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

Three dimensional ballistocardiography: methodology and results from microgravity and dry immersion

P-F. Migeotte, J. Tank, N. Pattyn, I. Funtova, R. Baevsky, X. Neyt, *Member, IEEE*, and G.K. Prisk, *Senior Member, IEEE*

***Abstract*—Balistocardiography was recorded in 3-D on a free floating astronaut in space as well as on healthy volunteers participating to a dry immersion study in a terrestrial laboratory. We demonstrate a new technique suitable for the analysis of 3-D BCG. The spatial curve of the displacement vector is analyzed instead of the three components of acceleration. The technique presented is invariant from the axis of representation and provides important novel physiological information.**

I. Introduction

BALLISTOCARDIOGRAPHY (BCG), in the past and in our day-to-day terrestrial environment, was typically studied on subjects lying on a table equipped for the monitoring of its forces, accelerations, velocities or displacements in the 2-dimensions (2-D) of the horizontal plane. Since the early days of the BCG technology, attempts were made to record a vecto-ballistocardiogram (V-BCG), i.e. a simultaneous recording of the accelerations or forces in the 3-dimensions (3-D) of space [1]. Due to the influence of gravity and the consequent technical limitations, these attempts were never very successful. Hixon et al., in 1962, reported what is, to our knowledge, the first representation of a V-BCG recorded in microgravity [2]. However the 3-D representation was made with a metallic stand and pieces of wood to represent the tip of the vector at different timings of the cardiac cycle.

We had access to a unique data set of 3-D BCG which was recorded in 1993 on a crew member of the Spacelab-D2 mission. In a previous paper [3], the description of the balistocardiogram along three axes revealed that the information along the antero-posterior axis was of comparable magnitude as the 2 others, which showed that for the physiological interpretation of the mechanical heart function, 3-D recording is crucially important. However, at that time, we were still analyzing the projections of the BCG on the three classical anatomical axes of reference, which does not provide for information that is independent from the frame of reference.

We developed a set of algorithms to perform a 3-D analysis of the BCG curves, and providing numerical information that is independent from the choice of a reference axis. Our method consists of computing the components of the displacement along the 3 axis and using the Frenet-Serret formulas to compute the scalar parameters characterizing the 3-D curve described by the displacement vector, i.e. the length, the curvature and torsion of the curve within the cardiac cycle.

These scalar parameters are independent of the axis representation and have the potential to provide a stable means by which to characterize BCG curves. This should allow a physiological interpretation and provides new non-invasive information about the physico-physiological phenomenon under-pinning the BCG.

In the present paper, we demonstrate this method on the recordings obtained on the free floating astronaut of the D2 mission. We also show similar results using 3-D acceleration recordings obtained in healthy subjects “floating” in an earthly laboratory dry immersion setup.

Our results show that a V-BCG curve present interesting features in the curvature and torsion but also that the displacement curve takes place most of the time in a plane that is close to the sagittal plane of symmetry. Moreover, data recorded on the ground show important similarities with the results obtained in space, thus suggesting that the validity of these results is not limited to the microgravity environment. However a calibration of the curves obtained on the ground will be needed in order to quantify the influence of gravity and the damping induced by the experimental setup.

II. Protocols and Experimental Procedures

A. *Microgravity data*

The BCG along the three anatomical orthogonal axes (using a triaxial accelerometer), the respiratory movements of the ribcage and the abdomen (using respiratory inductance plethysmography), as well as the electrocardiogram (ECG) were recorded in one subject in sustained microgravity, over a period of 15 min. Respiration, ECG and BCG signals were sampled at 50 Hz, 500, and 300 Hz respectively and were

Manuscript received April 11, 2011. This work was supported by the Belgian Federal Science Policy Office (BELSPO) via the European Space Agency PRODEX program.

