Report

Microgravity: an ideal environment for cardiac force measuring

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Abstract

In the article main principles of ballistocardiography are considered. Special attention is paid to registration of the spatial ballistocardiogram. There exist two principles of ballistocardiography: dynamic and seismic. In the event of dynamic ballistocardiography body displacements align to an extent with shifting of the general center of body gravity. Ideal conditions for ballistocardiogram acquisition could be reached if rigidity of internal body relations had an infinitely large value, while rigidity of external relations was nearing the zero. Then displacements of the entire body would depend only on the forces imparted by the cardiovascular system. Microgravity is the only environment providing these ideal conditions for ballistocardiography. Microgravity allows effective application of the dynamic BCG principle to recording pulse-induced body movements corresponding to the center of mass displacements. This kindled interest of the first researchers in space medicine in ballistocardiographic investigations during space flight. Since free flying requires enough space, the investigations became possible only with construction of orbital stations. The first in-space ballistocardiogram was recorded on December 26, 1977 from Yu. Romanenko, commander of the first expedition to the Russian OS Salyut-6.

The data about ballistocardiographic researches at orbital stations Salyut and MIR which were conducted to 70-90th years is presented. The first attempt the spatial ballistocardiogram registration has been made in 1984 during the Soviet - Indian flight on OS Salyut-7. The first records spatial ballistocardiogram have been made during space experiment "Vector" on OS the MIR in 1990. New experiment "Cardiovector" on the ISS is being prepared for 2014-16.

Keywords

Ballistocardiography • Microgravity • Space experiment • Orbital station • Spatial ballistocardiogramm • Cardiac contractility • Center of body gravity

Imprint

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Introduction

The major function of the heart is to pump blood from veins into arteries. Isaac Starr, a distinguished US cardiologist, once said, “The heart is not just a dynamo, but it is primarily a pump.” However, it is a known fact that today's cardiologic practice gives preference to the electrophysiological investigation, i.e., taking records of electrical phenomena rather than mechanical processes that describe the pumping function of the heart. The reason is that historically electrocardiography (ECG) as a method of cardiac state identification appeared to be very simple for understanding by physicians and physiologists, especially if arrhythmia, stenocardia or myocardial infarction were an issue. Also, the electrocardiography procedure is fairly simple, whereas echocardiography and the more so catheterization challenges doctor's knowledge and skills.

Yet it should be noted that studies of the heart functions began with evaluation of cardiac contractility. Ancient pulse diagnosis relies on tracing the pulse wave propagation to peripheral vessels. Blood pressure measurement is also important for evaluation of vascular filling. One of the current methods of studying cardiac contractility and a topic for discussion in this paper is ballistocardiography (BCG); the method was invented by W. Einthoven before electrocardiography (1905). BCG was proposed by US scientist M.S. Gordon in 1879 and elaborated by I. Starr and J.L. Nickerson in the 1930-40s; in 1950s W. Dock designed a simple instrument to register ballistocardiogram in a patient lying in bed or a platform. Later on, the instrument was advanced to broaden ballistocardiography applicability in clinics and physiological investigations. In 1950-70s, BCG was one of the most popular methods both in medicine and physiology. According to the apt remark by W.R. Scarborough, all that is needed for ballistocardiogram recording is “to lie down and have a good rest”. In fact records of body microoscillations have a very complex genesis. They pick up not only body movements produced by blood ejection, but also sense the processes of their deceleration and damping. Hence, there is no direct link between the cardiac output parameters (volume, rate and force) and body movements. In their turn, displacements of the heart per so as well as blood masses in vessels due to cardiac contractions cause shifting of the body mass center. These are the displacements which represent the contractile function of the heart. Different instruments
and different principles of ballistocardiogram recording make it possible to reduce, to a varying degree, distortions introduced by friction and damping. However, ballistocardiograms that will mirror the center of mass shifting can be obtained only in microgravity where body is free flying without support.

It should be remembered that body movements instigated by cardiac output are directed as along the head-to-foot axis (they are typically recorded during BCG investigations), so other axes. By the ballistocardiographic nomenclature proposed by the American Heart Association in 1956 (W. Scarborough, S. Talbot), there are six degrees of freedom for a free moving body: displacements along X, Y and Z and turns about axes α, β and γ (fig. 1). Vector ballistocardiographic investigations were first attempted by J. Braunstein (1950) and continued by W. Scarborough (1953), W. Dock (1952-1956) and Yu.D. Safonov (1958). Figure 2 shows an example of vector ballistocardiogram (A.A. Knoop, P.J. Pretorius, J.H. Hotink, 1962). Records from a revolving body were termed torsion ballistocardiograms. The first torsion ballistocardiograms were acquired by W. Ernsthausen et al. (1953).

