34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Recent Advances in Cardiovascular Monitoring Using Ballistocardiography

Omer T. Inan, *Member, IEEE*

Abstract— **Ballistocardiography (BCG) is a non-invasive method for monitoring cardiovascular health. While in the early 1900s, when it was invented, the BCG was intended to be a tool used exclusively in the clinic, the recent resurgence of BCG research has actually focused on *extra*-clinical applications ranging from home monitoring to measuring signals from astronauts in space. This repositioning of the diagnostic technique has largely been spurred by recent advances in measurement technology: historically, BCG instrumentation was large, cumbersome, and difficult to maintain; currently, it is small, easy-to-use, and does not require any sophisticated maintenance. This review presents the latest technological improvements in BCG instrumentation. These developments should further help to establish the BCG as a useful diagnostic tool in the coming years.**

I. INTRODUCTION

By the year 2030, the American Heart Association (AHA) estimates that 40% of the US population will have cardiovascular disease (CVD), 24M Americans will die from the disease each year, and the total costs of CVD will exceed $800B per year in the US [1]. These numbers reflect an unsustainable problem; an immediate need for technological developments directed at lowering the overall cost of cardiovascular care, increasing the availability of cardiovascular monitoring to large populations, and tailoring therapeutic interventions to individuals' requirements. Monitoring cardiovascular health outside of the clinic is as important and pressing a need now as it ever has been.

Because of recent research efforts, this need can be addressed by ballistocardiography (BCG), a tool that was invented in the mid-1900s [2] but refined only in the past decade by the research community to be well-suited for cardiovascular monitoring in the home. BCG measurement instrumentation has reformed from encumbering, specialized tables or beds to simple approaches utilizing weighing scales [3-5], chairs [6-7], bedposts / mattresses [8-10], or wearable systems [11-13].

This review very briefly introduces the history of BCG to put the current research in the context of the large body of work that was done in the first half of the 20th century, discusses recent technological advances in BCG measurement, and provides some guidance on future research that could solidify the resurgence of the BCG as a tool for monitoring cardiovascular health in the home.

II. BRIEF HISTORY OF BALLISTOCARDIOGRAPHY

The concept of a "BCG" dates back to the late 1800s, when Gordon first observed the following [14]:

> *A person standing erect in a perfectly easy posture on the bed of an ordinary spring weighing-machine, and maintaining, as far as possible, perfect stillness, will be found, if the instrument is delicately adjusted, to impart a rhythmic movement to the index, synchronous with the pulse…*

Inspired by Gordon, several researchers sought to take this scientific observation and develop techniques aimed at medical diagnostics.

In 1939, Starr, *et al.*, introduced a new tool that accomplished just this purpose [2]. Starr's group constructed a mechanical table with a steel spring opposing its lateral motion. The subject would lie supine, fixed to this table, and displacements were recorded mechanically. The signal measured on their innovative apparatus was named the ballistocardiogram (BCG), derived from the Greek words *ballein* (to throw), *kardia* (the heart), and *grafein* (to write).

Following this pioneering work, a multitude of studies were conducted using the BCG for the next few decades. Of these, there are several key findings that should be central in shaping our current efforts. The two most notable examples are: (1) Mandelbaum and Mandelbaum's study of post-myocardial infarction patients showed that improvements in BCG signal consistency over time were indicative of a recovering heart [15]; (2) Starr's long-term study of subjects over many decades demonstrated that a lower BCG amplitude in the first test meant a significantly higher incidence of heart attack and mortality later in life [16].

Unfortunately, in spite of these important findings, by the late 1960s and early 1970s, the scientific and medical communities had slowly diminished their interest in the signal as a clinical tool. The reasons for this declining sentiment were effectively summarized by Giovangrandi, *et al.*, as follows: lack of standardization, ambiguity regarding physiological origin, focus on diagnostics rather than trending, and the advent of echocardiography [17].

III. MODERN BCG INSTRUMENTATION

While some of these concerns still plague modern ballistocardiography, the focus of the field has shifted

---

O. T. Inan is with the Department of Electrical Engineering at Stanford University, Stanford, CA 94305 USA (phone: 650-723-5646, email: oeinan@gmail.com).

