35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Timing and source of the maximum of the transthoracic impedance cardiogram (dZ/dt) in relation to the H-I-J complex of the longitudinal ballistocardiogram under gravity and microgravity conditions*

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Abstract— **The transthoracic impedance cardiogram (ICG) and the acceleration ballistocardiogram (BCG) measured close to the center of mass of the human body are generated by changes of blood distribution. The transthoracic ICG is an integrated signal covering the whole thorax and spatial resolution is poor. Comparison between both signals can be used to elucidate the source of the ICG signal. We recorded the ECG, ICG, and BCG simultaneously in healthy subjects under resting and microgravity conditions during parabolic flights. The time interval between the R-peak of the ECG and the maximum of the ICG (R-dZ/dtmax) and the time interval between the R-peak of the ECG and the I-peak in the BCG (R-I) differed significantly ($p<0.0001$). The I-peak in the BCG always occurred earlier during systole than dZ/dtmax. The delay of dZ/dtmax ranged between 23 and 28 ms at rest and was lowest under microgravity conditions (12±4 ms, $p<0.02$). Our results suggest that both signals have different sources. Combination of modern imaging techniques with classical non invasive approaches to detect changes of blood distribution may provide new insights into the complex interaction between blood flow and mechanocardiographic signals like the BCG.**

I. INTRODUCTION

Thoracic impedance plethysmography is used in research and clinical settings to monitor ventilation, cardiac function or fluid shifts for more than 6 decades now.[1;1-3] Four or eight electrodes are usually placed on the thorax. A constant high frequency alternating current is transmitted to the body segment by the outer electrodes and the impedance (Z) between the inner electrodes is measured. Normal basal impedance (Z_0) values range between 10 and 50 ohms. The basal impedance increases with inspiration and decreases with expiration. The signal is superimposed by pulse-synchronous changes with a decrease of about 0.1-0.2 ohms (ΔZ) during the cardiac cycle.[2] Filtering the signal and calculating the first derivative over time provides the so called impedance cardiogram (ICG) in ohms per second. The shape of the ICG or dZ/dt signal resembles a triangular blood flow volume or blood flow velocity curve. Characteristic points of the ICG signal were used as references to identify heart sounds on the phonocardiogram with very high precision.[4] The opening and closing of the aortic valve, the preejection period (PEP), and the left ventricular ejection time (LVET) can be defined. Time intervals have been used to estimate left ventricular performance.[5] The amplitude of the signal in combination with the LVET are the main components of numerous equations to estimate stroke volume changes.[5-7] However, the physiological source of the maximum amplitude remains controversial and the acceptance of calculated absolute stroke volume values is rather low. Numerous factors influence the ICG like basal impedance, blood flow acceleration, blood flow velocity, and changes of the orientation of red blood cells.[1;5;6;8] There is evidence in the literature that the ascending aorta is the main source of the ICG.[9] Changes in blood distribution are also the source of the longitudinal ballistocardiogram (BCGy).[10] Recent studies suggest a close correlation between PEP measured with impedance cardiography and systolic BCG time intervals.[11] Bernstein D.P. suggested recently that the maximum of the ICG is related to blood flow acceleration and proposed a new stroke volume equation. The hypothesis was supported by the fact that the I-peak in the systolic H-I-J complex of the BCGy occurs at exact the same time.[6] We tested this hypothesis in healthy male subjects under gravity and microgravity conditions by comparing the time intervals between the R-peak in the ECG and the I-peak in the BCGy (R-I) with the time interval between the R-peak in the ECG and the maximum of the ICG (R-dZ/dtmax).

II. PROTOCOLS AND EXPERIMENTAL PROCEDURES

A. Resting measurements under gravity conditions

We studied eleven healthy male subjects (age 38±3 years, BMI 24±1 kg/m²) during morning hours, after an overnight fast under supine resting conditions. Measurements were started after instrumentation of the subjects for continuous

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*Research supported by the German Space Agency DLR (50 WB1117) and Belgian Federal Science Policy Office (BELSPO) via the European Space Agency PRODEX program. J.T. is with the Hannover Medical School, Institute of Clinical Pharmacology, Hannover, Germany (corresponding author: +49 5115322723; fax: +49 511532 2750; e-mail: tank.jens@mh-hannover.de). A.D. is with Department of Medicine, Division of Clinical Pharmacology, Vanderbilt University School of Medicine, Nashville, TN, USA (e-mail: andre.diedrich@vanderbilt.edu). P.F.M.; N.P.; A.A.; Q.D. are with the Vital signs and Performance Research Unit of the Royal Military Academy, Brussels, Belgium (email: pierre-francois.migeotte@elec.rma.ac.be). L.B.; P.G.; U.L. are with the German Aerospace Center (DLR), Institute of Aerospace Medicine, Space Physiology, Cologne, Germany (e-mails: limperu@unikliniken-koeln.de). E.L.; I.F.; R.M.B. are with the Russian academy of sciences, Institute of Biomedical problems, Moscow, Russian Federation (e-mails: rmb1928@mail.ru).

electrocardiogram (ECG), impedance cardiogram (ICG), respiration, seismocardiogram (SCG), and 3-D BCG recording (modified Pneumocard device, sample rate 1000 Hz). The BCG sensor was placed close to the center of mass (CM). Baseline measurements (5 minutes) at spontaneous respiratory rate were recorded and analyzed. Fig. 1 illustrates a baseline recording.

