3D Printed Dry Electrodes for Single-Lead Newborn ECG Monitoring

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Abstract

An important factor that physicians rely on in newborn diagnosis is heart rate (HR). A wireless hand-held single-lead 3D printed dry electrode electrocardiogram (ECG) monitoring device is developed and deployed for newborn HR assessment. The electrodes are 3D printed using conductive polylactic acid (PLA) filaments. A small subset of 3-minute newborn ECGs (n=5) with an average gestation period of 38 weeks collected at 500 Hz sampling frequency is used to ensure dry electrode single-lead ECG quality for rapid HR detection in newborn. To ensure signal reliability, statistical signal quality indices (SQIs) are computed such as kurtosis, skewness, variance, standard deviation (SD), and mobility. Furthermore, HR information is estimated using a modified Pan-Tompkins algorithm, and signal-to-noise ratio (SNR) in decibels (dB) is computed. Device HR estimation is compared to a clinical-grade HR monitor. Average SQIs showed good parameters for skewness, kurtosis, and mobility, respectively. The single-lead ECG device provided an HR detection accuracy of 92.1% with a maximum of 10 seconds acquisition time from contact to detection. Visually, the QRS complex and T waveform are obvious in all subjects with a 16.34 dB average SNR, but P-wave is not clear due to high frequency noise present. It is evident that 3D-printed dry electrodes can be used for HR applications where R-peak and RR-interval information can be extracted from the newborn ECG. This work is an investigation into dry electrode feasibility for newborn single-lead ECG for routine check-ups and remote monitoring applications.

1. Introduction

Neonatal health remote monitoring is a vital concept that requires the development of newborn-centric medical devices to be used and be accessible by parents and health professionals alike. Remote monitoring of newborns in hospitals and homes allows for decreased possibility of spreading infection while providing vital medical information to physicians to assist in their continuous newborn assessment [1,2]. Also, newborn HR is an important clinical indicator of the newborn's medical status that can indicate the successfulness of treatments. These technologies are used in teleconsultation, and telediagnosis of newborn patients [2]. Furthermore, the potential of performing routine checkups remotely provides access to economic benefits to both hospital and patients' paternity care through cost-saving without decreasing the quality of medical services, especially ECG and HR in low-income countries [2].

In turn, many researchers explored the mechanisms for appropriate and reliable neonatal HR monitoring technologies for the above-mentioned objectives. Most researchers focused on the development of technologies pertaining to their use in the hospital setting, especially the NICU. Khanam et al. developed a video-based non-contact neonatal vital sign monitoring tool for newborns in the NICU [3]. The authors used neural networks to estimate HR and respiration and obtained strong Pearson correlation coefficients. Their work shows potential in developing video and image-based technologies for remote monitoring of newborns [3]. However, the work required extensive physical and computational resources in the form of high-quality digital cameras and processing power to perform neural networks calculations. Also, the work provides a novel method that is not standardized making it difficult for large-scale clinical adoption. On the other hand, Chung et al. developed wireless patches for continuous neonatal vital sign monitoring [4]. The authors developed two sets of sensors placed on the chest and foot simultaneously to collect ECG, PPG, and body temperature [4]. While Rettedal et al. created Neobeat (Laerdal Medical, Stavanger, Norway) a dry electrode HR detector that relies on back-like ECG signals for neonatal resuscitation efforts in the NICU [5]. The device only displays HR and does not contain wireless capabilities to transmit or store ECG signals which is not suitable for neonatal remote monitoring.

Most researchers focused on neonatal cardiac remote monitoring in the hospital which is not suitable for remote or rural areas where medical services and resources are scarce. On the other hand, a few researchers focused on rural remote monitoring. Keerthy and Nagesh examined a wireless pulse-oximeter device for HR detection in newborns. Their results show promise in deploying pulse oximetry in remote settings [6].

To the best of our knowledge, it is apparent there is a lack of a handheld dry electrode single-lead ECG solution that can perform accurate HR estimations using clinically relevant chest-based ECG signals and wirelessly transmit and analyze signals for healthcare professionals. This work provides an attempt in the development of the above-mentioned device using 3D printed dry electrodes to acquire and display HR within 10 seconds of electrode-skin contact and record and transmit single-lead ECG for further analysis.

