Evaluating Piezoelectric Ballistocardiography for Post-Surgical Heart Rate Monitoring

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Abstract

Ballistocardiography (BCG) is a non-invasive technique measuring heart and circulatory activity, proposed as an alternative to ECG for long-term heart rate monitoring. This study evaluates a custom multi-node piezoelectric BCG sensing mat for heart rate measurement compared to single-lead ECG in post-cardiac surgery patients.

14 patients (10 males, mean age 63.47 ± 9.35) post-coronary artery bypass (N=8) or heart valve repair (N=6) were enrolled at Maastricht University Medical Center. Patients in the cardiac ICU used a bed with a custom BCG sensor mat (10 PVDF-TrFE piezoelectric sensors, 90x50 cm²). BCG and ECG were recorded simultaneously for an average of 15 hours per patient. BCG heart rate values were extracted over ten-second epochs using a multi-node rule-based algorithm. Performance was assessed using mean absolute error (MAE) comparing BCG and ECG heart rates.

Heart rate values derived from the piezoelectric BCG mat resulted in a weighted mean MAE of 1.41 bpm with 66.14% coverage compared to ECG.

Piezoelectric BCG shows promise as an accurate heart rate measurement method in post-cardiac surgery patients, offering a non-invasive alternative to ECG. These findings support further development of this technology for clinical use in remote heart rate monitoring.

1. Introduction

Ballistocardiography (BCG) is a non-invasive technique that measures the mechanical vibrations produced by the heart's contractions. While electrocardiography (ECG) remains the gold standard for cardiac monitoring, BCG offers a potential alternative, particularly for long-term monitoring and in settings where ECG may be impractical or uncomfortable [1–4]. This study evaluates a custom-built piezoelectric BCG sensing mat for heart rate measurement in post-cardiac surgery patients.

The primary objective of this research is to assess the accuracy and reliability of piezoelectric BCG for heart rate monitoring compared to ECG. By comparing the heart rate values derived from the BCG mat to those obtained from ECG recordings, we aim to determine the feasibility of using BCG as a viable alternative in clinical applications.

The study focuses on post-cardiac surgery patients, as this population often requires continuous heart rate monitoring to assess recovery and identify potential complications. The use of a piezoelectric-based BCG sensing mat offers several potential advantages, including its non-invasive nature, ease of use, and potential for long-term monitoring without the need for frequent electrode reapplication.

This paper is structured as follows: Section 2 outlines the materials and methods used in the study, including the sensor configuration, data collection process, and algorithm description. Section 3 presents the results of the study, comparing the BCG-derived heart rates to the ECG reference. Section 4 discusses the implications of the findings and their potential clinical significance. Finally, Section 5 concludes the paper by summarizing the key findings and suggesting future research directions.

2. Materials and Methods

2.1. Sensor Configuration

In this study, we utilized a custom-built multi-node piezoelectric BCG sensing mat for heart rate monitoring developed by the Holst Centre (imec & TNO, Eindhoven, Netherlands). The sensing mat comprised 10 PVDF-TrFE piezoelectric sensors arranged in a grid formation over a

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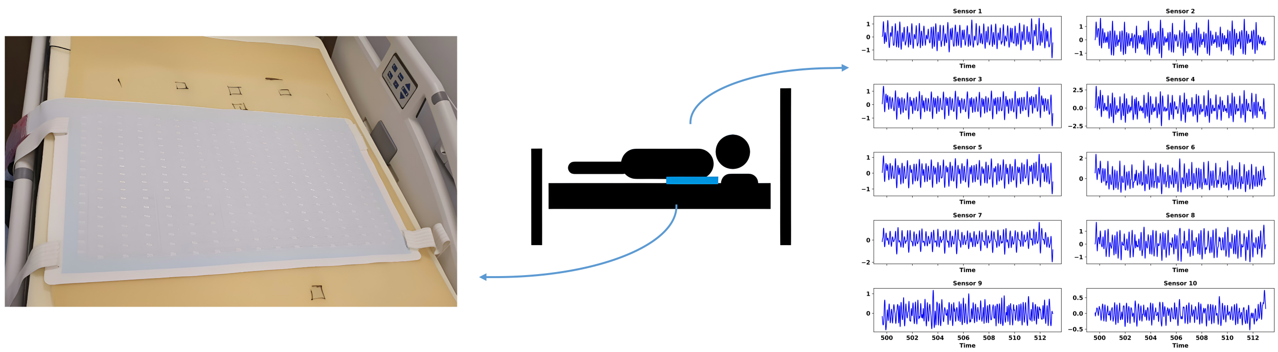