P-F. Migeotte, X. Neyt, N. Pattyn and S. De Ridder are with the Signal and Image Centre of the Royal Military Academy, Brussels, Belgium (email: pierre-francois.migeotte@elec.rma.ac.be). G.K. Prisk is with the Department of Medicine and Radiology, University of California, San Diego, USA (email: kprisk@uscd.edu). Supported by the National Space Biomedical Research Institute thought NASA, NCC 9-58. J. 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 academy of sciences, Russian Federation.

up-sampled at the lowest common multiple frequency 1500 Hz using a low-pass cubic-spline interpolation algorithm. The technical details are fully described in [3]. In brief: the longest uninterrupted period of the recording, during which no contact with the Spacelab structure or with the other astronauts occurred (verified from a video recording), a continuous 176 s period was used. During this period, no significant rotation was observed. Consequently, acceleration data represent only linear accelerations.

B. *Dry immersion study*

3-D accelerations together with ECG and respiration signal (nasal thermistor) were recorded, at 1kHz using a modified PNEUMOCARD system (see more details in [4]), in healthy subjects floating in the dry immersion set-up of the Institute of Biomedical Problems of the Russian Academy of Sciences (IBMP).

C. *Ethical approval*

The protocols were non invasive and were reviewed and approved by the respective institutional ethical review boards, and informed consent of the subjects were obtained.

D. *Axis System*

We chose to use the nomenclature for the axes that is the standard in ballistocardiography, where *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.

III. Methods

A. *Ensemble averaging*

R waves of the ECG were automatically identified, visually inspected, and edited as required. Timings of the R waves were used as reference points to identify each cardiac cycle. For each cycle, the ECG and BCG data were sliced and represented as function of a normalized time axis: the beginning of each cycle was set to 0 and the end to 1. Normalized curves of the ECG and BCG from different heart-beats were superimposed and ensemble averaged to compute BCG and ECG signals. The normalized time axis was then rescaled in order that the end of the cycle would correspond to the computed mean RRI (i.e. 1230 ms for the epoch considered here). This procedure allowed ensemble averaging in the presence of the normal heart rate variability.

B. *Drift removal*

According to Newton's second law of motion, after one cardiac cycle, all components of the displacement vector should be back to their initial position. However, in order to get such an ideal representation, accelerations due to respiration and to other movements, not correlated with the heart-beats, were removed using low pass filtering. Velocity and displacement were obtained by single and double integration of acceleration data. Components of acceleration and displacement are shown in Fig. 1 together with a color coded ECG. The curves were computed for heart beats occurring at functional residual capacity (FRC, end-expiration, 31 beats), and at the end of inspiration, FRC + tidal volume (FRC+TV, 40 beats). The FRC data set (Fig. 1) will be used to further illustrate the method.

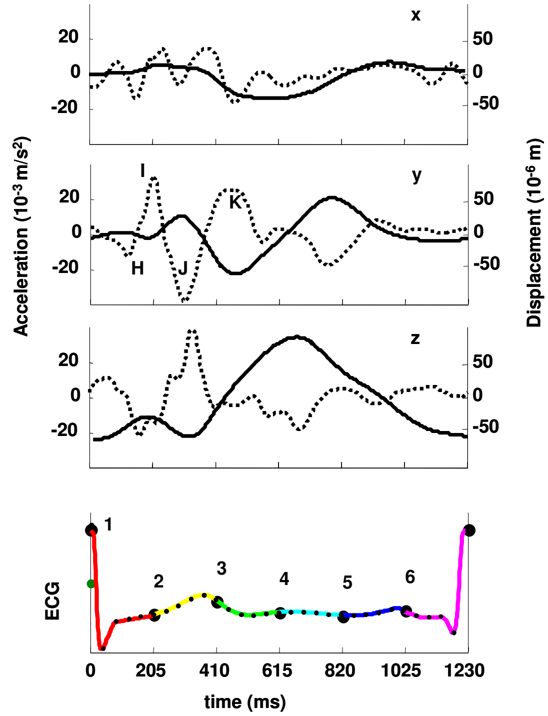

Fig. 1. Projections of the BCG (acceleration dotted curve, and displacement solid lines) on the 3 anatomical axes (left to right (x), feet to head (y), antero-posterior (z)). ECG (lower panel) is color coded and time stamps are added to allow further identification of timing of events in the cardiac cycle.