TABLE I
MODERN BCG SYSTEMS: KEY ACCOMPLISHMENTS AND FUTURE AIMS (IN ALPHABETICAL ORDER)

Modern BCG System	Measurement Axis	Key Advantages / Accomplishments	Challenges / Limitations
Accelerometer at Center of Mass [12]	3-Axis	- Characterized 3D BCG Vector - Measured 3D BCG in microgravity	- Need reduced gravity either in space or using dry immersion
Bed [8-10]	Longitudinal or Out-of-Plane	- Minimal motion artifacts (typically) - Can readily be integrated into home	- Changes in sleep position can affect signal quality and morphology - Difficult to pair BCG with other physiological measurements (e.g., ECG)
Chair [6-7]	Longitudinal or Out-of-Plane	- Minimal motion artifacts (typically) - Can readily be integrated into home	- Postural differences between measurements can affect signal integrity - Difficult to pair BCG with other physiological measurements (e.g., ECG)
Ear-Mounted Vital Signs Monitor [13]	Primarily Longitudinal	- ECG can be measured simultaneously - Miniature, potentially low-cost system	- Head position may affect signal integrity - Repeatability yet to be assessed
Weighing Scale [3-5]	Longitudinal	- Correlation to CO / contractility changes - Acquire multiple physiological signals in addition to the BCG	- Postural differences between measurements can affect signal integrity - Motion artifacts must be automatically detected and mitigated
MagIC Vest [11, 18]	Primarily Longitudinal	- Correlation to CO changes - Acquire multiple physiological signals in addition to the BCG	- Variations in signal based on sensor position - Motion artifacts must be automatically detected and mitigated

dramatically away from standard diagnostics and more towards analyzing changes in the same person's signal over time—trending. To this end, researchers have developed wearable measurement systems, systems embedded in a bed or chair, and systems using weighing scales. Table I summarizes the key accomplishments and limitations of modern BCG systems, shown in alphabetical order.

A. Wearable, Accelerometer-Based BCG Systems for Continuous Monitoring

Wearable BCG systems consist primarily of accelerometer-based approaches, where the sensor is affixed to the body either on the chest, the head, or the center-of-mass. Since the body recoils due to the heartbeat, this results in an acceleration that can be detected externally, as long as the sensor is rigidly coupled to the body. The advantages of these systems are in their simplicity, unobtrusiveness, and ability to continuously monitor the heart. The potential limitations of these systems are the positional variations of the signal (for example, the chest-based signal changes significantly on the sternum versus on the lower-left side of the chest) and motion artifacts.

Castiglioni, *et al.*, measured the vibrations of the chest using a three-axis accelerometer, and noticed that the lower frequency components (0.6-20 Hz) were related to the recoil of the body due to blood flow (BCG) and the higher frequency components (> 18 Hz) were derived from the heart sounds (seismocardiogram, or SCG) [11]. Furthermore, they found that the changes in the I-J amplitude of the BCG component after exercise were similar to the changes in cardiac output as measured by Finometer (Finapres Medical Systems, Amsterdam, The Netherlands).

This effort was continued by Di Rienzo, *et al.,* with the integration of the three-axis accelerometer into their MagIC system—a textile vest for measuring physiological parameters in daily life [18]. With this system, they measured the BCG outside of the laboratory and demonstrated that the signal could be measured repeatedly over the course of a prolonged recording.

A different wearable system designed for continuous monitoring was developed by He, *et al.,* with the placement of a three-axis accelerometer on the head of the subject at the ear [13]. Together with the R-wave peak of the simultaneously-measured electrocardiogram (ECG), they showed that the peak of this "Head-BCG" could be used to estimate changes in contractility: the changes in the R-J interval of the BCG were correlated to changes in the pre-ejection period (PEP) caused by Valsalva maneuver and tilt tests.

Migeotte, *et al.*, affixed a three-axis accelerometer to the center-of-mass (COM) of a subject to measure the three-dimensional BCG in microgravity [12]. By allowing the subject to float freely for the measurement, all three vector components of the BCG were accurately acquired, and a vector-BCG was analyzed. This approach may elucidate the physiological origin of the waveform components present in the longitudinal signal.

B. Bed or Chair-Based BCG Systems

Bed-based BCG systems typically target sleep studies or monitoring vital signs in bedridden patients. The measurement modality of these systems is most similar to the original BCG systems, which were based on beds or tables. Chair-based systems are useful for non-ambulatory patients, or patients who cannot stand still on their own. The advantages of both bed and chair based systems are the reduction of motion artifact, the comfort of the user, and the ability to readily integrate the systems into the home. Some potential limitations are postural effects on the signal integrity, the difficulty of pairing the measured BCG signal with other physiological measurements such as ECG without comprising the unobtrusiveness, and—in the case of the chair-based measurements—reduced signal amplitude. An additional technical limitation may be the unintended mixture of longitudinal and transverse BCG components, rather than the ability to effectively isolate one or the other.