![Diagram of ballistocardiographic nomenclature](image)

**Figure 1.** Nomenclature of Ballistocardiographic's force (W. Scarborough, S Talbot, 1956).
It has been mentioned earlier that motion translation from the heart and vessels and body movements to sensing elements is very intricate. There exist two principles of ballistocardiography: dynamic and seismic. In the event of dynamic ballistocardiography body displacements align to an extent with shifting of the general center of body gravity. The situation is quite different in the event of seismic ballistocardiography, as body movements caused by cardiac forces have own frequency similarly to a weight hanging on a spring. Role of the spring is played by the body tissues mediating the contact between the body and ground (a platform beneath the body). Seismic BCG is recorded using all direct techniques with a sensing element attached immediately to the human body. Dynamic BCG utilizes special couch-like platforms. Figure 3 presents graphically two types of mechanic oscillating systems illustrating the principles of dynamic and seismic BCG [1-5].

**Figure 2.** Example of vector ballistocardiogram (A.A. Knoop, P.J. Pretorius, J.H. Hotink, 1962).
For dynamic BCG we should consider two kinds of relations, i.e., internal between the cardiovascular system and skeleton and external between the skeleton and surface under the body. Ideal conditions for ballistocardiogram acquisition could be reached if rigidity of internal body relations had an infinitely large value, while rigidity of external relations was nearing zero. Then displacements of the entire body would depend only on the forces imparted by the cardiovascular system. Under these conditions we could put the sign of equality between the driving force (F) and body inertia (M*a), i.e., the cardiovascular forces would be spent on nothing else but body displacement:

\[ F = M*a; \]

Microgravity is the only environment providing these ideal conditions for ballistocardiography.

On the Earth relatively close to ideal conditions for ballistocardiography can be achieved with the use of so-called ultralow frequency systems. These are suspended platforms with natural frequency below 1 Hz and rather good damping. In a simple ballistic system of the
seismic type (fig. 3) in addition to the cardiovascular driving forces (F) there also act the forces of elastic recoil (B) and deceleration (D). Movement equation, therefore, has the following form:

\[ F = M \cdot a + B \cdot v + D \cdot x, \]

where \( a \) - is acceleration, \( v \) – velocity and \( x \) – displacement.

Consequently, seismic BCG records displacements of the center of body gravity with gross distortions, as ballistocardiogram is a result of interference of forced and natural body oscillations.

Microgravity allows effective application of the dynamic BCG principle to recording pulse-induced body movements corresponding to the center of mass displacements. This kindled interest of the first researchers in space medicine in ballistocardiographic investigations during space flight. Since free flying requires enough space, these investigations became possible only with construction of orbital stations. The first in-space ballistocardiogram was recorded on December 26, 1977 from Yu. Romanenko, commander of the first expedition to the Russian OS Salyut-6 (Baevsky R.M., Funtova I.I., 1982). Systematic BCG investigations were conducted in the period of 1980-84 with cosmonauts flown on OS Salyut-6 and 7 (Baevsky R.M., Funtova I.I., 1984). In 1984, spatial ballistocardiograms along three axes were recorded in the joint USSR-India space flight (Baevsky R.M., P.S. Chattardji, Funtova I.I. M.D. Zakatov, 1987). First ballistocardiograms on the NASA space program were obtained in late 1983 during the 7-day mission of space “shuttle” Columbia (Scano A., 1984). Table 1 summarizes the BCG investigations performed aboard USSR (Russia), NASA and International space stations [6-14].
Table 1. Ballistocardiographic investigations in space expeditions

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<tr>
<th>General description</th>
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<th>Year</th>
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<td>Early BCG investigations in short and long-term expeditions</td>
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<tr>
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<tr>
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<td>Spatial BCG along 6 axes combined with ECG, SCG, impedance CG and respiration recording</td>
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<td>2014-2016*</td>
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* Scientific experiment CARDIOVECTOR is planned for implementation on board the ISS in 2014-2016.

Further we shall give a more detail consideration to the most noteworthy stages of BCG investigations in space flight.