Figure 1. The image illustrates the setup used in this study. Left image shows the actual sensing mat placed on the hospital bed, middle figure shows the sensing mat placement according to the patient position and right figure shows an example 10-channel data of piezoelectric sensor.

90x50 cm^2 area. Each sensor node was equipped with high sensitivity to capture subtle mechanical vibrations caused by the heartbeats and other physiological movements. The sensors were connected to an acquisition system capable of sampling at a rate of 300 Hz, providing the temporal resolution necessary for precise heart rate measurement. Figure 1 illustrates overall setup of sensing mat.

These piezoelectric sensors detect dynamic pressure variations resulting from mechanical vibrations associated with heart and lung activities. In contrast to ECG, which necessitates direct skin contact, these sensors are embedded within a mat that is then placed on top of a mattress beneath the bed sheets, allowing for non-invasive monitoring over extended periods. The piezoelectric sensors are constructed with a piezoelectric active material, poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)), sandwiched between electrodes on a flexible substrate. To ensure user comfort and sensor protection, the sensors are laminated with textile layers.

The mat also incorporates an amplification board and a data acquisition module, embedded within the mattress to minimize any discomfort to the patient. The mat is securely fastened to the mattress using elastic straps and Velcro connections to prevent movement and maintain signal integrity. Data from the sensors are transmitted via a waterproof connector to an external data acquisition system.

2.2. Data Collection

Data collection was conducted with 14 patients who had undergone cardiac surgery at the Maastricht University Medical Center. The patient cohort consisted of 10 males, with a mean age of 63.47 ± 9.35 years, who had either coronary artery bypass grafting (N=8) or heart valve repair (N=6). The study took place in the cardiac ICU, where the patients were placed on beds equipped with the BCG sensor mat. Simultaneous single-lead ECG recordings served as the reference standard for heart rate measurement. Data were continuously recorded for an average of 15 hours per patient, providing a comprehensive dataset for analysis. Table 1 summarizes the demographic characteristics of the participant population, covering age, weight, height, Body Mass Index (BMI), and sex.

Table 1. Summary statistics of participants' demographics.

Age	Height [cm]	Weight [kg]	BMI	Sex [M/F]
63 ± 10	172 ± 6	91 ± 26	30 ± 8	10/4

The study protocol was reviewed by the Medical Ethical Committee of Maastricht University Medical Center and all participants provided written informed consent.

2.3. Algorithm Description

The heart rate estimation from BCG signals was carried out using a structured algorithm that included pre-processing, heart rate estimation using a multi-node rule-based approach, and post-processing.

2.3.1. Pre-processing

The pre-processing stage involved filtering the raw BCG signals to remove noise and artifacts. A bandpass filter with cut-off frequencies set between 0.5 Hz and 20 Hz was employed to focus on frequency components related to cardiac activity. The signals were then segmented into 10-second epochs with a 5-second overlap, which balanced temporal resolution and computational efficiency.

2.3.2. Heart Rate Estimation

To estimate heart rate, the initial step involved calculating the auto-correlation of each signal segment. A

Table 2. Overall performance of heart rate estimation algorithm.