Chung, *et al.,* installed load cells under the feet of a bed to measure heart rate while the subject was sleeping using the BCG—their overall aim was to detect wakefulness without the need for electrodes attached to the body [8]. It should be noted that the measured BCG was not along the longitudinal axis of the body, since the load cells measured the displacements of the body out of the plane of the bed, rather than in line with the plane as with the more traditional BCG measurement methods.

A similar approach was developed by Bruser, *et al.*: these authors connected four strain gauges in a Wheatstone bridge configuration under one slat of the bed, and detected the BCG out of the plane of the bed [10]. With the use of an elegant beat-detection algorithm, this work demonstrated that greater than 95% coverage for heartbeat detection could be achieved with the BCG signal for 16 subjects. Shin, *et al.*, also demonstrated accurate heartbeat detection using the BCG measured from a patient in bed—however, their approached involved an air mattress with balancing tube and a differential pressure sensor [19].

Paalasmaa demonstrated a unique approach to bed-based BCG monitoring: by using a custom-designed bedpost vibration sensor sensitive to shear forces, he was able to measure the longitudinal BCG from subjects lying in bed [9]. Furthermore, Paalasmaa designed a latent-variable based approach for quantifying the respiratory changes in the BCG signal. This algorithm could help improve heartbeat detection, as well as elucidate the physiological reasons for respiratory effects on the BCG for future studies.

Chair-based approaches have been developed for both longitudinal and out-of-plane BCG measurement by several groups, primarily using electromechanical film (EMFi) sensors. Koivistoinen, *et al.,* outfitted the seat of a chair with EMFi sensors and measured BCG signals from two seated subjects. Signals were measured from only two subjects, but they were found to be visually similar to BCG signals from the existing literature. Walter, *et al.,* outfitted the seat cushion of the driver's seat in a car with an EMFi mat to measure the BCG [20]. They aimed to use the information from the BCG for automatically monitoring driver fitness in the elderly population. However, with the engine turned on, the authors found that the BCG signal was too corrupted by vibration artifacts for the measured BCG to be usable. It should be noted that approaches using adaptive signal processing are available for potentially reducing such vibration noise, and could be employed in future implementations [21].

C. *Weighing-Scale Based BCG Measurement*

BCG measurement on electronic weighing scale was first discovered by Williams, of Linear Technology Corporation (Milpitas, CA) [4]. He was developing an ultra-precise electronic scale, when he realized that the "noise" in his signal was in fact synchronized to the standing subject's heartbeat, and was a BCG. After exercise, the amplitude of the signal would increase compared to its baseline value. The advantages of this form of BCG measurement are the day-to-day repeatability of the measurements, the prevalence of the weighing scale in the home, and the fact that the weighing scale is already used for heart failure patients to monitor their fluid status changes at home. The potential disadvantages are the presence of motion artifacts (since the subject is standing for the duration of the measurement), changes in the signal caused by postural variations, and the practical limitation on measurement duration (the subject can only stand still for so long).

In 2009, our group demonstrated that BCG measurement on a weighing scale was, in fact, robust and repeatable [3]. We found that the signal quality was high enough such that the effects of ectopic beats—in particular, premature ventricular contractions (PVCs) and premature atrial contractions (PACs)—could be observed. Furthermore, we showed that changes in the BCG signal measured on the scale were correlated to changes in cardiac output measured by Doppler echocardiography for subjects recovering from exercise [22]. Recently, Shin, *et al.*, used a weighing-scale based BCG system to analyze heart rate variability following a Valsalva maneuver and exercise [5], further demonstrating that the signal quality was sufficient for automatic heartbeat detection and analysis.

IV. CONCLUSION

Modern BCG instrumentation accomplishes many things that the previous century's predecessors could not. Markedly, the systems are much less obtrusive and can be deployed outside of the clinic—in the home, in the car, even in space. In addition to these instrumentation advances discussed here, modern techniques have also employed novel signal processing algorithms for improving BCG signal-to-noise ratio (SNR) [21, 23], automatically detecting BCG features such as heart rate [10, 24], and modeling the BCG signal [9, 25]. Continued innovation in both of these engineering areas—instrumentation and signal processing—is necessary for the BCG to become a useful clinical tool.