C. *3-D curve*

The coordinates of the data set of Fig.1 were reversed (multiplied by -1). in order to represent the displacement of the moving parts (predominately blood) during one cardiac cycle and not the movement of the centre of mass of the subject. The de-trended and inverted *x, y,* and *z* components of the position vector are used to construct a 3-D plot of the displacement during the cardiac cycle (not represented here). Such curve represents a 4-Dimensional data set (3D of space and 1D of time), which is not easy to represent in a 2D presentation. Therefore we plotted the 3 projections of the curve on the 3 anatomical planes (Fig 2) and used a color coding to represent different periods within the cardiac cycle (Fig. 1): starting with red for the period following the R wave, then yellow, green, cyan, blue and ending with pink just before the next R wave. Thus the systolic phase is in pink, red and yellow, and the diastolic phase in green, cyan and blue. Each of those periods was further subdivided in 5 regular time intervals.

D. *Characterization of the 3-D curve*

We used the Frenet-Serret relationship of vector differential analysis to characterize the curve with scalar parameters independent of the frame of reference (Fig.3). Let

$$\vec{r} = x\hat{i} + y\hat{j} + z\hat{k} \quad (1)$$

describes the location of the point (x,y,z) in the coordinates $(\hat{i}, \hat{j}, \hat{k})$. $d\vec{r}$ is the vector of infinitesimal changes *dx, dy, dz*. The infinitesimal distance, *ds*, between two nearby points is given by:

$$ds = \sqrt{dx^2 + dy^2 + dz^2} \quad (2)$$

Using the dot notation for derivative over time, $\dot{r}$ and $\ddot{r}$ denotes the velocity and acceleration vectors, respectively. The curve can be further characterized by its curvature

$$\frac{1}{\rho^2} = \frac{|\dot{r} \times \ddot{r}|}{\mathrm{ds}^6} \quad (3)$$

and its torsion

$$\frac{1}{\tau} = \frac{|\dot{r} \cdot \ddot{r} \cdot \dddot{r}|}{|\dot{r} \times \ddot{r}|^2} \quad (4)$$

where ρ and τ are the radius of curvature and torsion.

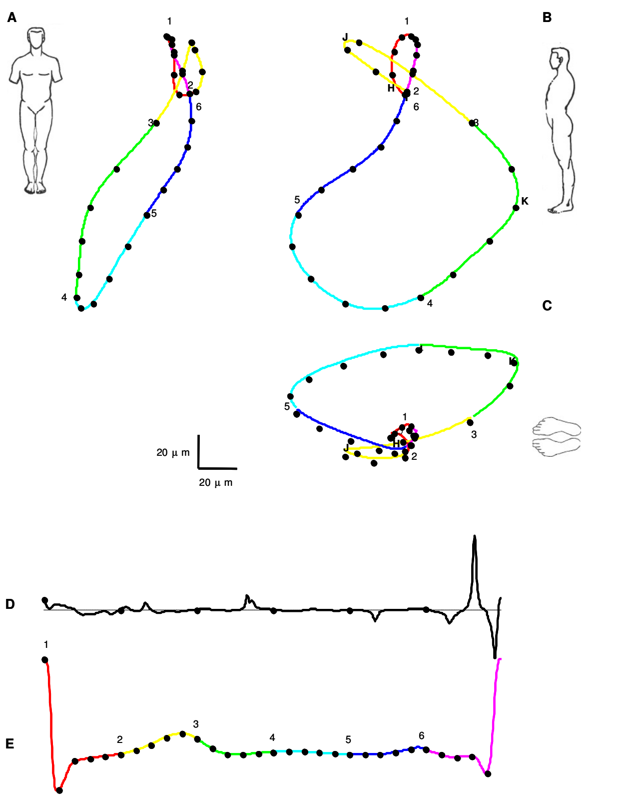

Fig. 2. Projections of the displacement on the 3 anatomical planes: (A) frontal, (B) sagittal, and (C) transverse. (D) is the torsion curve and (E) the ECG curve, which is color coded to represent regular time intervals as in Fig. 1. Displacements were inverted and the loop thus represents the movement of moving elements within the body (mostly blood).

These parameters are presented in Fig. 3. It is interesting to note that curvature and torsion both present peaks that occur mostly in the systolic phase. They should be related to opening and closure of cardiac valves, i. e. events when there is a resistance to blood flow and thus a change of direction. It is also interesting to note the variability in the occurrence of these peaks depending on the phase in the breath cycle (FRC vs FRC+TV), likely resulting from changes in intrathoracic pressure.