Participant ID	Total Record Duration (mins)	Mean Absolute Error (BPM)	Coverage (%)	ECG HR Median (BPM)	PM HR Median (BPM)	ECG HR STD (BPM)	PM HR STD (BPM)
1	160	1.19	73.51	84.51	84.51	2.16	4.49
2	160	0.45	86.69	73.44	55.64	24.40	7.98
3	1254	1.07	69.83	79.58	79.21	6.10	6.15
4	1223	1.37	69.86	69.44	69.00	6.50	5.97
5	1338	1.11	88.09	95.24	95.43	8.15	8.31
6	2762	1.90	72.03	89.15	88.67	7.12	9.96
7	1288	2.09	68.52	62.83	60.40	6.99	6.78
8	15	2.96	42.42	76.82	59.55	20.54	5.67
9	369	0.83	77.15	89.82	89.78	3.56	2.37
10	322	1.82	67.94	75.09	72.63	10.26	5.71
11	1038	1.04	42.89	96.15	95.74	8.71	5.82
12	1486	0.88	28.05	68.03	66.67	8.40	6.70
13	1207	0.83	63.45	69.77	70.75	9.52	10.13
14	110	7.77	27.09	54.55	80.63	10.48	8.66
Mean	909	1.41	66.14	75.25	74.82	7.77	6.09

Savitzky-Golay Finite Impulse Response (FIR) filter, using a third-order polynomial with a 10-millisecond window, was subsequently applied to the auto-correlation to improve peak detection. Heart rate was determined for each pair of identified peaks by computing the inter-peak interval and signal sampling rate.

Three criteria were used to validate the accuracy and reliability of the estimated heart rate by selecting nodes with high-quality signals. First, the periodicity percentage, as outlined in [1], was calculated based on the peak intervals, considering a maximum heart rate variability (HRV) of 200 milliseconds, which is consistent with the upper normal limit for healthy individuals. This metric assessed the consistency of peak recurrence. Second, the amplitude variation between the first and subsequent detected peaks was measured. If the periodicity percentage was above 75% and the amplitude variation was less than 50%, the signal quality was considered adequate, and peaks from that node were regarded as reliable. Finally, if at least three nodes met these criteria within a segment, the final heart rate was determined by calculating the median across these nodes, ensuring a robust estimation of heart rate.

2.4. Post-Processing

In addition to calculating the median heart rate for segments that met the quality standards, an additional refinement step was applied to remove potential outliers from the computed heart rates. A median filter with an 11-point window, equivalent to a 60-second duration, was used. Each heart rate value was then compared to its corresponding median within the filter window. Heart rate values that deviated by less than 16 beats per minute from the window's median were accepted as final, post-processed heart rates [5]. This post-processing step effectively mitigated the influence of outliers and irregularities, resulting in more accurate and reliable heart rate measurements.

3. Results

3.1. Heart Rate Estimation

The performance of the custom multi-node piezoelectric BCG sensing mat was evaluated by comparing the heart rate estimations derived from the BCG signals with the reference ECG recordings. The analysis was conducted on data collected from 14 post-cardiac surgery patients, covering a total recording time of approximately 210 hours.

The weighted mean absolute error (MAE) between the BCG-derived heart rates and the ECG reference was calculated across all patients. The weighted average considered the length of the recording to prevent very short recordings from some subjects from influencing the overall results. The weighted average MAE observed was 1.41 bpm, demonstrating the high accuracy of the BCG sensing mat in heart rate estimation. In addition, coverage was determined by the proportion of segments that met the signal quality criteria. Despite some segments being excluded due to noise or artifacts, the average coverage was over 66%, sufficient for continuous long-term monitoring in a clinical setting taking into account different heart rhythms of patients. Table 2 represents the overall performance of proposed algorithm. Figure 2 shows a comparison of BCG and ECG heart rates for a representative patient.

3.2. Comparison with Previous Studies

The custom multi-node piezoelectric BCG sensing mat demonstrated a weighted mean absolute error (MAE) of 1.41 bpm, which is competitive with Elnaggar et al.'s [1] multichannel bed-based BCG system (MAE of 1.09 bpm) and significantly better than Sadek and Biswas's [6] system (MAE of 10.12 bpm). Our study, like those by Elnaggar et al. [1] and Ochoa and Revilla [7], utilized non-invasive BCG methods, ensuring reliable and non-intrusive heart

