.387 for RI and RJ interval, respectively.

## V. Discussion

The main limitation of our study is the limited amount of artifact-free data. Indeed, for the analysis of the BCG in weightlessness, only 5.6% of the total could be exploited. A larger period of free-floating in $\mu$G is highly desirable. The only way to achieve this in PF would be to improve the quality of remaining levels of airplane accelerations or increase the length of the parabola. But these possibilities are beyond our control. Therefore, the correlation between the RI or RJ interval and the PEP, suggested by [5], could not be verified. This is due to the small number of exploitable data in PF and the ensemble averaging method which limited us, as stated in the results, to three averaged data points for the RI and RJ intervals per subject in $\mu$G. A second limitation of this study is the scopolamine injection. Indeed, to avoid motion sickness, all subjects were medicated during the flight, but the ground measurements were performed without medication. Although this probably affects the comparison between baselines and $\mu$G measurements, the effects of scopolamine on our data are unfortunately not quantifiable.

The study of Limper et al. [7] showed that RRI is decreasing during PF. This is in agreement with our comparison between supine baseline measure and $\mu$G but against our comparison between standing baseline measure and $\mu$G, where RRI was higher in $\mu$G. We assume that this is due to the low number of data exploitable (5.6%) and the dynamic of the cardiovascular system inside a PF. Indeed, the studies [1], [2] showed that cardiovascular parameters are different at the beginning (0-10s) and at the end (11-20s) of the parabola. Furthermore, the subjects are exposed to a hyper-G phase preceding the short $\mu$G phase ($\sim$20s). This is known to have a large influence on the cardiovascular system [7]. Eventually, our group of subjects was limited to five people and was inhomogeneous: two women, three men, one of them highly experienced with parabolic flights. This limitation is due to the limited number of subject than can be on-board the plane and is something we will improve with our future participation to other PF campaigns.

## VI. Conclusion

Weightlessness implies an increase in LVET and a decrease in PEP, which confirms the results of [6], [8]. An increase in the C-wave amplitude is also observed. According to the Sramek equation [11], the stroke volume is proportional to the peak value of the dZ/dt waveform and the LVET. Therefore, in agreement with other studies [1], [2], [7], our results suggest that microgravity induces an increase of the stroke volume. The novelty of the present study lies in the analysis of the ballistocardiogram which shows that IJ amplitude is also increasing in $\mu$G. This suggests that IJ amplitude might be correlated to the stroke volume. This confirms our hypothesis that ballistocardiography could be used as a noninvasive method for the assessment of left ventricular performance and warrants further research to define this precise relationship.


## Acknowledgment

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