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Preliminary Results from BCG and ECG Measurements in the Heart Failure Clinic

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***Abstract*—We report on the preliminary deployment of a bathroom scale-based ballistocardiogram (BCG) system for the in-hospital monitoring of patients with heart failure. These early trials provided valuable insights into the challenges and opportunities for such monitoring. In particular, the need for robust algorithms and adapted BCG metric is suggested. The system was designed to be robust and user-friendly, with dual ballistocardiogram (BCG) and electrocardiogram (ECG) capabilities. The BCG was measured from a modified bathroom scale, while the ECG (used as timing reference) was measured using dry handlebar electrodes. The signal conditioning and digitization circuits were USB-powered, and data acquisition performed using a netbook. Four patients with a NYHA class III at admission were measured daily for the duration of their treatment at Stanford hospital. A measure of BCG quality, in essence a quantitative implementation of the BCG classes originally defined in the 1950s, is proposed as a practical parameter.**

***Index Terms*—Ballistocardiogram, cardiovascular monitoring, non-invasive monitoring, heart failure**

I. Introduction

Heart failure (HF) claims hundreds of thousands of American lives each year. An estimated 5,000,000 Americans suffer from the disease, and in the elderly population nearly one in 100 are afflicted. It is also estimated that 70% of all costs generated by HF patients are due to hospitalization [1]. In an era where reduction of costs is a requirement for the sustainability of the health care system, novel approaches that can improve the quality of care and ultimately reduce hospital visits have to be considered. Home monitoring of HF patients is one of these approaches, one which is in fact supported by an increasing number of studies for its ability to reduce hospitalization rates (see for instance [2]).

Ballistocardiography (BCG), the measure of the hemodynamic forces imparted by the pulsatile blood flow on the body, is shaping up as an attractive monitoring method, as it provides, non-invasively, valuable information on the hemodynamics and heart function [3, 4]. In particular, our group developed a bathroom scale-based ballistocardiogram system that is ideally suited for home use [5], and could be seamlessly integrated with the current standard of care for HF management at home – weight monitoring.

However, many questions remain about the practicality of this modality for HF monitoring, notably with respect to the quality of data collected from such populations, as well as the specificity and the sensitivity of the information content. Early work has shown that absolute measurements were typically not reliable, especially when applied to diseased populations [4]. For instance, cardiac output calculated from BCG features was shown to be underestimated in patients with aortic insufficiency, compared to healthy subjects [6]. However, the few longitudinal studies available offer more positive prospects. Notably, Mandelbaum measured the BCG of one hundred recovering heart attack patients during clinic visits over 18 months [7]. He concluded that the BCG, and more specifically the quality of the BCG, as graded in four classes first introduced by Brown [8], was a valuable prognostic indicator of functional recovery.

In an attempt to start addressing these questions, we sought to first collect data from HF patients in a controlled hospital setting. Rather than monitoring decompensation at home for many weeks, such a setting offers the chance to monitor over a short period of time (a week or less) the likely improvements brought by treatment. This paper reports on early observations from a small first group of patients.

II. Methods

A. Ballistocardiogram System

The BCG component of the system was based on a modified bathroom scale (InnerScan BC-534, Tanita, Tokyo, Japan). The original strain gauges were re-connected in a Wheatstone bridge configuration similar to a previously-reported implementation [9]. The bridge was powered with +5V and its output interfaced to a single-supply differential amplifier circuit (84 dB gain, 0.1-20 Hz bandwidth).

B. Dry-electrode Electrocardiogram System

A simple two-electrode system using a handlebar with large metal contacts was chosen for convenience. The primary function of the ECG was to provide a timing reference for the heart beat, and the minor distortions associated with dry electrodes were thus acceptable, especially considering the ease-of-use of a handlebar compared to conventional gel electrodes.

The ECG circuit used was a single-supply adaptation of a previously-published circuit [9]. Briefly, this ECG circuit used a transimpedance amplifier as the front-end, with active

