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

Preliminary Results from Standing Ballistocardiography Measurements in Microgravity

Richard M. Wiard, *Member, IEEE*, Omer T. Inan, *Member, IEEE*, Laurent Giovangrandi, *Member, IEEE*, Charles Marsh Cuttino, *MD*, and Gregory T.A. Kovacs, *Fellow, IEEE*

Abstract—**We report on the feasibility of standing ballistocardiogram (BCG) measurements recorded in a microgravity environment. A clinically-tested BCG monitoring scale was adapted for parabolic flight for the microgravity measurements. Upon completion of this flight campaign, the BCG scale was shown to make measurements in micro-g and one-g environments—which is a first demonstration for a standing BCG system. This screening experiment demonstrated proof-of-concept attributes of the hardware design necessary for future characterization studies with multiple subjects. This scale-based BCG system is proposed as a practical device for hemodynamic monitoring for astronauts in Earth, Lunar, Martian, orbital, and interplanetary environments.**

Index terms—**Ballistocardiogram, noninvasive monitoring, astronaut health, microgravity hemodynamics**

I. Introduction

Astronauts on extended space missions live in environments where their cardiovascular systems can degrade, due to a lack of gravity. It is well-known that cardiovascular physiology changes in weightless environments and astronauts often return to one gravity (1g) with microgravity-induced hypovolemia, signaled by orthostatic intolerance and reduced maximal oxygen uptake (VO_2 max) [1, 2]. Furthermore, reductions in circulating blood volume, reduced red cell mass, cardiac atrophy, and a reduced cardiac output, and possible immune suppression are linked to prolonged exposure to weightlessness. New medical devices are needed to ensure that the cardiovascular system pumps and distributes blood in sufficient quantities to meet metabolic demands during both rest and physical exertion.

Ballistocardiography (BCG) is a noninvasive method used to measure hemodynamic forces produced by cardiac and cardiovascular-related movements of blood flow within the body. The general field of BCG was researched intensively from the 1940's to early 80's; the method faded away, and interest had reemerged in the mid-2000's [3]. Space-related BCG research began in 1964 with Hixson's microgravity experiments [4], and more recent experiments have been conducted using accelerometers placed on the body to measure the three-axis BCG (3D-BCG) in microgravity and dry-immersion test environments to establish the displacement vecto-ballistocardiogram (B3D Program) [5-8].

R.M. Wiard (rwiard@stanford.edu), O.T. Inan, and L. Giovangrandi are with the Electrical Engineering Department, Stanford University, Stanford, CA 94305 USA.
C.M. Cuttino, MD is with Orbital Medicine, Inc., Richmond, VA, USA.
G.T.A. Kovacs is with the Electrical Engineering Department and Department of Medicine, Stanford University, Stanford, CA 94305, USA.

To determine efficacy, space-based BCG recordings are subject to clinical validation against relevant cardiovascular measures (cardiac output, stroke volume, preejection period, etc.). Practical challenges exist to correlate space-based BCG device performance across large patient populations. As such, this paper describes a methodology with a future aim to correlate the standing microgravity BCG recordings to relevant cardiovascular parameters—using an earth-based BCG recording system that has undergone extensive human subject testing and characterization.

II. Methods

Human subject test protocols were approved by the institutional review boards (IRB) at NASA's Johnson Space Center (JSC) and Stanford University to record the BCG with multiple devices in 1g and microgravity (0g) environments.

A. Standing Ground-Based BCG Hardware

The reference (1g) BCG recorder is a modified electronic weighing scale that measures minute BCG forces, typically on the order of 1-3 Newtons [9]. This BCG scale has been previously characterized in subject populations for cardiac output change, preejection period, heart failure, cardiac resynchronization therapy, and athlete fitness [10-14]. From these studies, BCG timing and amplitude metrics have been derived from populations to establish normal ranges, as well as sensitivity to change within an individual subject. This BCG scale was used to establish a 1g cardiovascular baseline prior to parabolic flight.

B. Standing Microgravity-Based BCG Hardware

The BCG recording scale was modified for use in parabolic flight as the investigational device. A 2 x 2 ft. aluminum baseplate was bolted to the aircraft (Boeing 727-200, Zero Gravity Corporation, Vienna, VA) frame loosely and isolated from aircraft vibrations using viscoelastic dampers (Sorbothane Inc., Kent, OH), see Figure 1. The BCG scale was then secured to the baseplate with a stanchion/crossbar fixture used to preload the scale strain gauges. Foot straps with quick-releases were used to maintain firm contact between the subject's feet and scale.