Salyut-6, expedition 1 in 1977. The first in-space ballistocardiogram was recorded on December 10, 1977. This was a longitudinal ballistocardiogram taken from crew commander Yuri Romanenko on his first month on space flight (fig. 4).
The record evidenced striking differences in amplitude and form of BCG complexes as compared with pre-launch investigations. A piezoelectric accelerometer-type transducer developed by the Institute of Applied Physics of the Russian Academy of Sciences measured with an accuracy of 3 mV/cm/s within the bandwidth of 0.3 to 2000 Hz. The accelerometer (26x36x11 mm, 30 grams) was contained in a case 30x30x30 mm of size fastened close to the body mass center near the iliac bone with the help of an elastic belt and a metal plate. Measurements were made in a free flying cosmonaut with his arms and legs aligned with the body axis. Signals were registered using a supplemental amplifying unit borrowed from medical monitoring equipment Polynom-2M (24).

Salyut -7, USSR-Indian joint flight in 1984. BCG was recorded in three members of the 8-day space flight (31). Accelerator’s sensitivity was 20 mV/m/s. Experimental measurements were performed twice before launch, also twice during the flight (on days 3 and 5) and on days 1 and 4 post landing. The experimental protocol included BCG recording with the transducer attached to different parts of the body: the sternum, between the shoulder-blades, the waist, and the iliac crest. Records were made during quiet breathing and breath-holding. Records of signals from the transducer located between the shoulder-blades were published in (24, 31). Transducer location was changed to acquire records along different body axes. BCG was made in three transducer positions: 1) foot-to-head, 2) left-to-right, 3) ventro-dorsal. Figure 3 illustrates amplitude ratios for the H-I, I-J, J-K segments in all three crew members (C1, C2, C3) pre, in and after the flight. Individual differences can be assessed looking at the longitudinal records which were stable in one cosmonaut, increased in another and decreased in a third one (fig. 5).
Figure 5. Average amplitude of systolic segments of BCG (HI segment - top, IJ segment – middle, JK segment - bottom) during 3D registrations of three cosmonauts measured before, two times during the flight (day 3 and 5) and after the landing (in Soviet-Indian mission at Orbital Station Salyut-7).
OS Mir, expedition 6 in 1990. BCG investigations involved two members of that 179-day expedition. On April 10, the first spatial ballistocardiogram was acquired using a transducer made of three mutually perpendicular piezoelectric accelerometers (experiment VECTOR). Spatial BCG transducer was a cylindrical unit 40 mm in diameter and 20 mm in height. The transducer (35 mV/cm/s; 0.25-75 Hz; 40 g) was fixed between the shoulder-blades with a metal plate and elastic belt (fig. 6a). Additionally to the d-dimensional spatial BCG, ECG and SCG were recorded also (fig. 6b). To downlink the experimental data, a BCG amplifier (fig. 6c) had an interface with the standard medical monitoring system GAMMA.

Figure 6. Space experiment "Vector". Three-dimensional accelerometer sensor detecting the spatial BCG (a); chest belt with electrodes for electrocardiogram and sensor for seismocardiogramm (b); an additional block to the equipment "Gamma" (c).

Experimental sessions with the spatial BCG recording were performed on flight days 56 and 110. The protocol consisted of BCG recording at rest and during breath-holding. Results of those investigations have never been published and are presented in this paper for the first time. Figure 7 gives examples of spatial ballistocardiograms recorded during commander’s breathing cycle on flight day 56.
Figure 7. Examples of a 3D-BCG recording during inhalation and exhalation after 56th day staying in space during experiment “Vector” on board at the space station MIR by crew commander (CO) of the 6-th expedition.

Acceleration and force values on flight days 56 and 110 calculated from maximal I-J segments in three directions during expiration-holding are shown in figure 8. On flight day 56, the highest acceleration was measured in one cosmonaut along the head-to-foot axis and along the lateral axis in the other. The sum force vector was equal to 5.85 N and 10.18 N, respectively. The picture was found to be changed on flight day 110. The first increased acceleration and force up to 7.26 N. The second displayed the highest force and acceleration values along the head-to-foot axis and decreased force slightly along the lateral axis (down to 9.41 N).
Figure 8. Space experiment “Vector”. Change of acceleration (left) and force (right) defined from the IJ segment of the 3D-BCG of two cosmonauts in the foot to head direction (top), in the left to right direction (middle), and in the ventral-dorsal direction (bottom) after 56 days in space and after 110 days in space (CO and BE, MIR, expedition 6).