Figure 1. Original recording of ECG, IPG, ICG, triaxial BCG, SCG and respiration under resting conditions while supine.

B. Measurements before and during parabolic flights

Five healthy subjects (2 women, age 35±6 years, BMI 23±2 kg/m²) were studied during a parabolic flight campaign (ESA57th). Subjects were instrumented as described above before the flight. Recordings were made before the flight in upright and supine positions. The subjects were also measured while free-floating during the ~20s of microgravity phases obtained during the parabolic maneuver of the A300-ZéroG airplane of NOVESPACE.

C. Ethical approval

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

III. METHODS

A. Impedance cardiography

The eight electrode technique was used to record the ICG. Two spot electrodes were placed on both sides of the neck and two spot electrodes were placed at both mid-axillary lines with the inner electrodes at the level of the processus xiphoideus.

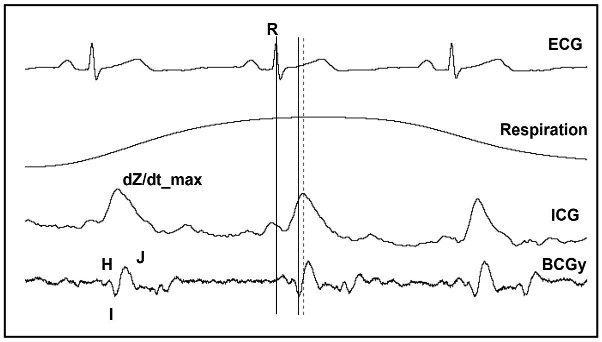

Figure 2. Illustration of the characteristic peaks defined in the ECG, ICG and BCGy signals. The R-peak in the ECG (thick line) was used as reference point to measure the time intervals. dZ/dtmax (thin line) is the maximum of the first derivative over time of the transthoracic impedance plethysmogram (ICG). The I peak in the BCGy signal (dotted line) reflects the maximum acceleration of the body in response to the acceleration of blood in the ascending aorta followed by a deceleration phase (I-J).

B. Peak detection and ensemble averaging for resting measurements under gravity conditions

R waves of the ECG were automatically identified, visually inspected, and edited if required. Timings of the R waves were used as reference points to identify each cardiac cycle and to detect the maximum in the ICG and the characteristic H-, I-, and J-points in the BCG signals. For a more robust analysis the ECG, ICG and BCG from different heart-beats were superimposed and ensemble averaged.

C. Peak detection and ensemble averaging for measurements during parabolic flights

R waves of the ECG were automatically identified, visually inspected, and edited if required. Timings of the R waves were used as reference points to identify each cardiac cycle. For each cycle, the ECG, ICG and BCG data were superimposed and represented as function of a normalized time axis: the beginning of each cycle was set to 0 and the end to 1000. Normalized curves of the ECG, ICG and BCG from different heart-beats were then ensemble averaged to compute ECG, ICG, and BCG. This procedure allowed ensemble averaging in the presence of the normal heart rate variability. For statistical analysis the time intervals were multiplied by the mean R-R interval.

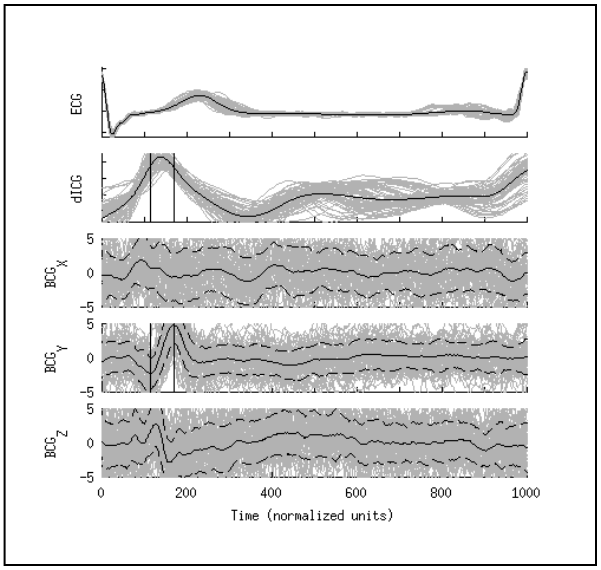

Figure 3. Example of ensemble averaged analysis of 71 heart beats obtained during repeated microgravity phases while free floating in one subject. The black lines indicate the characteristic I and J peaks in the BCGy signal in relation to the maximum of the ICG signal.

D. Statistics

Results are presented as mean values plus/minus the standard error of mean. For comparison between the time intervals the paired t-test was used. Differences were considered significant at $p<0.05$.