C. Wearable Accelerometer BCG Hardware

A custom-designed wireless physiological monitor was used to record the electrocardiogram (ECG), the accelerometry BCG (accel-BCG) (P/N: LIS344ALH,

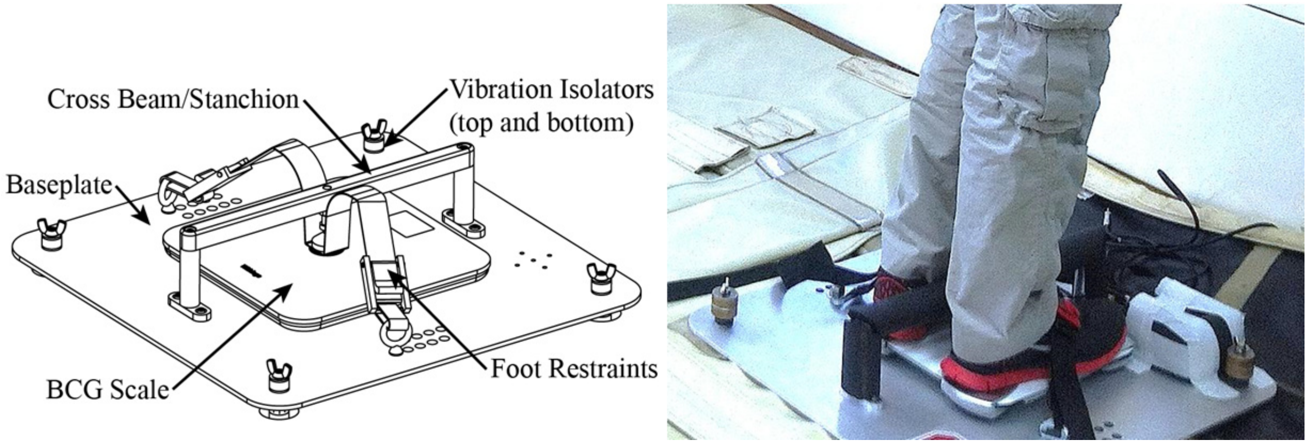

Fig. 1. Left, microgravity BCG scale setup comprised of baseplate, scale, cross beam/stanchion, and foot straps, secured to aircraft floor with four vibration isolators. Right, subject on experimental BCG setup in microgravity aircraft.

STMicroelectronics, Geneva, Switzerland), and an additional accelerometer used to measure the parabolic motion of the aircraft. The signals were acquired with a 10-bit analog-to-digital converter and streamed via Bluetooth (Shimmer Research, Dublin, Ireland) to a laptop computer for real time monitoring, data storage, and post-processing.

D. Study Details

Test subject selection was based on microgravity participation guidelines prescribed by NASA's Reduced Gravity Office (RGO) and the JSC-IRB. Pre-flight, baseline recordings were taken of the subject's ECG, scale BCG, and accel BCG. The accel BCG was taped securely to the lower lumbar region of the back. In-flight, subjects participated in two measurement setups (1) standing BCG measurements in microgravity (Fig. 2, left) and (2) free-floating BCG measurements (Fig. 2, right). Accel BCG and ECG were measured for all measurement setups. The data collection occurred during the reduced gravity portion of each parabolic maneuver, typically lasting 17 seconds.


Fig. 2. Left, standing BCG recordings in microgravity. Right, two free-floating accelerometry BCG test subjects.

E. Signal Processing

The ECG, standing BCG, and accelerometry BCG raw signals were sampled at 256 Hz and post-processed using MATLAB® (The MathWorks®, Natick, MA) with digital lowpass filters and ensemble averaging methods described in [9]. The RJ timing interval was then computed from the ensemble averaged signals, as well as BCG amplitude information.

