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Noninvasive cardiovascular monitoring based on electrocardiography and ballistocardiography: a feasibility study on patients in the surgical intensive care unit

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***Abstract*— The time interval between the peaks in the electroccardiogram (ECG) and ballistocardiogram (BCG) waveforms, TEB, has been associated with the pre-ejection period (PEP), which is an important marker of ventricular contractility. However, the applicability of BCG-related markers in clinical practice is limited by the difficulty to obtain a replicable and consistent signal on patients. In this study, we test the feasibility of BCG measurements within a complex clinical setting, by means of an accelerometer under the head pillow of patients admitted to the Surgical Intensive Care Unit (SICU). The proposed technique proved capable of capturing TEB based on the R peaks in the ECG and the BCG in its head-to-toe and dorso- ventral directions. TEB detection was found to be consistent and repeatable both in healthy individuals and SICU patients over multiple data acquisition sessions. This work provides a promising starting point to investigate how TEB changes may relate to the patients' complex health conditions and give additional clinical insight into their care needs.**

I. INTRODUCTION

Electrocardiography and ballistocardiography are noninvasive monitoring techniques that capture different aspects of cardiovascular function. The electrocardiogram (ECG) is generated by electrical changes due to the periodic depolarization/repolarization of the cardiac muscle at each heartbeat. Therefore, the ECG captures the electrical activity of the heart and is typically measured using electrodes placed on the skin. The ballistocardiogram (BCG) is generated by the repetitive motion of the center of mass of the human body as blood moves within the circulatory system at each heartbeat [1]. The BCG captures the mechanical and fluid-dynamical properties of the cardiovascular system as a whole and can be measured via multiple sensing modalities, e.g., bed sensors [2], [3], chair sensors [4], load cells [5], electromechanical film under the mattress [6] and weighing scales [7], [8].

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The time interval between the peaks in the ECG and BCG waveforms (TEB) has been associated with relevant cardiovascular markers, thereby yielding great potential for noninvasive monitoring of cardiovascular function. For example, TEB was found to be associated with the time between ventricular contraction and aortic valve opening, also known as pre-ejection period (PEP) [9]–[11]. PEP can be obtained via echocardiography and impedance cardiography and is considered as an index of ventricular contractility [12].

One of the main challenges in the clinical use of BCG is the difficulty in obtaining repeatable and consistent signals outside cohorts of healthy individuals evaluated in controlled laboratory conditions [13]. In this study, we test the feasibility of BCG measurements on critically ill patients admitted to the surgical intensive care unit (SICU). The ECG is acquired via a three-lead system while the BCG is acquired via an accelerometer placed under the head pillow. Based on [9]–[11], we focus on TEB as a feature of clinical relevance and we show that TEB measurements obtained with the proposed sensing modality are consistent and repeatable both in the case of healthy individuals and SICU patients.

II. METHODS

A. Data Acquisition

This study has been conducted in the SICU of the University Hospital - MU Health Care (Columbia, MO) directed by Dr. Ahmad. The study protocol, approved by the Institutional Review Board (IRB-2029122), did not interfere with the position of the patient, the inclination of the SICU bed and the regular activity of the clinical staff. This data collection mode fits the reality of a critical care environment, such as that of SICU, and adds value to the proposed method.

A total of 6 SICU patients and 2 healthy individuals were recruited for the study (see Table I). Inclusion criteria for the recruitment of SICU patients include surgical critical illness that requires hemodynamic monitoring and active resuscitative interventions to optimize cardiovascular performance in the correction of oxygen debt. Exclusion criteria include pediatric and pregnant patients and those being cared for by a medical intensive care team. An AD Instruments PowerLab Data Acquisition system was utilized to acquire simultaneously signals from a three-lead ECG and a three-axis accelerometer positioned under the head pillow (BCG

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signal) at the rate of 200 samples per second. The orientation of the three-axis accelerometer is shown in Fig. 1, with the x, y and z axes representing the shoulder-to-shoulder, head-to-toe and the dorso-ventral directions, respectively.

TABLE I

PARTICIPANT DETAILS

Subject	Gender	Age	Height (cm)	Weight (kg)
1	Male	38	179	78.0
2	Male	44	162	88.4
3	Male	79	172	65.5
4	Female	33	157	60.0
5	Female	68	175	70.0
6	Female	41	157	136.0
1-H	Male	26	177	89.0
2-H	Male	58	174	92.0

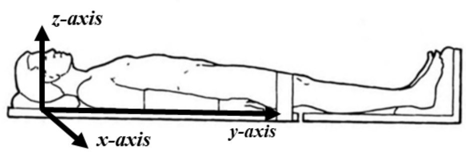

Fig. 1. Orientation of the 3-axis accelerometer positioned under the head pillow utilized for BCG acquisition.