On flight day 110, the sum force vector was not changed significantly. This might be attributed to the fact that alterations in BCG form and amplitude, particularly along the lateral and ventrodorsal axes, could be linked with interventricular interactions or shift of the mechanic axis of the heart. The changes could be also produced by a temporary delay of opening and closure of the pulmonary and aortic valves which brings about differences in isovolumetric contraction as well as the right and left ventricular ejection time. Furthermore, change in blood volume in microgravity may influence venous heart filling same way as the positioning of abdominal organs and the diaphragm. This may alter the angle between the direction of left ventricular ejection and ascending aorta and thus lead to predominance of pulses along the lateral and ventrodorsal axes. One more explanation of the changes could be inequality of contraction activities of the right and left ventricles. Assuming that the right ventricle activity dominates in the lateral direction, the high BCG amplitude in the second cosmonaut on flight day 56 can be ascribed to still insufficient work of pulmonary circulation.
due to the massive blood shifting toward the upper body during early adaptation to microgravity. Difference in BCG lateral amplitudes of the cosmonauts is less noticeable on flight day 110. However, it should be pointed out that the form of BCG complexes has morphed significantly. For instance, in the second cosmonaut changes reached the second degree on the Braun scale.

International space station, experiment CARDIOVECTOR, 2014. Next step in the advancement of space BCG will be experiment CARDIOVECTOR planned for implementation on the ISS Russian segment in 2014-2016. In the future experiment ballistocardiogram will be recorded simultaneously along 6 axes, i.e., three linear and three rotation axes. Also registered will be ECG, SCG, impedance CG and pneumotachogram (fig. 9). Appearance of the device and placement of the transducers on human body are shown in figure 10. The spatial BCG transducer is fixed between the shoulder-blades using a special belt. Figure 11 presents several fragments of ballistocardiographic data recorded with device Cardiovector and an example of portraying spatial BCG phases along three linear axes.

To summarize, beginning from 1977, BCG investigations on the USSR and Russian orbital stations showed that BCG is a source of new knowledge about the microgravity effects on the cardiac activity. It has been demonstrated that microgravity alters the right/left heart ratio and that work of the ventricles can be measured quantitatively. The multiyear research led to the development of a substantiated program of fundamental investigations into the contractile function of the heart during space flight.
Figure 9. The sample of recordings of cardiological parameters with the help of onboard device “Cardiovector” (together with electrocardiogram (ECG), impedance cardiogram (ICG), and its first derivative, spatial ballistocardiogram with three linear axes (X, Y, Z), seismocardiogram (SCG) and pneumotahogram (PTG)).

Figure 10. Appearance of space device “Cardiovector”. Placement of sensors and electrodes on the subject (a); fixing the 3D BCG sensor (b).
The program was embodied in device Cardiovector enabling registration of body movements along 6 axes simultaneously with examination of the cardiac electrical activity and hemodynamics.

It is significant that acquisition of precise quantitative information on cardiac contractility in the environment that allows measure force without distortion may awake interest of terrestrial physiologists and physicians in ballistocardiography. We must learn how to measure and statistically validate true ballistocardiographic forces to use them as standards for investigations on the Earth. This knowledge can be gained only on the conditions ideal for ballistocardiogram recording, which are microgravity.

**Figure 11.** Spatial BCG: (a) the phase portraits of spatial ballistocardiogramm by three linear axes (X-Y, X-Z and Z-Y axes); (b) spatial vectorballistocardiogramm by three linear axes.
Conclusions

The ultimate goal of the proposed BCG investigations in microgravity is to provide an instrument of monitoring energy support of the cardiac function and predicting probable hemodynamic disorders in different periods of long-duration space flight. The energy aspect of BCG investigations applies only to assessment of the cardiac pump transporting blood within the vascular system. As for mechanisms of the myocardium energy supply and its functional reserve, these are issues belonging to the domain of molecular and cell physiology and biochemistry. However, BCG and seismocardiography must help construction of biophysical models representing translation of the general heart work into its external work. Pending is the problem of evaluating work loads on the left and right ventricles which is critical for controlling circulation adaptation to microgravity, estimating the level of pulmonary circulation relief imminent during space flight. It appears that in microgravity work of the cardiac ventricles is coordinated on a different pattern than on Earth and that intrasystemic hemodynamic relations also modify. Experiment CARDIOVECTOR onboard the ISS RS will fill the gaps in information gathered previously in experiment PNEUMOCARD. Anticipated data of precise cardiac contractions measurements in space microgravity using spatial ballistocardiography will contribute to construction of biomechanic and biophysical models of circulation in space that will find medical applications on the Earth, too.

Discussion and conclusions

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.
Author contributions
R.M.B., I.I.F., E.S.L. and J.T. prepared the manuscript and analyzed the data, J.T. drafted the manuscript. All authors read the ICMJE criteria for authorship and approved the final manuscript.

References


