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Ballistocardiography with fiber optic sensor in headrest position: a feasibility study and a new processing algorithm

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Abstract—**Ballistocardiography (BCG) is a promising unobtrusive method for home e-healthcare systems, and has attracted increasing interest in recent years along with technological advances in related biomedical, electrical engineering and computer science fields. While existing systems have investigated the efficacy of BCG setups in bed, backrest, seat or scale positions, we propose to study BCG in headrest position that will allow new practical and portable applications. To this end, we designed and implemented a multi-modality sensing system including a high-sensitivity microbend fiber optic BCG sensor. In this preliminary study, we have collected multi-modality physiological data on 3 human subjects. We ran extensive analysis on BCG in correlation with ECG, and identified special characteristics of the signal in the new BCG setup. The result suggests that new appropriate computing techniques are necessary for accurately recovering the heart beat signal. Therefore, we developed a novel algorithm for heart beat detection. We evaluate the algorithm with the data and demonstrate that it can accurately compute heart rate intervals in the headrest BCG despite significant signal distortion.**

I. Introduction

Ballistocardiography (BCG) is one of the cardiological examination methods that, particularly, provides a representation of heart-beat induced repetitive movements of the human body during cardiac cycles [1]. It can be a favorable method for home e-healthcare solutions, mainly because it can assess the cardiac and respiratory physiological signatures in an unobtrusive manner [2], [3] as opposed to obtrusive or intrusive manners in other methods.

Recent developments in related electrical engineering fields have enabled a variety of BCG modalities using charge-sensitive devices [4], electromechanical film devices[5], fiber optic devices[6], and Doppler radar technology[7]. For example in [6], the authors reported a highly sensitive microbend fiber sensor embedded in a cushion that produces waveforms well corrected with simultaneously recorded photoplethysmograph signals.

Conventionally, BCG sensors acquire mechanical movement information from locations in bed [2], [8], backrest [6], seat [9], or weighing scale [3]. However, few studies have addressed BCG sensing in headrest position. On one hand, headrest position e.g. in pillows allows a more portable and economic solution as opposed to bulky bed sensors. Furthermore, human body's position in a bed can be less variable with respect to the pillow, thus potentially allowing a more consistent way of measuring BCG. On the other hand, because the head is not a rigid part of the body and the mechanical propagation of movement from heart to head can be rather complex, the headrest BCG may be largely different from conventional BCG. This raises a critical question whether it is feasible to recover cardiac signal from such BCG.

To the best of our knowledge, this is the first study that rigorously addresses this open question on headrest BCG. Particularly, we developed from [6] a microbend BCG sensor embedded in a headrest, and conducted extensive study involving 3 healthy subjects seated in a comfortable massage chair, while physiological data were being recorded using a multi-modality sensing platform including the BCG sensor, galvanic skin response sensor and polysomnography device for electrocardiogram (ECG), pulse oximetry and respiratory airflow monitoring.

With the headrest BCG and ECG data, we ran extensive analysis and identified the special temporal and spectral characteristics of the signal in the new BCG setup. The result suggests that new appropriate computing technique is necessary in order to accurately recover the heart beat signal. Therefore, we developed a novel algorithm for heart beat detection. We evaluated the algorithm with the data and demonstrate that it can accurately detect heart beats and matches ECG in heart rate estimate (e.g. with sub-0.4 beat-per-minute accuracy in 2-minute average).

The rest of the paper is organized as follows. Section II describes the system setup and the data collection procedure. Section III presents our analysis of temporal and spectral characteristics of the headrest BCG signal. Section IV describes our new processing algorithm for heart rate detection for the new BCI modality, and also evaluates its effectiveness. Section V concludes the report.

II. System setup and data collection

Fig. 1 illustrates the basic setup of the experiment system. The system integrated a redeveloped fiber optic sensor from [6]. The fiber sensor was chosen because it is lightweight, low-cost, chemically inert and inherently immune from electromagnetic interference. Particularly, a fiber sensor with a thickness less than 2mm was put into a headrest cushion that measured approximately 25 cm by 35 cm. The sensor was

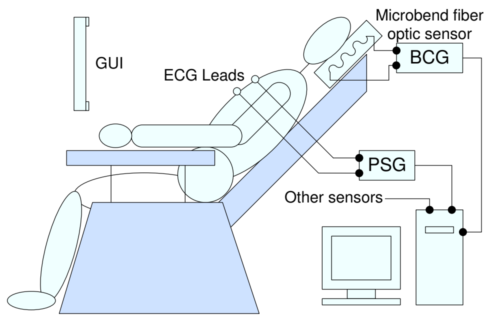

Fig. 1. System Diagram for Experiment, with microbend fiber optic BCG at headrest position.

