Comparison of Electrode Configurations for Impedance Plethysmography Based Heart Rate Estimation at the Forearm

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***Abstract*—Electrical impedance plethysmography (EIP) is a cost effective and power efficient physiological measurement method that could potentially be applied for measuring pulse waves along limbs in ambulatory conditions. The pulse wave information could be utilized to determine the heart rate or other relevant parameters such as heart rate variability or cardiac rhythm. We compared three electrode configurations for EIP at the forearm, with the focus on assessing its utility in a wearable device. The evaluation included EIP measurements with ten healthy participants using adhesive gel electrodes. The evaluated electrode configurations were tetrapolar configuration along the forearm and tetrapolar and bipolar configurations around the wrist. For each electrode configuration, the measurements were performed in stationery condition and during finger movement. The collected data was evaluated for finding out differences in the signal to noise ratio (SNR) between the configurations during the two conditions. The results show that pulse wave signal with adequate SNR for heart rate estimation is obtained from the wrist area while stationary and mostly also during the presence of mild movement. There was no significant difference in the data quality between wrist area and conventional configuration along the limb.**

Keywords*— *bioimpedance, electrical impedance, impedance plethysmography, heart rate detection, signal processing, heart rate measurements, bioimpedance measurements

I. Introduction

Electrical impedance plethysmography (EIP) has traditionally been investigated and applied mainly for medical applications such as the measurement of pulse wave velocity [1], monitoring of respiration in adults [2] and in young children [3], measurement of stroke volume and cardiac output [4], detection of deep venous thrombosis [5], heart failure [6] as well as in estimation of risk for vascular diseases [7].

Non-invasive physiological measurement methods integrated with wearable technologies enabling ambulatory monitoring have gained significant importance recently [8]. In addition to detecting and monitoring parameters that are medically relevant, wearable technologies are utilized in monitoring heart rate and heart rate variability in athletes and sports enthusiasts to reach optimal training regimens and monitoring the recovery as well as sleep quality [9]. Currently, wearable technologies used for heart rate monitoring and recovery assessment in sports and wellness applications are utilizing either chest straps for electrocardiography (ECG) measurement or increasingly wrist-worn photoplethysmography (PPG), which enables comfortable long-term use also outside the exercise sessions. PPG technology is based on transmission and absorption of the applied light through the skin [10-12]. Although simple and cost-effective, PPG has various of setbacks such as decrease in overall measurement accuracy and signal to noise ratio (SNR) that is affected by patient skin tone, body mass index, and superficial blood perfusion, as well as movement artefacts, environmental conditions, and the relatively high-power consumption that is evitable due to the required illumination of the skin [12-15].

EIP is an alternative non-invasive physiological measurement method that utilizes the observation of electrical impedance changes measured from the skin surface caused by the variations in the blood volume in the arteries and arterioles at the applied limb, chest, or other parts of the body [16,17]. In EIP, a small amplitude, high frequency alternating current is applied through the skin. The said current travels through the tissues favoring blood because of its relative conductivity compared with the surrounding tissues, creating an electrical potential difference directly proportional to impedance across the electrodes of measurement [18,19]. Electrode placement is a crucial factor when the measurement quality and characteristics are considered in EIP based HR detection [20-21]. In a recent study, various algorithmic approached have been evaluated in EIP-based HR estimation: Pan-Tompkins method, discrete wavelet transform, empirical model decomposition, Hamming self-convolution window and wavelet transform [22]. Aside these methods, techniques such as thresholding, filtering, automatic peak detection varying window, mathematical morphology, artificial neural network have also been used [22]. Various techniques for the analysis of EIP waveform morphology by extracting descriptive signal features has also been studied [7]. Despite the previous EIP research efforts and the recent strong interest in wearable technologies, there has been only few studies evaluating the potential of EIP technology for the measurement of pulse waves and the estimation of HR from the wrist area, i.e. with electrode configurations suitable to be integrated in a wrist-worn device [23, 24].