Furthermore, for the BCG to be widely adopted as a tool for medical monitoring, more clinical validation is required. BCG systems must be demonstrated to be effective in improving outcomes, reducing hospitalizations, providing early warning of disease, etc. This will require the medical community to grant ballistocardiography a second chance, and to develop strong collaborations with engineers to use BCG hardware in clinical trials with focused objectives. It will be important in establishing such collaboration that the BCG is not seen, or proposed, as an alternative to echocardiography, electrocardiography, or other already-accepted techniques—rather, the BCG can complement the information obtained by these measurements, providing a more complete assessment of the patient's overall health.

ACKNOWLEDGMENT

I thank Dr. G. T. A. Kovacs (Stanford University) for his insight and guidance, and Dr. L. Giovangrandi (Stanford University), R. M. Wiard (Stanford University) and M. Etemadi (University of California, San Francisco) for their helpful discussions on the subject.

REFERENCES

[1] P. A. Heidenreich, J. G. Trogdon, O. A. Khavjou, J. Butler, K. Dracup, M. D. Ezekowitz, E. A. Finkelstein, Y. Hong, S. C. Johnston, A. Khera, D. M. Lloyd-Jones, S. A. Nelson, G. Nichol, D. Orenstein, P. W. F. Wilson, and Y. J. Woo, "Forecasting the future of cardiovascular disease in the United States: A Policy Statement from the American Heart Association," *Circ*, v. 123, pp. 933-944, 2011.

[2] I. Starr, A. J. Rawson, H. A. Schroeder, and N. R. Joseph, "Studies on the Estimation of Cardiac Output in Man, and of Abnormalities in Cardiac Function, from the Heart's Recoil, and the Blood's Impacts; The Ballistocardiogram," *Am. J. Physiol.*, v. 127, no. 1, pp. 1-28, 1939.

[3] O. T. Inan, M. Etemadi, R. M. Wiard, L. Giovangrandi, and G. T. A. Kovacs, "Robust Ballistocardiogram Acquisition for Home Monitoring," *IOP Physiol. Meas.*, v. 30, no. 2, pp. 169-185, 2009.

[4] J. Williams, "Bridge circuits: marrying gain with balance," *Application Note 43*, Linear Technology Corporation, Milpitas, CA, 1990.

[5] J. H. Shin, S. H. Hwang, M. H. Chang, and K. S. Park, "Heart Rate Variability Analysis Using a Ballistocardiogram During Valsalva Maneoevre and Post Exercise," *IOP Phys. Meas.*, v. 32, no. 7, pp. 1239-1264, 2011.

[6] T. Koivistoinen, S. Junnila, A. Varri, and T. Koobi, "A New Method for Measuring the Ballistocardiogram using EMFi Sensors in a Normal Chair," *Proc. of the 26th Annual Int'l. Conf. of the IEEE EMBS,* San Francisco, CA, 2004.

[7] O. Postolache, P. S. Girao, G. Postolache, and M. Pereira, "Vital Signs Monitoring System Based on EMFi Sensors and Wavelet Analysis," *IEEE IMTC*, Warsaw, Poland, 2007.

[8] G. S. Chung, J. S. Lee, S. H. Hwang, Y. K. Lim, D.-U. Jeong, and K. S. Park, "Wakefulness Estimation Only Using Ballistocardiogram: Nonintrusive Method for Sleep Monitoring," *Proc. of the 32nd Annual Int'l. Conf. of the IEEE EMBS,* Buenos Aires, Argentina, 2010.

[9] J. Paalasmaa, "A Respiratory Latent Variable Model for Mechanically Measured Heartbeats," *IOP Phys. Meas.*, v. 31, no. 10, pp. 1331-1344, 2010.

[10] C. Bruser, K. Stadlthanner, S. de Waele, and S. Leonhardt, "Adaptive Beat-to-Beat Heart Rate Estimation in Ballistocardiograms," *IEEE Trans. Inf. Tech. in Biomed.*, v. 15, no. 5, 2011.

[11] P. Castiglioni, A. Faini, G. Parati, and M. Di Rienzo, "Wearable Seismocardiography," *Proc. of the 29th Annual Int'l. Conf. of the IEEE EMBS,* Lyon, France, 2007.