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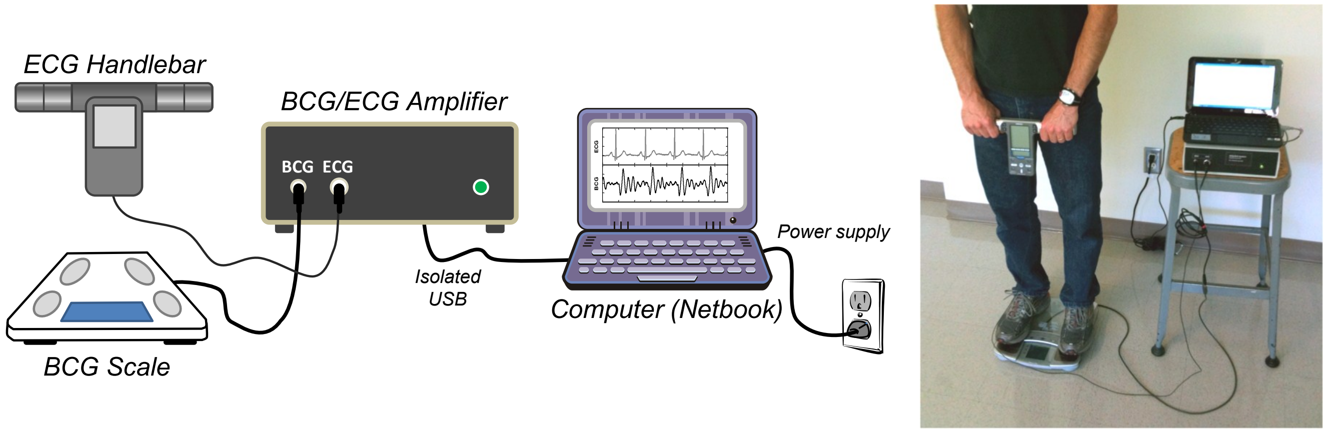

Figure 1. Left: illustration of the BCG/ECG system deployed in clinic. The signal conditioning box is powered through the isolated USB. Right: picture of the whole system, with a test subject standing on the BCG scale and holding the two-electrode, handlebar ECG.

current feedback to one of the electrodes to force the input common-mode voltage to stay within the voltage rails; bandwidth was 0.5-100 Hz. This configuration provided good quality ECG in most circumstances due to a high CMRR, even with only two contacts on the body.

C. *System Integration*

The overall system was designed for convenience and safety. The amplified BCG and ECG signals were digitized by a low-cost USB-based analog acquisition module (NI DAQ-6009, National Instruments, Austin, TX). The same acquisition module also provided power (+5V) for both signal conditioning circuits. This resulted in a compact, self-powered USB-based BCG/ECG system. A medical-grade USB isolator (ISOUSB-hvc, IFTOOLS, Germany) was used to ensure complete electrical isolation (power and data) for the safety of the patient. A small netbook running custom Matlab®-based acquisition software was finally used as a visualization and data logging tool (Fig. 1).

C. *Signal Processing*

Due the presence of a large amount of noise in the recorded BCG, and the reduced signal level given the patient population, ensemble averaging techniques were necessary to recover the underlying signal. First, ECG R waves were extracted using a simple peak detection algorithm, followed by visual inspection and manual correction if necessary. An ensemble median (more robust to large artifacts than average) was then computed from the segmented BCG beats over the entire record (30s). Peak-to-peak amplitudes and rms power was then extracted from this median beat, as well as timings between R waves and BCG waves. A novel metric quantifying the consistency of the signal within a recording, and by extension the consistency of the mechanical action of the heart, has also been defined. This consistency metric is analogous to a signal-to-noise ratio (SNR). To compute this metric, the recording is split into three consecutive subgroups of eight beats. Ensemble medians were computed for each of these three subgroups. The consistency was defined as the inverse of the averaged ratio (over the three subgroups) of the variance of the noise (sample-wise difference between the subgroup ensemble median and the whole-recording ensemble median) and the variance of the signal (whole-recording ensemble median).

E. *Human Protocol*

This study was approved by the Stanford IRB under protocol #10342. Four patients with heart failure (three male, one female, average age of 57) were referred by their treating physician following their admission to the cardiology clinic. Following proper consent, two 30s recording separated by about 2 minutes were taken, once a day for the rest of their stay at the clinic. The times of the measurements were not strictly controlled (dependent on patient schedule). In one case (#9001), the patient was re-admitted three weeks after his first stay, and measured again at that time. In another case (#9004), the patient was readmitted a month later for implantation of a left-ventricular assist device (LVAD - HeartMate II from Thoratec Corp., Pleasanton, CA), after which a measurement was also taken. Upon completion of the data collection, data from this study were compared with the clinical data available throughout their treatment (weight, cardiac output, cardiac pressures, various biochemical markers, NYHA class). However, due to the non-interfering nature of this preliminary study, these clinical data were typically spotty.