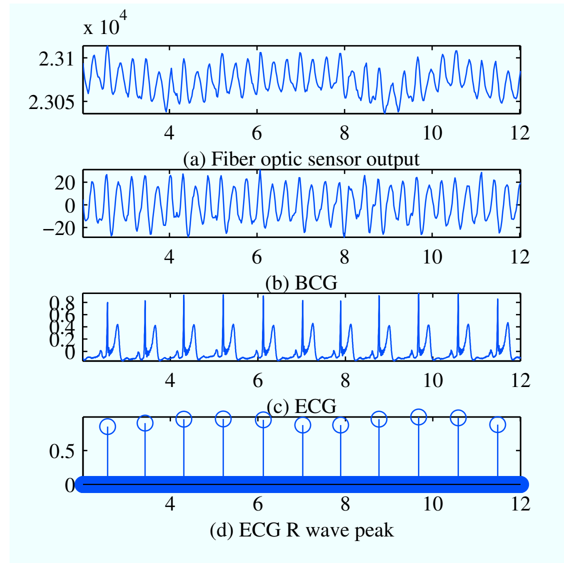

Fig. 2. Comparative waveforms in headrest BCG sensor and ECG. Horizontal axis denotes frequency in Hz, vertical axis is the time in seconds.

connected to a transceiver which consisted of a light source, a light detector, a microprocessor and auxiliary electronic circuits. The transceiver digitized BCG measurement at 50Hz with 16bit resolution, and communicated with the computer via a USB-serial link. A low-pass filter at 250Hz was also implemented in the transceiver.

Electrocardiogram (ECG) was acquired using a 24-bit polysomnography amplifer from Compumedics at a sampling rate of 512 Hz. Two surface ECG electrodes were placed: one about 3-5 cm below the right clavicle and the other on the 6th or 7th left intercostal space, as recommended in the American Academy of Sleep Medicine manual [10].

We also had other sensors integrated such as Galvanic skin response sensor and EEG. But they are not directly relevant to this particular study.

A. *Human subjects and data acquisition protocol*

We recruited 3 healthy adult volunteering subjects. Consent forms were obtained before data collection, and the study has been approved by the Institutional Review Board of University of Singapore.

In data collection, we instructed the subjects to complete a predefined series of tasks: 2 minutes rest, a battery of cognitive tests, 2 minutes rest, approximately 10 minutes massage session for relaxation, and 2 minutes rest. In this headrest BCG feasibility study, we consider the rest periods only.

III. Temporal and Spectral Analysis of Headrest BCG

The signal collected through the fiber optic sensor can pick up subtle movement signal of the subjects head due to breathing, heart beats and body movements. In this study, we focus on signals collected when movement artifact is minimal, i.e. when the subject was resting still with head leaning against the headrest cushion. Fig 2.(a) illustrates an example of raw signal from the sensor. In this subfigure, the signal that reflects breathing is of relatively low frequency (e.g. 1 breathing cycle is from time 4-9 seconds). As a traditional method, a band-pass filter is used to remove the breathing component and the BCG is obtained as shown in Fig 2.(b). Unlike in conventional BCG, specific waveforms (such as I, J, K and etc waves) are hardly distinguishable. Nevertheless, the R wave in ECG (Fig. 2.(c)) may still be identified in BCG if the corresponding peak component can be detected. Fig 2.(d) shows an example of the detected R waves in ECG.

We conducted temporal-spectral analysis of the BCG in conjunction with ECG to investigate how the major frequency components in BCG correlate to ECG. We computed spectrograms using a 15-second short-time-window on both BCG and ECG, and illustrate here a typical example in Fig. 3. In this plot, the horizontal axis is the frequency in Hz, and the vertical axis is the time in seconds. The total duration of BCG/ECG recording in this example is about 400 seconds. From ECG spectrogram, it can be seen that the frequency component with larger values around 1 Hz is primarily from heart beating. Also, a number of harmonics with lower values can also be observed. In the BCG spectrogram, however, the only dominant frequency component that can be identified is in between 3-4 Hz, which actually corresponds to the third harmonic of the heart beat.