Healthy individuals were awake laying supine on a vacant SICU bed. The SICU patients were sedated and mechanically ventilated with an arterial catheter used for hemodynamic monitoring using the Flotrac^{TM} device (Edwards Life Sciences, Irvine, CA). Sensor recordings were performed while they were immobile to avoid motion artifact. The position of the patient on the bed as well as the inclination angle of the head of the bed were annotated, as they may have differed depending on the specific patient conditions (Table. I). For each subject, data were acquired continuously for at least 2 minutes. Data acquisition was repeated for each subject at least 3 times with intervals of approximately 10 minutes.

B. Data Processing

A 6^{th} order Butterworth bandpass filter that performs a zero-phase filtering was applied to the ECG signal (cutoff frequencies: 0.7 and 40 Hz) and to the BCG signal (cut-off frequencies: 0.7 and 20 Hz) to remove high-frequency noise and low-frequency respiratory variations. The Signal-to-Noise Ratio (SNR) was computed for each of the three directions in the BCG signal as the variance of the band-pasS signal over the variance of the high pass filtered noise. The SNR values over all acquisition sessions and all study participants were found to be $\text{SNR}_x = 1.0 \pm 0.7$, $\text{SNR}_y = 2.6 \pm 2.0$, $\text{SNR}_z = 7.9 \pm 4.5$. This result shows that the head-to-toe (y) and dorso-ventral (z) directions contain the strongest portion of the signal, which is consistent with [7]. Given that different inclinations of the SICU bed may redistribute the BCG signal in the y and z directions in different ways, and different inclinations may be required by different patients depending on their conditions (see Table I), we combine the BCG signals along the prominent axes into a single quantity, henceforth referred to as *normed BCG* (nBCG) defined as:

$$\text{nBCG} = \sqrt{\text{BCG}_y^2 + \text{BCG}_z^2} \quad (1)$$

where BCG_y and BCG_z represent the filtered BCG signals in the y and z directions. A 2^{nd} degree polynomial regression was used to smooth the computed nBCG signal. The R peaks in the ECG were detected by using the standard Pan-Tompkins algorithm [14]. As a result, for each acquisition session we obtain a sequence of time instants t_j, with $j = 1, \ldots, N$, at which R peaks occur. Next, for each time interval (t_j, t_{j+1}), with $j = 1, \ldots, N-1$, the time at which the nBCG attains its maximum is detected and denoted by τ_j. Finally, the TEB for that session is defined as the sequence $\text{TEB}_j = \tau_j - t_j$ of the time distances between the R peaks in the ECG and the maxima in the nBCG.

III. RESULTS

The methodology for signal processing is illustrated on a healthy individual (Subject 2-H) and a SICU patient (Subject 3) in Figs. 2 and 3. Fig. 2 reports a 5 second sample of the filtered three-axis BCG signal, along with an annotation of the time instants at which the R peaks in the ECG occur (vertical dashed lines). The dorso-ventral signal (z) for the healthy individual exhibits a clear periodic pattern characterized by prominent peaks in the systolic part of the cardiac cycle. In the case of the SICU patient, the distance between R peaks is drastically reduced and the pattern in the BCG signal is more irregular.

Fig. 3 shows the nBCG signal before smoothing (black curve) and after smoothing (blue curve) for the same subjects and the same 5 second window considered in Fig. 2, along with the R peak annotations (vertical dashed lines). The maxima of the nBCG signal are also reported (red crosses) and the TEB is computed as the time distance between each nBCG maximum and the preceding R peak. These results show that the proposed methodology for signal acquisition and processing enables TEB detection for both the healthy individual and the SICU subject.

The boxplots in Fig. 4 show the distributions of the TEB values over 1 minute for the three sessions of data acquisition on the same study subjects considered above (Subject 2-H and Subject 3). The red line within each box represents the median, whereas the upper and lower limits of the blue-lined boxes represent the 75^{th} and 25^{th} percentile, respectively. Outliers (blue circles) are identified by setting a maximum whisker length of 1 s. The results show that the values of the TEB medians are consistent for a given subject and reproducible over different sessions both in the case of a healthy individual (Subject 2-H) and a SICU patient (Subject 3). Interestingly, the TEB distribution on the healthy individual appears to be narrower than that of the SICU patient, who exhibits a wider distribution and more outliers.