E. Plane of Symmetry

To identify if there is a particular orientation in the 3-D loop of the displacement, we used singular value decomposition (SVD).

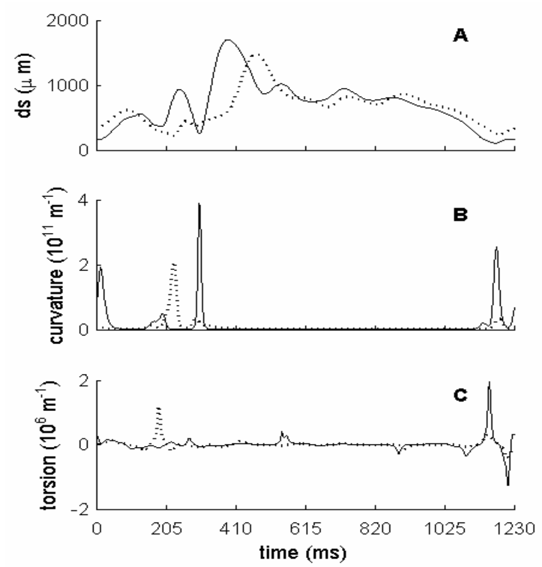

Fig. 3. Scalar parameters characterizing the displacement curve in 3D: (A) displacement (ds), (B) curvature, and (C) torsion within one cardiac cycle at two different phases of the respiration cycle, (FRC) plain line, (FRC+TV) dotted line.

Let *R* be the 1000 x 3 matrix of the displacements along the *x*, *y* and *z* axes of coordinates. Decomposition of *R*, the position vector, via SVD is given by

$$R = U \cdot S \cdot V^* \quad (4)$$

where *U* is a 1000 x 3 unitary matrix, *S* is a diagonal 3 x 3 matrix of singular values (*w*), *V* is a 3 x 3 matrix made of orthogonal unity vectors forming a new frame of reference. The weights *w* are a measure of the variance (sum of square) for each column vector of *U* in this new frame of reference. As they are orthogonal to each other the 3 weights are independent fractions of the total variance. If the information in the loop had no particular orientation, the 3 weights would be of the same order of magnitude. In the present case the third weight was much less than the other two. Setting this weight to 0 in *S*, and using (4) with the new *S*, the loop is reconstructed in a 2-D plane, which is the best plane of symmetry (in the least square sense) on which the loop can be projected. The smallest neglected weight, in percent, is the fraction of information lost in the projection. Then the loop can be rotated until its projections in two of the planes appear as straight lines. Fig 4 shows the result of SVD and rotations applied to the curve of Fig. 2. We found that the curve had a plane of symmetry that could account for 91.8% of the variance of the curve (i.e. only 8.2 % of the variance came from excursion outside that plane).

This plane was tilted by 15.8° in yaw (counterclockwise along the feet-to-head axis) and 19.8° in roll (to the right along the ventro-dorsal axis). When applied only to the diastolic part of the loop (green, cyan, blue), we found that only 2 % of the loop is outside the plane of symmetry.

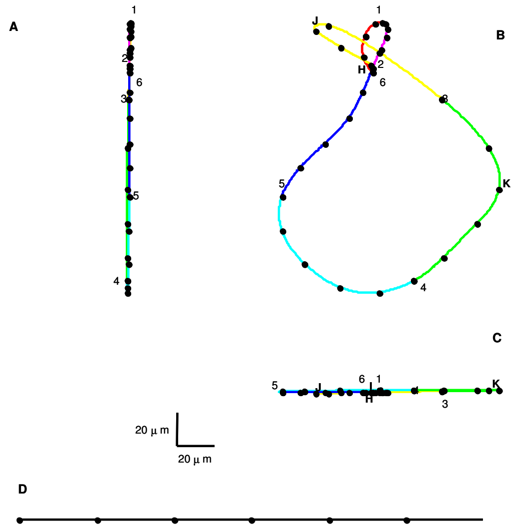

Fig. 4. Projections of the displacement along the 3 anatomical planes (as in Fig 2) reconstructed via SVD after one of the singular value has been set to 0. The curve is inscribed in a plane (torsion values (D) vanished). This plane was rotated by 19.8° and 15.8° along the vertical and transverse axes.