III. Results

A. *Data Collection in Clinical Environment*

Data were collected on the four patients for a period between four and eight days, depending on the duration of their stays. User acceptance was very good, as the measurements only took a few minutes, and did not require any specific preparation or cumbersome procedure. BCG quality was generally poor compared to typical signals from a healthy population. Multiple factors influenced this quality, both extrinsic and intrinsic. Patients were minimally coached (resulting in occasional jerks, head movements), and generally weak due to their conditions (reduced balance). These extrinsic factors resulted in uncorrelated noise that could be reduced through ensemble averaging methods. Intrinsic factors include the lower BCG signal sometimes associated with compromised hemodynamics. However,

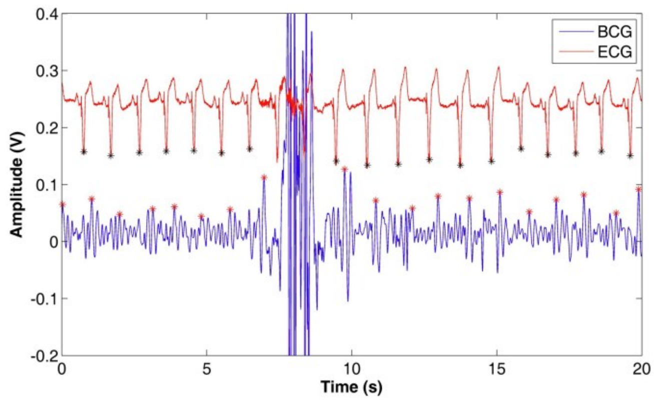

Figure 2. Example of typical ECG and BCG signals. Note the rather low quality of the raw BCG. The large spike in the middle of the recording was a movement artifact.

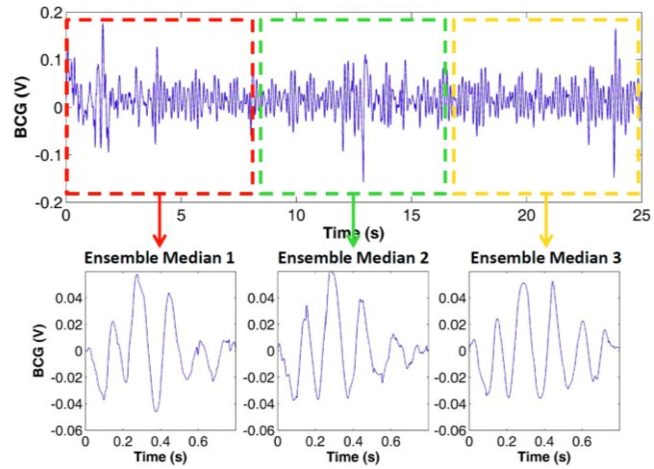

Figure 3. Illustration of the segmented ensemble medians (EM) used for calculating the signal consistency (or SNR) metric. See text for details.

ensemble averages (or medians, as used here) were always able to retrieve the underlying BCG structure, as shown in Fig. 2 and 3. The waveforms were more oscillatory in nature, making wave interpretation and quantification less reliable.

B. Ballistocardiogram Monitoring of HF Treatment

Analysis of the amplitudes, power and timings of ensemble medians for each day did not reveal noticeable trends over the course of the patients' stay. Based on prior work [10, 11], a change in amplitude or power would be interpreted as a change in cardiac output (or stroke volume). While the lack of clear trends in BCG amplitude may be due in fact to a lack of significant change in those parameters, the absence of consistent controls during this preliminary study prevents such a conclusion. Indeed, no patient had two measurements of cardiac output or stroke volume using the same method (echocardiography or thermo dilution) during their stay. Other clinical data routinely measured, such as blood pressure, heart rate, weight, or creatinine levels, did not correlate with BCG amplitudes/power or timings either. Of interest, weight steadily decreased in three out of the four patients (#9002 remained constant) under the action of diuretics.

In light of these inconclusive results, yet consistent improvement of the patients as noted by the care takers (and of the patient themselves), we looked at the consistency of the mechanical action of the heart based on the SNR metric. The SNR improved for three out of the four patients, while remaining unchanged for the fourth (#9002). Comparing with the broad and somewhat subjective metric of NYHA class, three out of four patients were class III at admission (data missing for #9004). All three were class II at the time of their