III. Results

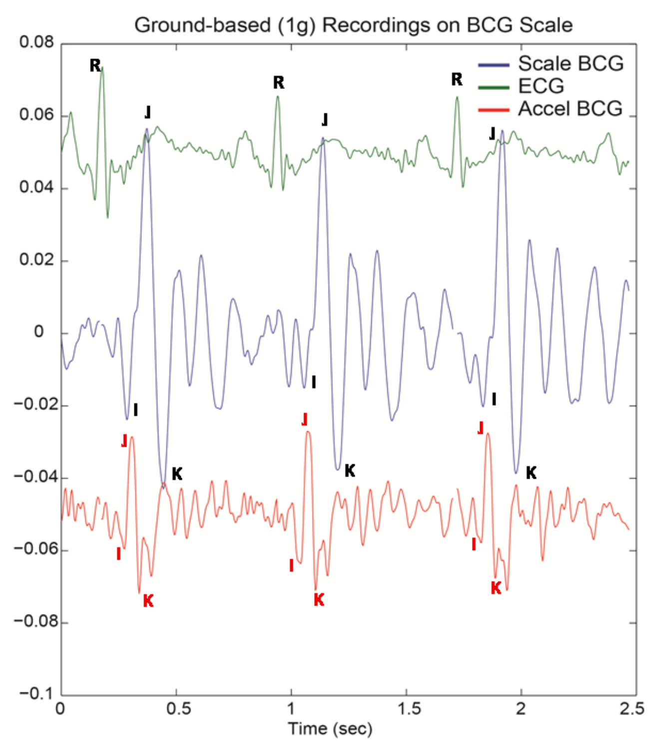

Fig. 3. Subject-matched example of 1g standing BCG measurements for scale-BCG (blue trace) and accel-BCG (red trace).

A. Exemplary Time Traces: Ground-Based Measurements

Exemplary time traces are depicted in Figure 3 for the ground-based (1g) measurements for one subject (51 year old, male). The ECG, scale BCG, and accel BCG were measured with good fidelity. The scale RJ interval was 191 ms and accel RJ interval was 133 ms. The relative scale IJ and JK amplitudes were 80 mV and 99 mV, respectively. The accel IJ and JK amplitudes were 31 mV and 43 mV, respectively. The HR was 76 bpm for 1g.

B. Exemplary Time Traces: Microgravity Measurements

For the same subject, time traces are depicted in Figure 4 for the microgravity-based (0g) measurements. The scale RJ interval was 200 ms and accel RJ interval was 246 ms. The relative scale IJ and JK amplitudes were 87 mV and 79 mV, respectively. The accel IJ and JK amplitudes were 46 mV and 84 mV, respectively. The HR was 50 bpm for 0g.

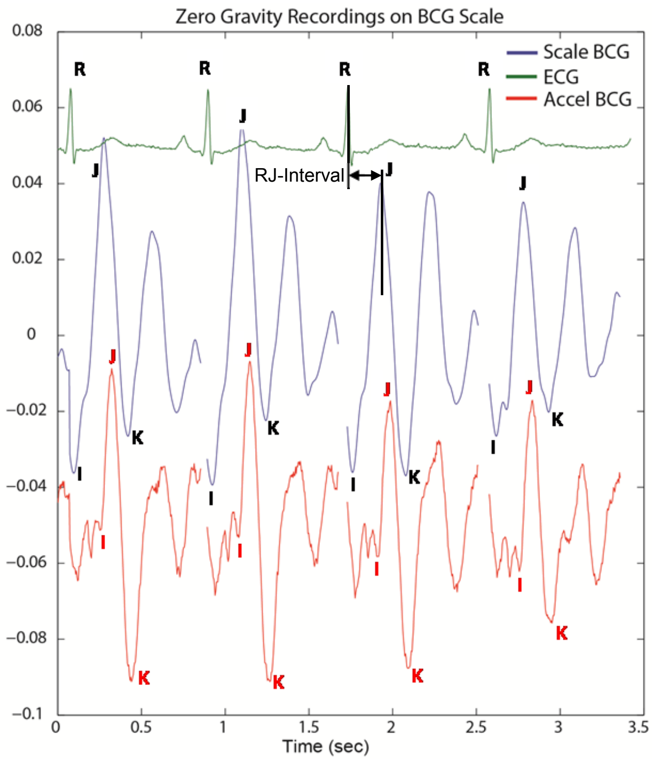

Fig. 4. Subject-matched example of 0g standing BCG measurements for scale-BCG (blue trace) and accel-BCG (red trace).