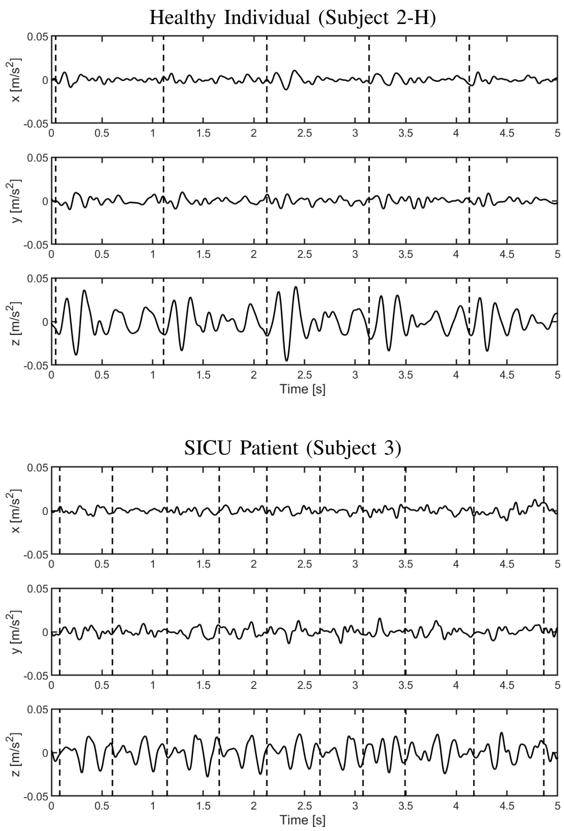

Fig. 2. Three-axis filtered BCG signals for a healthy individual (Subject 2-H) and a SICU patient (Subject 3). The time locations of the R peaks in the ECG are also annotated (vertical dashed lines).

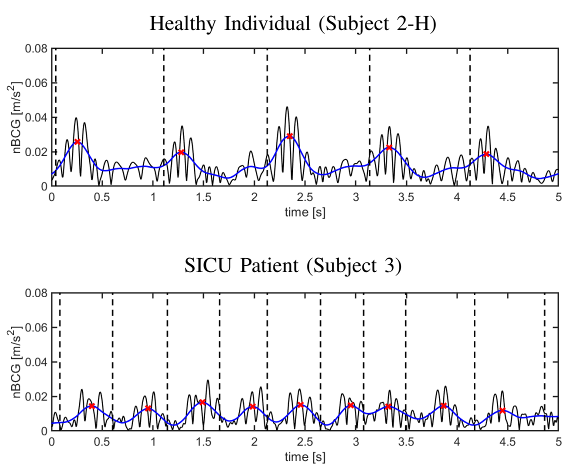

Fig. 3. nBCG before smooothing (black) and after smoothing (blue) for a healthy individual (Subject 2-H) and a SICU patient (Subject 3)

So far, the data acquired on Subjects 2-H and Subject 3 have been used to illustrate the proposed methodology for TEB detection. The results obtained for all subjects during 1 minute windows over three sessions of data acquisition are reported in Table II. In each table cell, the 25^{th} and 75^{th} percentiles are reported in italics below the median value. Results show that the median values of TEB are consistent for a given subject over multiple sessions. Remarkably, this holds true both in the case of healthy individuals and SICU patients.

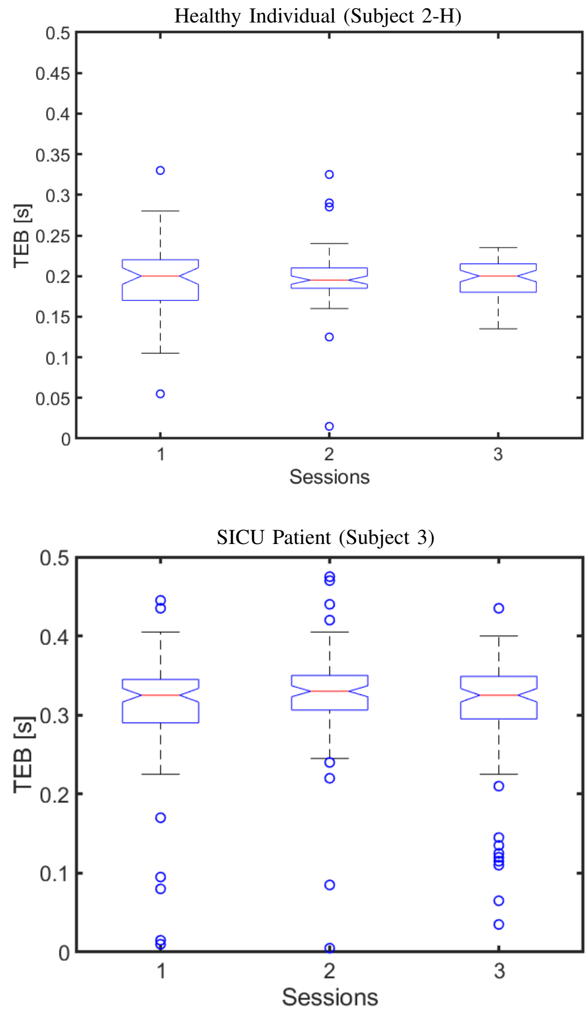

Fig. 4. Repeatability of TEB acquisition over three sessions on a healthy individual (Subject 2-H) and a SICU patient (Subject 3). Red lines indicate the median values, whereas the upper and lower box limits report the 75^{th} and 25^{th} percentiles. Outliers (blue circles) are defined by setting the whisker length (dashed lines) to include the maximum extension of datapoints that are not considered outliers by the algorithm.