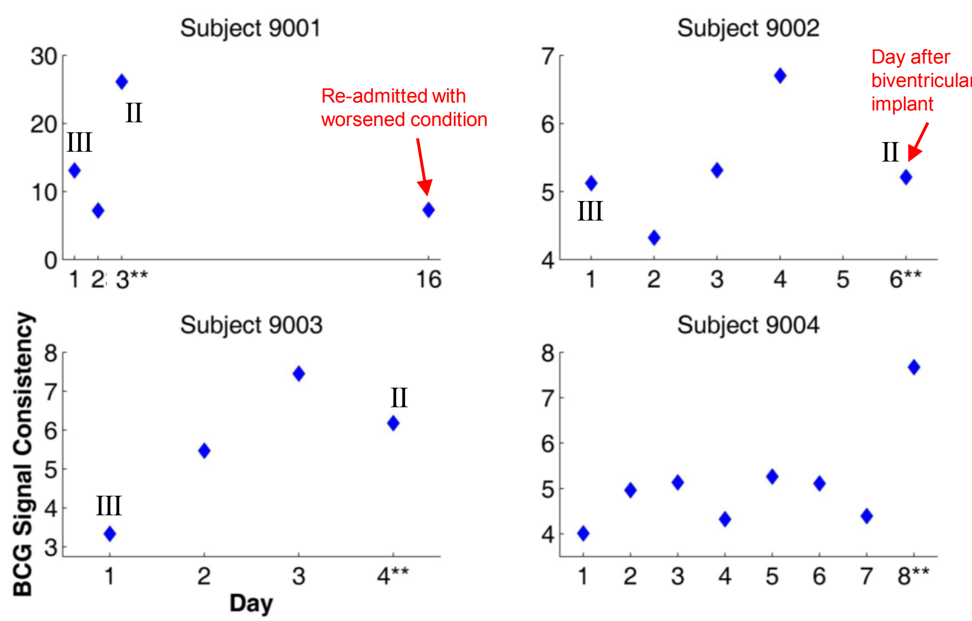

Figure 4. BCG consistency index (as quantified by the SNR) for each of the four patients, throughout their stay. Major events are specifically labeled. Note how the indices generally improve over the stay, and reflects NHYA classes at admission and discharge. No NYHA class data was available for #9004. ** indicates day of release.

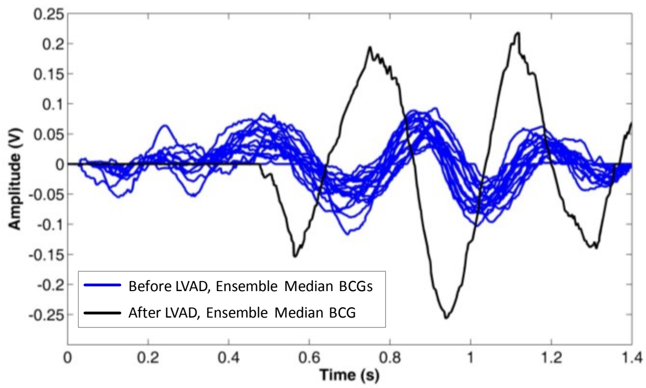

Figure 5. BCG of a patient with a LVAD, pre- (16 recordings over 8 days) and post-implantation.

discharge (Fig. 4). Patient #9002, who showed no change in SNR, received a bi-ventricular pacemaker the day before his discharge, and had a significantly faster heart rate post-implantation (95 bpm vs. 75 bpm pre-implantation). It is unclear at this time how these variables may affect this metric. Of particular interest - patient #9001 was later re-admitted as NYHA class III again, which was reflected by the same low SNR presented at his first admission.

C. Impact of LVAD on Ballistocardiogram

Patient #9004 was followed for eight days before being discharged. He then returned to the clinic to have an LVAD implanted. Fig. 5 shows the ensemble median for 16 recordings (two per day, eight days) prior to LVAD implantation, and the ensemble median for the recording two weeks post-implantation. A significant increase in amplitude can be observed.

IV. Discussion

This paper reports on early observations of practical use of a bathroom scale-based BCG system in a hospital setting for the monitoring of patients with cardiac heart failure. We believe that these observations, albeit preliminary, highlight some key opportunities (as well as challenges) of such monitoring, and thus might benefit the BCG community.

An expected result was the large amount of noise in the raw BCG associated with these patients. The standing position on the scale is obviously a contributing factor, compared to bed systems used in most of the earlier work. However, the use of ensemble averaging techniques appears very effective at extracting the underlying structure of the BCG beat, as can be noted by the surprisingly similar BCG shape over 8 days for patient #9004 (Fig. 5). This is particularly encouraging considering the relatively short duration of recordings (30s).

Regarding the value of conventional BCG parameters, such as wave amplitudes, power, or timings for assessing patient condition, the present observations remain largely inconclusive, due to the paucity of reference data to correlate with (we did not requested any exams that were not treatment-driven). One noteworthy data point was the lack of correlation with weight, which supports the BCG as an orthogonal measurement ('dry axis') to weight ('wet axis').

While conventional BCG features also did not show any significant trend following the overall improvement of the patients as characterized by their NYHA class, the consistency metric introduced here showed promising results. While preliminary, these results appear consistent with earlier reports which used the subjective grade (class I through IV) metric introduced by Brown [7, 8]. Further studies with this quantitative measure of signal quality are certainly warranted.

Finally, the first BCG measurements of a patient with a LVAD were presented. With the complexity of the hemodynamics resulting from such a pulse-less LVAD [12], it is premature to interpret the resulting BCG, but it does demonstrate its ability to detect associated hemodynamic changes. Specific studies, possibly with concurrent Doppler flow measurements, will be necessary to use these results.

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