IV. RESULTS

A. Resting measurements under gravity conditions

Mean heart rate (HR) was 62±2 beats per minute. The mean time interval between the R-peak of the ECG and the maximum of the ICG (R-dZ/dtmax) was 132±4 ms. The mean time interval between the R-peak of the ECG and the I-point in the BCGy signal (R-I) was 104±6 ms. The mean value of the individual differences between the two time intervals was 28±3 ms ($p<0.0001$).

B. Measurements during parabolic flights

Mean heart rate was higher during these measurements (HR supine: 82±5; standing: 98±9, microgravity: 82±9 beats per minute). The supine mean values for the R-dZ/dtmax time intervals were 95±10 ms, 95±11 ms during standing, and 91±14 ms during the microgravity phases while free floating. The supine mean values for the R-I time intervals were 72±7 ms, 69±9 ms during standing, and 79±14 ms during the microgravity phases while free floating. The R-I intervals were significantly shorter compared to the R-dZ/dtmax intervals (supine: 23±4 ms, $p<0.009$; standing: 26±5 ms, $p<0.006$; microgravity: 12±4 ms, $p<0.02$).

V. DISCUSSION

The major finding of our study was that the R-I time interval measured in the BCGy (foot-to-head axis) was always shorter compared to the R-dZ/dtmax time interval. The difference was rather small but consistent. The shorter time intervals during the microgravity study (supine and standing) may be explained at least in part by the higher HR.

The occurrence of the dZ/dtmax at about 95 to 132 ms in our study is in accordance with state of the art imaging techniques to detect maximum blood flow velocity and maximum blood volume flow in the ascending aorta. Doppler ultrasound studies in healthy subjects showed a time to peak flow velocity in the ascending aorta of 98 ms.[12] Magnetic resonance imaging techniques allow for high precision triaxial blood velocity and volume flow measurements in the large arteries perpendicular to the flow direction but with rather low temporal resolution (MRI).[13;14] The mean values of acceleration time in the ascending aorta defined with MRI ranged between 110 and 119 ms.[13] Several studies during parabolic flights[15;16] and during space flight[17] evaluated systolic time intervals using echocardiography and ICG. However, data combining ICG and BCG are lacking. The studies provide information about the pre ejection period (PEP) and left ventricular ejection time (LVET). Migeotte et al.[15] and Johns et al.[16] showed an increase in LVET during the early zero g phase in parabolic flights and a shortening of PEP. LVET was also found prolonged during short term space flight.[17] We did not detect dramatic changes of the time to peak acceleration or time to peak volume flow during the zero g phase of parabolic flights compared to preflight values.

Based on Newtons law of the conservation of momentum the I peak of the BCGy reflects the maximum acceleration of the body in response to the maximum acceleration of blood in the ascending aorta and is a measure of cardiac mechanical force.[18] Our results contradict the hypothesis that the maximum of the ICG is related to the acceleration of aortic blood flow. Experimental studies clearly demonstrated that the source of the ICG is volume blood flow in the ascending aorta.[5;9] Systolic time intervals and there relationship were proposed as a measure of contractility using both the BCG[11] and the ICG[19]. The peak acceleration measured in relation to the later occurring peak volume flow could provide important information about the relationship between the mechanical force generated by the heart and the resulting volume flow in the ascending aorta. We speculate that a change in aortic compliance or stiffness could influence this time delay. Data from short term space flight in terms of reduced heart rate, reduced diastolic blood pressure,[20] and increased cardiac output[21] indicate that the cardiovascular system is under less stress than expected. In contrast, an increase in sympathetic nervous activity[22] and a decrease in arterial compliance has been described[23].

The assessment of cardiac force and volume blood flow by BCG and ICG respectively has several limitations. Placement of the BCG sensor close to the center of mass may result in an additional time delay of the H-I-J component due to the distance between the heart as the generating force and the sensor. The 8 electrodes ICG technique covers the complete thorax and detects blood distribution changes in the large veins, large arteries, cardiac chambers, and in the lung. The detection of blood volume changes by the impedance recording system depends mainly how the blood vessel is oriented in respect to the generated current lines.[1] Hence, the use of different electrode techniques and electrode placement may result in the detection of different vessels, in a different shape of the ICG and in different time intervals.[1]

Triaxial blood flow velocity MRI studies have shown a helical flow in the ascending aorta with a highly skewed distribution. Flow patterns in the aorta were found highly variable between subjects and depend on arch curvature. Blood with low momentum showed retrograde flow along the inner wall of the aortic arch late during systole.[24] These findings indicate that the heart and the vessels are adjusted to eject blood without producing a strong ballistic force. Structural changes of the heart and the large vessels together with changes in the mechanical axis during long term space flight may disturb this system adjusted for gravity conditions on earth. Studies combining imaging techniques with ICG and 3D-BCG may help to further improve existing physiological models to characterize the individual readjustment to zero g conditions. Assessment of the BCG and ICG signals during long term weightlessness can be a cheap, easy to use and valuable monitoring tool to assess the adaptational process.

ACKNOWLEDGMENT

We thank the participants of the study for the effort and the time they spend to support our research. We are especially grateful to the staff members of NOVESPACE for the perfect management of the parabolic flights.

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