IV. The Proposed Heart Rate Estimation Method and Evaluation

A. *Robust algorithm for heart beat detection*

The schematic chart of the heart rate estimation method is shown in Fig 4. The method consists of the following steps: first, the above-mentioned band-pass filter is used to eliminate the majority of breathing artifacts in BCG; in the screen analysis step, the harmonic structure in the frequency domain of BCG is identified, such that the signal of the analysis window is considered with heart rate signal but without major interfering artifacts; in the cleaning step, the BCG signal of a short window is cleaned by removing all frequency components other than the dominant third harmonics; in the

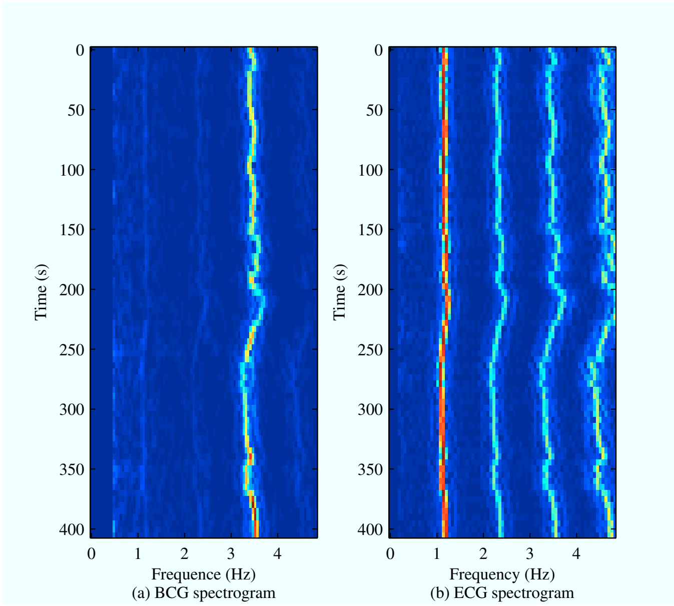

Fig. 3. Comparative spectrogram of headrest BCG vs ECG

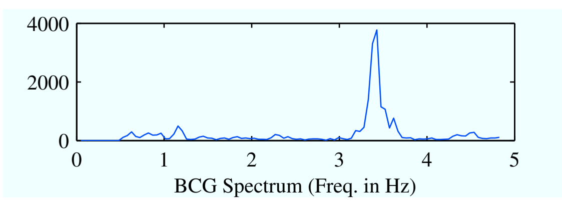

Fig. 5. An example of headrest BCG spectrum.

final step, heart rate is estimated based on the detected peaks in the cleaned BCG.

1) Windowing: In the proposed method, the BCG is analyzed continuously using shifting windows. A screening analysis window is applied using a longer duration (15 seconds in our experiments) such that sufficient amount of information of harmonic structure in the signal is captured. The cleaning window is of shorter period (5 seconds in our experiment), such that heart rate variability information would not be screened out. The step size (3 seconds) of sliding the windows can be even shorter than the cleaning analysis window, so that overlapping of the consecutive windows could avoid the boundary effects of the processing.

2) Signal screening analysis: The BCG signal in the screening analysis window is transformed to frequency domain by using discrete Fourier transform (DFT) with Hanning window. The dominant peak of the target third harmonic is detected in the power spectrum. Based on the detected peak, the corresponding fundamental frequency (of 1/3 frequency) is verified by identifying the local peak of the frequency. Fig. 5 below shows a typical example of data, in which the harmonic component is of frequency about 3.5 Hz and the fundamental frequency is about 1.2 Hz. Note that we tentatively consider the target heart rate range between 40-150 BPM.

If the harmonic structure is not detected, the BCG signal is considered of low quality. The low quality signal may be due to body movement artifacts or unfavorable contact between head and the sensor cushion. In such cases, the signal is rejected.

3) Signal cleaning processing: In this step, the BCG in the cleaning window is transformed to frequency domain using DFT and only a narrow frequency band centered at the dominant frequency (as detected in the screening step) is kept before transforming the signal back to time domain by using inverse DFT. By applying the cleaning processing, both the irrelevant lower and higher frequency components are removed from the signal, and as a result, the peak detection in the waveform can be more accurate.

4) Heart rate estimation: In the fiber optical BCG sensor output, negative values represent larger forces of the head pressing against the cushion. The negative peaks are detected in the cleaned BCG signal by using a basic local minimal value detection algorithm. Based on our harmonic analysis above, we suppose that each heart beat corresponds to 3 peak-to-peak intervals, the heart beat duration for any measurement moment can be estimated by the 3 overlapping full heart beat cycles. In our method, heart rate or heart beat duration is estimated in sub-beat resolution.

B. Evaluation results

The performance of the heart rate estimation method is evaluated in comparison with the heart rate derived from ECG. The heart rate from ECG is computed at each R wave moment by measuring the R-R intervals between this R wave and its previous R wave. For any time point between two consecutive R waves, the instantaneous heart rate value is linearly interpolated on the values of the two R waves. This allows us to build a ground truth of heart rate at arbitrary time points.