2. Methods

2.1. SAR-NE Dataset

Toronto Metropolitan University's Signal Analysis Research (SAR)-Neonatal (NE) dataset consists of ECG and HR information being collected using a dry electrode wireless single-lead ECG handheld device for rapid neonatal vital sign monitoring and HR estimation [7]. Data collection is occurring in a community hospital in Toronto, Canada with institutional review board (IRB) approvals. Up to date, 5 newborn ECGs and their respective HR are collected and analyzed. The dataset is benchmarked to clinical grade HR monitoring devices such as 3-Lead ECG machines, and/or pediatric pulse oximeters. Newborn ECG and HR collections are performed by placing the single-lead ECG device on the approximate location of the newborn sternum in supine position for 3-minute ECG recordings. Device-estimated HR information and clinical HR is recorded using a digital camera. Newborn vital sign data is deidentified and a random identifier is assigned to comply with confidentiality and privacy of protocols as outlined in the protocol [7]. The collected data per newborn features HR calculated on 2 second ECG intervals, 3-minute ECG recordings per newborn and annotated clinical HR, and visually annotated significant motion artifact periods through video recordings.

2.2. Heart Rate Detector Prototype

The single-lead neonatal ECG device features 3D printed dry electrodes for signal acquisition. The electrodes are manufactured using conductive polylactic acid (PLA) filaments. The electrodes are further attached to single-lead ECG circuitry for signal denoising and detrending to form a hand-held single-lead ECG monitoring device for neonatal quick real-time HR estimations. The acquired signals are later followed into an embedded microcontroller for ECG and HR estimation recordings and wireless transmission to a nearby dedicated computer device. The 3D printed dry electrodes are placed in the V2 position, as shown in Figure 1. ECG signals are acquired with a sampling rate of 500 Hz and 12-bit ADC characteristics. The signal undergoes a 3 to 48 Hz hardware-based band-pass filter for electromagnetic interference (EMI) elimination. The signal is later transmitted wirelessly through BLUETOOTH low energy (BLE). A graphical user interface (GUI) is used to provide real-time HR and ECG information and record it. The wireless transmission can only be performed between device and dedicated GUI using an encryption key authentication method.

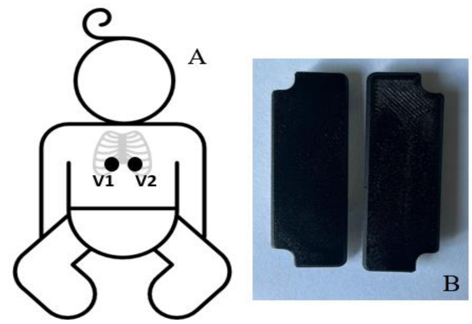

Figure. 1 (A) Electrode placements on V1 and V2 locations, (B) 3D printed dry electrodes for single-lead ECG.

Spatiotemporal and statistical-based features are computed for ECG to examine signal quality through SQIs and determine accuracy behind 3D printed dry electrode-based HR estimations and its respective algorithms. The hand-held device is evaluated to a clinical pulse oximeter and/or 3-lead ECG device for HR comparisons. Spatiotemporal HR features include normalized root mean square deviation (NRMSD), mean absolute difference (MAD), and surrogate information such as RR-interval. While statistical features include kurtosis (kSQI), skewness (sSQI), root mean square (RMS), SD, mobility, and signal quality information such as SNR. Also, resistivity measurements are produced for the 3D printed dry electrode to determine its conductivity characteristics and appropriateness for neonatal ECG acquisition.

3. Preliminary Results

Single-lead neonatal ECG and HR information are analyzed to determine its robustness and effectiveness in obtaining accurate HR when compared to clinical grade devices. As shown in Figure 2, the neonatal ECG form can be identified visually. The QRS and T-wave waveforms are recognized, however there is a lack of a detectable P-wave. The identified RR interval information can be extracted from the QRS wave which in turn helps produce HR estimations.