IV. Dry Immersion Data

The dry immersion set up was used in order to allow recordings on subjects in a relatively isotropic environment while avoiding the electrical problems inherent to the presence of water. The data from a 40 s epoch where the subject was breathing spontaneously are shown on Fig. 5.

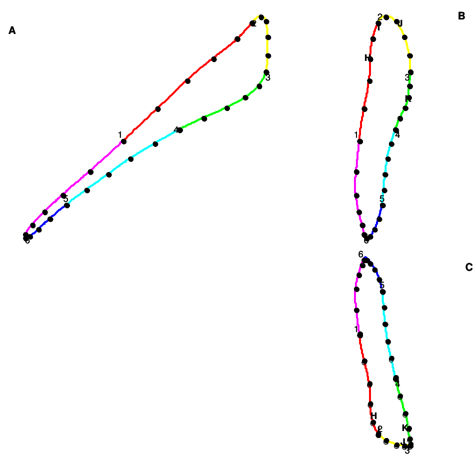

Fig. 5. Projections of the displacement on the 3 anatomical planes: (A) frontal, (B) sagittal, and (C) transverse. Orientation and color coding as in Fig. 2. Data are from a healthy volunteer lying down free of its movements (floating) in a dry immersion stet up.

As expected, the curve along the antero-posterior direction (Fig5. B & C) is damped and the shape is clearly different from Fig. 2. However, the displacement takes place also mostly in a plane. In our ground based data there is a large inter-subject variability which is likely due to uncontrolled experimental conditions introducing variable and probably non isotropic frictions and damping. Thus only a limited number of recordings were processed and additional recordings will be needed to allow the analysis of intra and inter-individual variability.

Conclusion

Both in space and on the ground, the displacement of the centre of mass of moving parts (i. e. mainly blood) takes place most of the time (and particularly during diastole) in a plane that is close to the sagittal plane of symmetry. The planarity of the curve is then likely linked to the symmetry of the arterial tree. Moreover the torsion vector shows peaks mainly during the systolic phase. No feature in curvature and torsion can be consistently correlated with the H I J K waves present along the y axis. This shows that these waves are intimately related to the projection of the vector on the traditional 3-axes system and have little physiological counterparts. This might thus explain the poor success of the medical application of BCG in the past while the analysis of amplitude of these waves was the focal point of interest.

Our ground based results shows that a V-BCG can be obtained even in normal gravity conditions. However, the experimental conditions introduce a damping and distortion of the curve that needs further analysis before any interpretation can be made. In conclusion, we showed that for a physiological interpretation it is extremely important to analyze the BCG curves in 3-D. To further characterize the influence of gravity on the V-BCG curve, and the physiological significance of the newly defined parameters, the ESA B3D project will consist in recordings of 3D-BCG on the ground and in microgravity.

Acknowledgment

We thank Profs Fernand Colin and Manuel Païva from the former Biomedical Physics Laboratory at the Université Libre de Bruxelles, where this study started for the many discussions and resulting interpretation of V-BCG.

References

[1] Baevskii RM, Chattardzhi PS, Funtov II and Zakatov MD. Contractile function of the heart during weightlessness according to the results of 3-dimensional ballistocardiography. *Kosm. Biol. Aviakosm. Med.* 21: 26-31, 1987.

[2] Hixson, W.C., Dietrich, E.B., ”Biotelemetry of the Triaxial Ballistocardiogram and Electrocardiogram in a Weightless Environment”, U.S. Naval Medical Center, Pensacola, *Monograph 10*, N66-16283

[3] Prisk GK., Verhaeghe, S. Padeken, D., Hamacher H., Paiva.M, Three-Dimensional Ballistocardiography and respiratory motion in sustained microgravity, *Aviat. Space. Environ. Med.,* 2001; 72: 1067-1074.

[4] Baevsky RM, Baranov VM, Funtova II, Diedrich A, Pashenko AV, Chernikova AG, Drescher J, Jordan J and Tank J. Autonomic cardiovascular and respiratory control during prolonged spaceflights aboard the International Space Station. *J. Appl. Physiol.* 103: 156-161, 2007.