Fig. 6 shows the BCG-derived estimation result in (a) and the ECG-derived ground truth in (b). The estimation error curve is plotted in (c). We also computed smoothed heart rate curve using a 15-second averaging window, and the result in the form of the estimation error is shown in (d).

Finally, we investigate if our algorithm can be used to accurately estimate the heart beat rate. Using the detected heart beats, we computed the average heart beat rate in each of the three 2-minute rest periods, for each subject respectively. The results are summarized and compared with ECG-based estimate in Table I. It can be seen that the headrest BCG-based estimate precisely matches that from ECG, while the error is below 0.4 beat-per-minute in all the test cases.

We also observed relatively higher estimation error for shorter measurement period (e.g. beat- or second- level). There can be multiple reasons. First we would like to note that the current experimental system setup has only sup-second level synchronization between BCG and ECG data sampling/acquisition. Second, it is possible that heart beat takes time to transmit from heart to a specific location, yielding a delay variable between each BCG and ECG (actually this

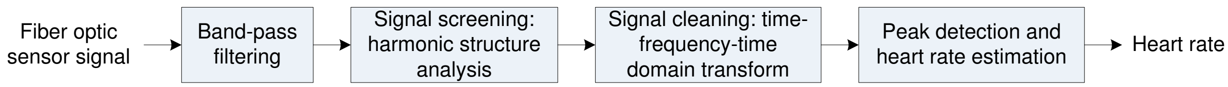

Fig. 4. Procedure of heart rate detection with BCG at headrest position.

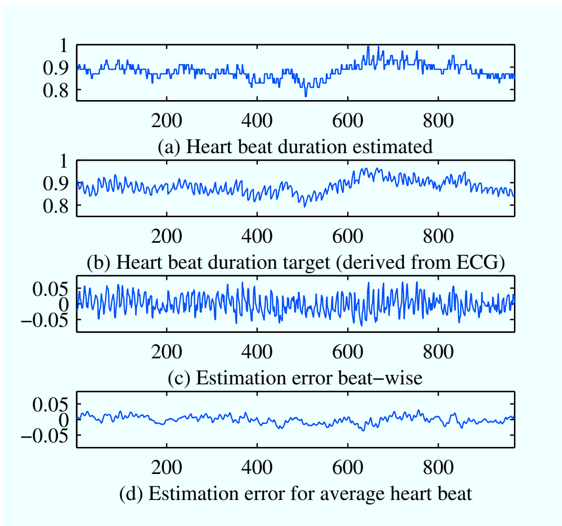

Fig. 6. An example of recovered heart beat duration (interval) from BCG (subfigure a) and from ECG (subfigure b). Subfigure c illustrates the deviation of BCG-based heart beat interval from ECG-based outcome. Subfigure d illustrates the same deviation but for BCG-based estimation with temporal smooth filtering.

Subject	Session	ECG	BCG	Error
Sub 1	1	68.9655	68.9338	0.0317
	2	68.6499	68.6577	0.0078
	3	69.0528	69.0846	0.0318
Sub 2	1	69.5814	69.2361	0.3453
	2	68.8231	69.0211	0.1980
	3	71.3946	71.5564	0.1618
Sub 3	1	70.9052	71.0564	0.1511
	2	69.1722	69.2281	0.0559
	3	71.8219	71.9597	0.1378

TABLE I
ESTIMATE OF AVERAGE HEART BEAT RATE IN HEADREST BCG VS ECG. UNIT: BEATS PER MINUTE.

phenomenon is well recognized and constitutes the basis of BCG based blood-pressure sensors [3], [9]). Thus, future work shall look into improved system setup with milli-second level multi-modal signal synchronization so as to conduct high time-resolution studies.

In this study, the processing algorithm was implemented using MATLAB on PC platform, and real-time heart beat detection had been achieved. As specified in the algorithm, a continuous 15 seconds (screening window) of signal without major distortion are needed for the detection of heart rate. This requirement appeared feasible for real applications. Nevertheless, implementing the algorithm in embedded system with lower processing capability and reducing the screening window for higher robustness would also be part of our future work.

V. CONCLUSION

In this paper, we have proved the feasibility of BCG in headrest position that will allow practical and portable applications. We designed and implemented a multi-modality sensing system with an integrated high-sensitivity microbend fiber optic BCG sensor in a headrest cushion. In the preliminary study we conducted experiment sessions on 3 human subjects. From the multi-modality data, we ran extensive analysis and identified the special time-frequency characteristics of the signal in the new BCG setup. We also developed a novel algorithm for estimating the heart beat intervals. We validated the algorithm with the data and demonstrate that it can accurately compute the heart beat intervals from headrest BCG.

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