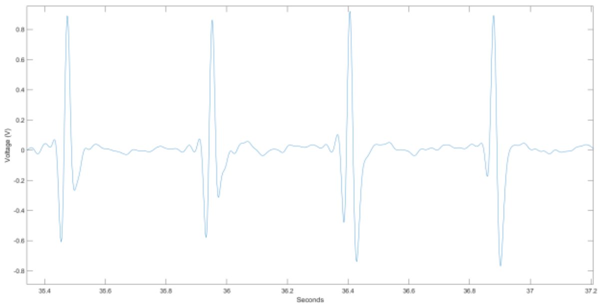

Figure. 2 A snippet of acquired ECG with clear QRS complex and T-wave representation.

On the other hand, the resistivity of the electrodes is measured to identify its electro-geometrical properties. The average measured resistance value of the electrode is 1.1 kOhm. While the theoretical calculated value for the sized electrodes is 1.23kOhm based on apparent x-y and z plane resistances of 15 Ohm•cm and 115 Ohm•cm respectively as presented in the material's datasheet. The difference between the measured and calculated values is approximately 120 Ohms. This comparison shows that the integrity of the material's electrical properties is maintained with 3D printing and shape formation.

Table 1. SQIs for Neonatal Single-lead ECG

RMS	0.085
kSQI	0.199
sSQI	37.9
SD	0.085
Mobility	2.23
SNR (dB)	16.3

Table 2. Prototype HR Statistical Metrics

NRMSD without motion	10%
NRMSD with motion	17.64%
MAD without motion (BPM)	11.4
MAD with motion (BPM)	17.8
Avg. time to HR (seconds)	3.7
SD (BPM)	15
Pearson Correlation (r)	0.85
Accuracy	92.1%

The handheld dry-electrode based single-lead ECG device achieved an accuracy of approximately 92% in HR detection when compared to clinical grade HR ground truths using 10 second signal durations. It is important to note that the perceived accuracy did not include HR calculations computed using ECG signals polluted with motion artifacts and outliers. As shown in Figure 3 and Table 2, the correlation between the prototype's HR and clinical grade HR is linearly correlated with a Pearson coefficient of 0.85 using 284 HR datapoints. These HR datapoints are based on 2-second ECG intervals excluding 2-second intervals that showed motion artifacts from a total of 453 HR datapoints. While the Bland-Altman analysis, as shown in Figure 4, shows a SD of 15 BPM with 95% confidence. On the other hand, the mean deviation between clinical grade and prototype HR is 18 BPM and 11 BPM for calculation using ECG signals with and without motion artifacts, respectively.

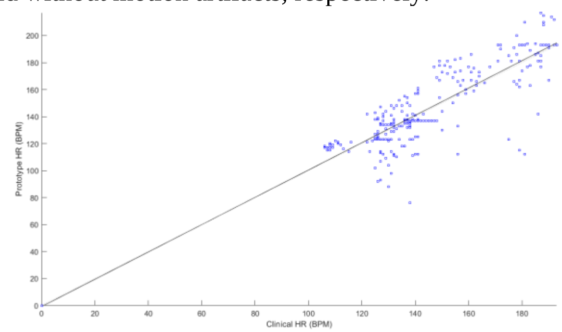

Figure 3. Prototype and Clinical HR Correlation graph for without motion datapoints (n = 284).

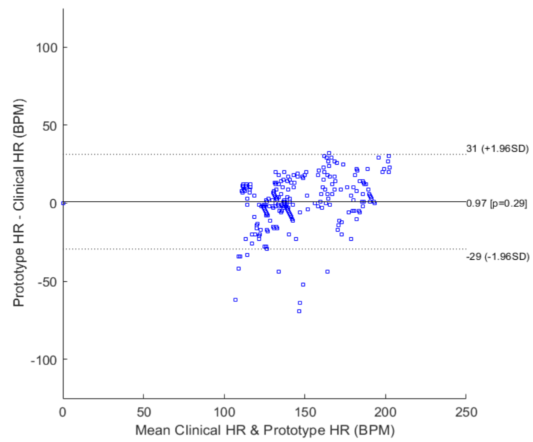

Figure 4. Bland-Altman plot for Prototype and Clinical HR.