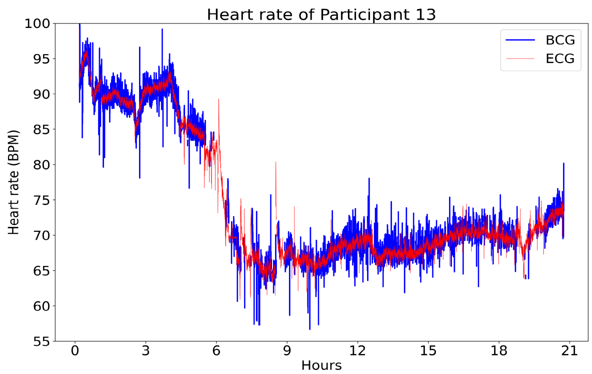

Figure 2. Comparison of BCG and ECG heart rates for a representative patient.

rate monitoring. The coverage of diverse subject pools in our study aligns with the comprehensive approaches of previous works, including patients with various conditions. The clinical applicability of the piezoelectric sensors for continuous patient monitoring is supported by the high accuracy and reliability of BCG-derived heart rates, similar to the findings of Jurčić and Zarate [8] and Ochoa and Revilla [7]. Overall, our results are competitive with and, in some aspects, superior to the methodologies and outcomes reported in previous studies.

4. Discussion

The custom piezoelectric sensor mat provided accurate heart rate values, as evidenced by the low MAE. These results support continued investigation of piezoelectric sensors for non-invasive heart rate monitoring in clinical settings. Improvements in the overall coverage need to be addressed in order to ensure that patients could have their heart rate monitored for the majority of the time they are in the bed. ICU environments have been known to cause poor sleep in patients who are admitted there [9]. This could have been a contributing factor as to why the coverage was low in some patients. The target environment for this type of sensing system would most likely be a non-ICU setting like a nursing home or for situations that require long term remote monitoring outside of a clinical setting.

5. Conclusion

The findings of this study indicate that the custom multi-node piezoelectric BCG sensing mat is a highly accurate and reliable tool for non-invasive heart rate monitoring in post-cardiac surgery patients. Future research should aim to optimize sensor placement and improve algorithmic processing to further enhance the system's performance and applicability in various clinical environments.

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References

[1] Elnaggar I, Hurnanen T, Sandelin J, Lahdenoja O, Airola A, Kaisti M, Koivisto T. Multichannel bed based ballistocardiography heart rate estimation using continuous wavelet transforms and autocorrelation. In 2022 Computing in Cardiology (CinC), volume 498. 2022; 1–4.

[2] Xie Q, Wang G, Lian Y. Heart rate estimation from ballistocardiography based on hilbert transform and phase vocoder. Papers With Code 2018;.

[3] Sadek I, Biswas J, Abdulrazak B. Ballistocardiogram signal processing: A review. Health Information Science and Systems 2019;7(10).

[4] Tramontano A, Tamburis O, Cioce S, Venticinque S, Magliulo M. Heart rate estimation from ballistocardiogram signals processing via low-cost telemedicine architectures: A comparative performance evaluation. Frontiers in Digital Health 2023;5.

[5] Kinnunen H, Rantanen A, Kenttä T, Koskimäki H. Feasible assessment of recovery and cardiovascular health: Accuracy of nocturnal hr and hrv assessed via ring ppg in comparison to medical grade ecg. Physiological Measurement 2020; 41(4).

[6] Sadek I, Biswas J. Nonintrusive heart rate measurement using ballistocardiogram signals: a comparative study. Signal Image and Video Processing 2018;13(3):475–482.

[7] Ochoa EJ, Revilla LC. Signal filtering and peak analysis of ballistocardiography for heartbeat detection. In International Conference on Biomedical and Health Informatics. Springer, 2024; 296–304.

[8] Jurčić K, Zarate PR. Heart rate detection from ballistocardiogram using continuous wavelet transformation. In International Conference on Biomedical and Health Informatics. Springer, 2024; 305–311.

[9] Martinez F, Poulter AL Seneviratne C, Chrimes A, Havill K, Balogh Z, Paech G. Icu patients' perception of sleep and modifiable versus non-modifiable factors that affect it: A prospective observational study. J Clin Med 2022;11.

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