[12] 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," *Proc. of the 33rd Annual Int'l. Conf. of the IEEE EMBS,* Boston, MA, 2011.

[13] D. D. He, E. S. Winokur, and C. G. Sodini, "A Continuous, Wearable, and Wireless Heart Monitor using Head Ballistocardiogram (BCG) and Head Electrocardiogram (ECG)," *Proc. of the 33rd Annual Int'l. Conf. of the IEEE EMBS,* Boston, MA, 2011.

[14] J. W. Gordon, "On Certain Molar Movements of the Human Body Produced by the Circulation of the Blood," *J. Am. Physiol.*, v. 11, pp. 533-536, 1877.

[15] H. Mandelbaum and R. A. Mandelbaum, "Studies Utilizing the Portable Electromagnetic Ballistocardiograph: IV. The Clinical Significance of Serial Ballistocardiograms following Acute Myocardial Infarction," *Circ.,* v. 7, pp. 910-915, 1953.

[16] I. Starr and F. C. Wood, "Twenty-Year Studies with the Ballistocardiograph: The Relation between the Amplitude of the First Record of 'Healthy' Adults and Eventual Mortality and Morbidity from Heart Disease," *Circ.*, v. 23, pp. 714-732, 1961.

[17] L. Giovangrandi, O. T. Inan, R. M. Wiard, M. Etemadi, and G. T. A. Kovacs, "Ballistocardiography—A Method Worth Revisiting," *Proc. of the 33rd Annual Int'l. Conf. of the IEEE EMBS*, Boston, MA, 2011.

[18] M. Di Rienzo, P. Meriggi, F. Rizzo, E. Vaini, A. Faini, G. Merati, G. Parati, and P. Castiglioni, "A Wearable System for the Seismocardiogram Assessment in Daily Life Conditions," *Proc. of the 33rd Annual Int'l. Conf. of the IEEE EMBS,* Bostom, MA, 2011.

[19] J. H. Shin, Y. J. Chee, D.-U. Jeong, and K. S. Park, "Nonconstrained Sleep Monitoring System and Algorithms Using Air-Mattress With Balancing Tube Method," *IEEE Trans. Inf. Tech. in Biomed.,* v. 14, no. 1, pp. 147-156, 2010.

[20] M. Walter, B. Eilebrecht, T. Wartzek, and S. Leonhardt, "The Smart Car Seat: Personalized Monitoring of Vital Signs in Automotive Applications," *Pers. Ubiq. Comput.*, v. 15, pp. 707-715, 2011.

[21] O. T. Inan, M. Etemadi, B. Widrow, and G. T. A. Kovacs, "Adaptive Cancellation of Floor Vibrations in Standing Ballistocardiogram Measurements Using a Seismic Sensor as a Noise Reference," *IEEE Trans. Biomed. Eng.*, v. 57, no. 3, pp. 722-727, 2010.

[22] O. T. Inan, M. Etemadi, A. Paloma, L. Giovangrandi, and G. T. A. Kovacs, "Non-Invasive Cardiac Output Trending During Exercise Recovery on a Bathroom-Scale-Based Ballistocardiograph," *IOP Phys. Meas.*, v. 30, no. 3, pp. 261-274, 2009.

[23] R. M. Wiard, O. T. Inan, B. Argyres, M. Etemadi, G. T. A. Kovacs, and L. Giovangrandi, "Automatic Detection of Motion Artifacts in the Ballistocardiogram Measured on a Modified Bathroom Scale," *Med. Biol. Eng. Comput.*, v. 49, no. 2, pp. 213-220, 2011.

[24] D. C. Mack, J. T. Patrie, P. M. Suratt, R. A. Felder, and M. Alwan, "Development and Preliminary Validation of Heart Rate and Breathing Rate Detection Using a Passive, Ballistocardiogram-Based Sleep Monitoring System," *IEEE Trans. Inf. Tech. in Biomed.*, v. 13, no. 1, pp. 111-120, 2009.

[25] R. M. Wiard, H. J. Kim, C. A. Figueroa, G. T. A. Kovacs, C. A. Taylor, and L. Giovangrandi, "Estimation of Central Aortic Forces in the Ballistocardiogram under Rest and Exercise Conditions," *Proc. of the 31st Annual Int'l. Conf. of the IEEE EMBS,* Minneapolis, MN, 2009.