IV. Discussion and Future Work

A. Feasibility of Standing BCG Measurements in Microgravity

Due to the preliminary nature of the results, this paper focused only on feasibility of standing 0g BCG measurements. The standing BCG was successfully measured in microgravity to demonstrate proof-of-concept for the prototype scale hardware (Figure 2). The Sorbothane® isolators attenuated a majority of the aircraft vibrations, though not all. The residual aircraft vibrations present in the raw signals were removed digitally with moving ensemble averaging in order to show multiple beats. The standing 0g and 1g RJ-intervals were 200 ms and 191 ms for the exemplary case. The RJ-interval was characterized previously in clinical studies at Stanford University, and shown to occur on average at 211 ms ±20 ms for larger populations [9, 10]. Therefore, the standing 0g RJ-interval was found to occur within an expected range for healthy subjects. One of the noted challenges in data collection was with the original foot strap design, which loosened repeatedly early in the study as subjects laid down for the 2g pull-up maneuver. BCG signal quality increased after the foot restraint design was improved.

B. Displacement and Accelerometric BCG Sensing in Standing Measurements

The accel BCG was worn for the standing BCG measurements in 0g and 1g. Surprisingly, the accel BCG was measurable from the lower lumbar region in 1g while the subject stood on the scale (Figure 3). The standing RJ-intervals remained essentially unchanged between 0g and 1g, while unexpectedly, the accel RJ intervals changed significantly between 0g and 1g (246 ms versus 131 ms, respectively). The 0g measurements in Figure 4 show similar morphologies between scale and accel BCG measurements, while the 1g morphologies are notably different. Normally, the accel BCG is measured when the body is allowed to freely move; this standing 1g accel BCG measurement is uncommon.

The experiment highlights key differences in BCG sensor selection, test setup, and the interpretation of their records. Contrasted to accelerometry BCG, the scale BCG is a displacement measurement calibrated to force. Both measurement fall under the ultra-high frequency BCG classification [15]. While the scale RJ-interval remained consistent between 0g and 1g, there is no assignable cause yet for the large difference in accel RJ-intervals between 0g and 1g and further investigation is required.

The 3D-BCG works conducted to date for the B3D Program highlights the importance of understanding BCG forces in other axes, which may contain important physiological information correlating to curvature and torsion [5, 7, 8]. Both 3D and 1D techniques discussed in this paper show promise for using ballistocardiography as a clinical measure of cardiovascular conditioning in space for astronaut health.

C. Clinical Validation and Future Work

Proof-of-concept has been demonstrated to measure the standing BCG in reduced gravity while on a modified scale. For space applications, scale BCG recordings are anticipated to be of higher signal quality, since the parabolic aircraft used in this study contributed additional sources of vibrations—which was an extreme challenge condition. The microgravity BCG scale platform could be a practical noninvasive device to monitor cardiovascular adaptations in space. Two advantages of the scale BCG is that (1) measurements can be performed in rather tight quarters, whereas free-floating measurements require enough space so astronauts do not drift into objects or walls, and (2) scale BCG measurements would have more consistent signal-to-noise (SNR) performance in multi-g setting, such as Lunar and Martian environments—as the 1g BCG measurements in this study suggest. However, one potential drawback is that standing BCG measurements only provide one anatomical axis of information, compared to 3-axes using accelerometry [5].

In future work, standing BCG measurements can be characterized extensively on earth using normal and diseased populations and/or appropriate analogs such as head-down tilt tables to study cardiovascular deconditioning [16]. BCG timing and amplitude metrics could then correlated to relevant cardiovascular measurements such as cardiac output, stroke volume, preejection period, etc. as demonstrated previously [9-14]. Correlations and limits of detection can then be established to determine if scale BCG is sensitive enough to measure the deleterious effects of space on the cardiovascular system.

V. Conclusions

Feasibility was demonstrated for standing BCG measurements in microgravity, using a modified BCG scale. Upon completion of clinical characterizations, the standing BCG platform could be used in multi-g environments such as Lunar, Martian, and space station missions.

Acknowledgment

The authors thank Terry Lee and Dominic Del Rosso of the NASA Reduced Gravity Office and Dougal Maclise of the NASA Flight Opportunities Program for sponsoring this microgravity campaign (solicitation NOCT110).

References

[1] A. W. Kirkpatrick, M. R. Campbell, J. A. Jones, T. J. Broderick, C. G. Ball, P. B. McBeth, N. E. McSwain, D. R. Hamilton, and J. B. Holcomb, "Extraterrestrial hemorrhage control: Terrestrial developments in technique, technology, and philosophy with applicability to traumatic hemorrhage control in long-duration spaceflight," *Journal of the American College of Surgeons,* vol. 200, pp. 64-76, 2005.