The case of Subject 4 is particularly interesting, since the position on the bed of this SICU patient was different in the three sessions. Specifically, the patient was tilted to the left in Session 1, to the right in Session 2 and to the center in Session 3. Fig. 5 reports the boxplots pertaining to each session and shows how the detected TEB median is robust with respect to the patient placement on the bed.

IV. DISCUSSION AND CONCLUSIONS

This study proposes a noninvasive technique based on a three-axis accelerometer placed under the head pillow to acquire the BCG signal. A signal processing approach is developed to capture the time interval between the maximum of the BCG, based on its head-to-toe and dorso-ventral components, and the R peaks in the ECG. This time interval, referred to as TEB, was found by other studies to be

TABLE II

MEDIAN, 25^{th} AND 75^{th} PERCENTILES FOR THE TEB VALUES FOR EACH SUBJECT OVER 1 MINUTE WINDOW IN 3 ACQUISITION SESSIONS

	TEB [s]		
Subject	**Session 1**	**Session 2**	**Session 3**
1	0.338 *0.320-0.380*	0.350 *0.330-0.369*	0.335 *0.315-0.370*
2	0.180 *0.159-0.221*	0.150 *0.120-0.183*	0.165 *0.135-0.205*
3	0.310 *0.275-0.335*	0.325 *0.296-0.350*	0.325 *0.295-0.346*
4	0.190 *0.180-0.210*	0.190 *0.170-0.210*	0.195 *0.173-0.230*
5	0.160 *0.145-0.175*	0.170 *0.150-0.195*	0.210 *0.180-0.255*
6	0.245 *0.235-0.250*	0.245 *0.230-0.253*	0.243 *0.230-0.250*
1-H	0.178 *0.140-0.225*	0.238 *0.163-0.293*	0.243 *0.230-0.250*
2-H	0.205 *0.186-0.220*	0.195 *0.185-0.210*	0.195 *0.180-0.215*

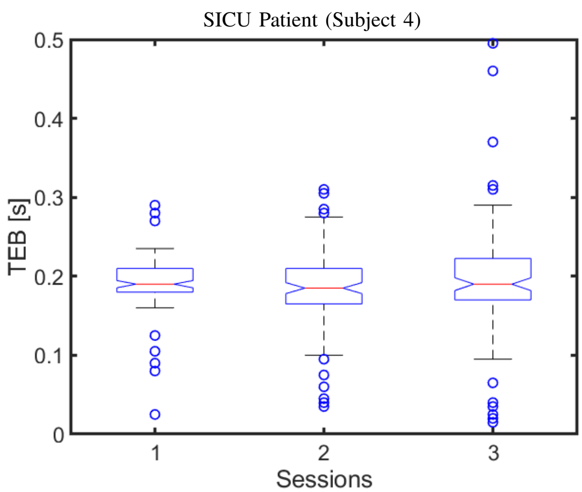

Fig. 5. Box plot of the TEB detection for a SICU patient (Subject 4) whose position on the bed changed over the three sessions (Session 1: left Session 2: Right; Session 3: Center).

associated with the pre-ejection period (PEP) [9]–[11], which is an important marker for ventricular contractility.

This study shows that the proposed methodology for TEB detection provides consistent results both on healthy individuals and SICU patients evaluated over multiple sessions. The method appeared to be robust with respect to the position of the patient on the bed (see Fig. 5), thereby yielding potential for patient monitoring in a critical care environment. We note that the TEB values may also be influenced by the bed inclination, which was not the same among all the study participants as their clinical conditions were different. Interestingly, though, while the bed inclination might have influenced the absolute TEB values, it did not affect the reproducibility of the results (see Table II). Future studies will be conducted to investigate potential associations between changes in TEB and changes in the patients' health conditions, as suggested by previous experimental and theoretical works [9]–[11], [15]. Furthermore, to strengthen the validity of the result of this study, more SICU subjects will be recruited and an animal study will be conducted to enlarge the dataset. A direct correlation between echocardiography and ECG-BCG measurements will be further investigated to assess ventricular contractility.

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