4. Discussion

3D printed dry electrodes are used to collect single-lead neonatal ECG for rapid HR detection in the goal of developing a reliable remote monitoring tool. This approach is utilized to examine the conductive materials' feasibility as a low-cost solution that can be used in resource scarce and remote settings. The electrodes conductive characteristics are seen to be consistent between pre and post printing process. This similarity in values leads to show that material integrity is maintained. This knowledge provides an insight toward 3D printed dry electrode development and make use of resistivity in developing application specific ECG acquisition devices.

Furthermore, ECG signal quality is examined to ensure that single-lead ECG signals are being collected appropriately and can be used in neonatal HR detection. As shown in Figure 2, the QRS complex and T-wave morphologies can be identified clearly. However, P-wave is not present. The evident QRS complex allows for the development of HR detection algorithms that use the QRS complex in calculating HR such as Pan-Tompkins. As shown in Table 1, sSQI of approximately 0.2, and a kSQI of 38 show the acquired ECG signals are slightly skewed which is a characteristic of ECG as a quasi-periodic signal. Also, an SNR of 16.34 dB provides insight into the relatively high quality of the signals being collected with a clear QRS complex and R-peak information for appropriate HR estimations.

The electrodes and consequent prototype can generate HR estimations with 92.1% accuracy with less than 10 seconds of ECG information when compared to clinical grade HR. As shown in Table 2, the absolute average HR difference between clinical and prototype HR calculations is approximately 11 BPM without considering motion noisy ECG signal information. The decrease in accuracy can be attributed to mislabeled or missed motion recognition by health professionals. Also, the presence of significant EMI noise due to the lack of shielding allowed for increase detection of peaks like R-peaks, which in turn decreased accuracy by overestimating HR. The NRMSD is 10% and 17.6% for clean and motion noisy ECG signal information respectively. These results show the impact of motion in ECG information and its role in decreasing accuracy in HR. But the average time to HR is 3.7 seconds to obtain a relatively accurate HR within 10 BPM of true HR. The low detection time allows for faster neonatal resuscitation intervention at birth.

While Pearson Correlation Coefficient of 0.85 in Table 2 provides an extended analysis of the correlation relation between prototype and clinical HR datapoints. The high r value represents a significant linear correlation between HR points as evident in Figure 3. This concept shows the positive trend between clinical and prototype HR. This information can assist in defining a correction factor that can be added to ensure that prototype HR can be adjusted for the discrepancy when compared to clinical HR. The plot shows an SD of 15 BPM with 95% confidence. In other words, 95% of the difference between clinical and prototype HR datapoints can be found in the +/- 15 BPM range. Overall, the preliminary results show potential in developing a handheld tool that relies on dry electrode chest single-lead ECG for neonatal HR monitoring. HR remote monitoring can become a reality with the current advances in wireless transmission protocols that ensure patient data privacy. It is important to note that these results are confided to the current 5 newborn dataset. This small dataset limiting factor does not allow for generalizations conclusions and hampers the accuracy of producing an accurate estimation of the prototype as of this date. Further data collection is required, currently underway, to offer an in-depth analysis of the HR comparisons and ECG quality to ensure prototype robustness and reliability.

5. Conclusion

A single-lead ECG-based HR detector is developed utilizing 3D printed dry electrodes and a modified Pan-Tompkins algorithm for quick HR estimations. The device is compared to clinical grade HR and tested using 5 newborn subjects to examine ECG signal quality, HR detection capabilities, and time from contact to HR display. Device results are promising where accurate HR with 92.1% accuracy is achieved. The work offers the study of a new material for ECG sensor development that can be robust and reliable for future single-lead ECG system. The end goal of the work is to determine the device’s applicability in neonatal remote monitoring and routine checkups. This prototype allows future access of ECG technology to rural areas that may not have access to medical services and health professionals. The work is a steppingstone in the development of newborn centric monitoring devices that are accessible to all.

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