[2] T. Heldt and R. G. Mark, "Understanding post-spaceflight orthostatic intolerance - a simulation study," presented at the Computers in Cardiology, 2005.

[3] L. Giovangrandi, O. T. Inan, R. M. Wiard, M. Etemadi, and G. T. A. Kovacs, "Ballistocardiography -- a method worth revisiting," *Proceedings of the IEEE Engineering in Medicine and Biology Society (EMBC), Boston,* pp. 4279-82, 2011.

[4] W. C. Hixson and D. E. Beischer, "Biotelemetry of the triaxial ballistocardiogram and electrocardiogram in a weightless environment. Monogr no. 10," *Research report. Naval School of Aviation Medicine,* pp. 1-112, 1964.

[5] G. K. Prisk, S. Verhaeghe, D. Padeken, H. Hamacher, and M. Paiva, "Three-dimensional ballistocardiography and respiratory motion in sustained microgravity," *Aviation space and environmental medicine,* vol. 72, p. 1067, 2001.

[6] S. De Ridder, P. F. Migeotte, X. Neyt, N. Pattyn, and G. K. Prisk, "Three-dimensional ballistocardiography in microgravity: A review of past research," presented at the Engineering in Medicine and Biology Society, Annual International Conference of the IEEE, 2011.

[7] P. F. Migeotte, J. Tank, N. Pattyn, I. Funtova, R. Baevsky, X. Neyt, and G. K. Prisk, "Three dimensional ballistocardiography: Methodology and results from microgravity and dry immersion," presented at the Engineering in Medicine and Biology Society, Annual International Conference of the IEEE, 2011.

[8] P. F. Migeotte, S. De Ridder, J. Tank, N. Pattyn, I. Funtova, R. Baevsky, X. Neyt, and G. K. Prisk, "Three dimensional ballisto- and seismo-cardiography: Hij wave amplitudes are poorly correlated to maximal systolic force vector," presented at the Engineering in Medicine and Biology Society, Annual International Conference of the IEEE, 2012.

[9] O. T. Inan, M. Etemadi, R. M. Wiard, L. Giovangrandi, and G. T. Kovacs, "Robust ballistocardiogram acquisition for home monitoring," *IOP Journal of Physiological Measurement,* vol. 30, pp. 169-185, 2009.

[10] O. Inan, M. Etemadi, R. Wiard, G. T. A. Kovacs, and L. Giovangrandi, "Non-invasive measurement of valsalva-induced hemodynamic changes on a bathroom scale ballistocardiograph," *IEEE Engineering in medicine and biology society conference proceedings,* vol. 2008, pp. 674-677, 2008.

[11] O. T. Inan, "Novel technologies for cardiovascular monitoring using ballistocardiography and electrocardiography," Ph.D Dissertation, Electrical Engineering, Stanford University, 2009.

[12] O. T. Inan, M. Etemadi, A. Paloma, L. Giovangrandi, and G. T. Kovacs, "Non-invasive cardiac output trending during exercise recovery on a bathroom-scale-based ballistocardiograph," *Physiological Measurement,* vol. 30, pp. 261-274, 2009.

[13] M. Etemadi, O. T. Inan, L. Giovangrandi, and G. T. A. Kovacs, "Rapid assessment of cardiac contractility on a home bathroom scale," *Information Technology in Biomedicine, IEEE Transactions on,* vol. 15, pp. 864-869, 2011.

[14] L. Giovangrandi, O. T. Inan, D. Banerjee, and G. T. A. Kovacs, "Preliminary results from bcg and ecg measurements in the heart failure clinic," in *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*, 2012, pp. 3780-3783.

[15] W. R. Scarborough, S. A. Talbot, J. R. Braunstein, M. B. Rappaport, W. Dock, W. F. Hamilton, J. E. Smith, J. L. Nickerson, and I. Starr, "Proposals for ballistocardiographic nomenclature and conventions: Revised and extended: Report of committee on ballistocardiographic terminology," *Circulation,* vol. 14, pp. 435-450, 1956.

[16] K. I. Iwasaki, R. Zhang, J. H. Zuckerman, J. A. Pawelczyk, and B. D. Levine, "Effect of head-down-tilt bed rest and hypovolemia on dynamic regulation of heart rate and blood pressure," *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology,* vol. 279, pp. R2189-99, 2000.