We evaluated three electrode configurations at the forearm for the EIP based HR detection and pulse wave measurements. Signal quality was observed in three different electrode configurations in resting condition and the effect of movement of fingers on the signal-to-noise ratio was evaluated. The aim was to conclude whether EIP measured at the wrist area produces similar signal quality compared with the traditional electrode placement along the limb and adequate for HR estimation enabling its use either as a sole measurement modality for wrist-based HR estimation or to be combined with PPG to improve the measurement accuracy. Through the following chapters description of the process, used equipment and participant profile will be defined and the data from 60 different measurements will be summarized and analyzed.

II. Materials and Methods

The study included measurements completed on 10 healthy participants (age 20–30 years). The subjects were informed about the study procedures prior to asking their consent for participation. Each participant underwent six different EIP measurements; resting condition measurements for three different electrode configurations, moving condition measurements (random finger movements) for each of the same three electrode configurations. For each subject, bioimpedance measurements were performed utilizing BIOPAC MP160 measurement module in connection with impedance plethysmography amplifier module EBI 100C, BIOPAC Systems Inc. For electrocardiogram measurements the module EEG-2R from the same company was utilized. Two different connector cables by the BIOPAC Systems Inc. were utilized for the measurements; one with the voltage and current outlets of the same polarities combined, thus producing bipolar EIP measurements, and the other with 4 outlets respectively corresponding to I+, V+, V-, I- values, thus producing tetrapolar measurements. BIOPAC EL500 electrodes (gel cavity 16mm diameter, 1.5mm deep) were utilized in EIP measurements and Ambu Bluesensor L-00-S electrodes in ECG measurements. "Acqknowledge Software" supplied by BIOPAC Systems Inc. was used for visualizing the signals during the measurements and storing them for later processing. For the measurements presented in this study 50 kHz sinusoidal EIP excitation signal with 400µA (rms) amplitude was used. Amongst the excitation frequency options provided by the measurement device used: 12.5 kHz, 25 kHz, 50 kHz, and 100 kHz, 50 kHz was found in the preliminary testing to produce the most stable plethysmography signal by visual especially for the measurements that were completed around the wrist.

A. Electrode Configiurations

As mentioned earlier, the study included 3 different electrode configurations. The first configuration was bipolar 2-electrode configuration, and the measurements were completed around the opposite corners of the wrist, one electrode close to the tip of the ulnar bone and the other placed below the tip of the radius bone (see Fig.1). The two other configurations used tetrapolar electrode setup. In the first one, the electrodes were placed around the wrist approximately one centimeter proximal from the tip of the ulnar and radius bones, the pairs of voltage and currents electrodes placed approximately two centimeters apart at posterior and anterior left forearm as shown in Fig.1. Current delivered in opposite corners of the electrodes with which the voltage is measured (see Fig.1). For the second 4-electrode configuration, the electrodes were located along the arm. The electrodes of the previous setup close to the ulnar bone were used for V+ and I+ and the electrodes connecting to V- and I- were located close to the arm pit as shown in panel A of Fig. 1.

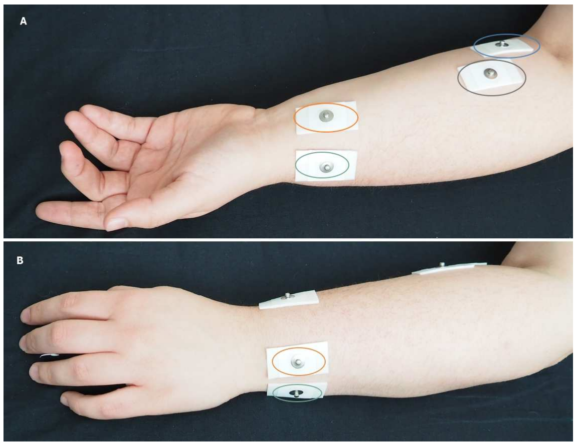

Fig. 1. Electrode locations used in the study. Panel A represents the anterior left forearm and panel B represents the posterior left forearm with the measurement electrode placements. 2-electrode configuration includes only the electrodes that are circled by orange in panels A and B. 4-electrode configuration around the wrist includes two current delivering electrodes (circled by green in panels A and B) and two voltage measuring electrodes (circled by orange in panels A and B). 4-electrode configuration along the forearm included electrodes circled by blue and green (panel A) as current delivering electrodes, and electrodes circled with orange and black (panel A) as voltage measuring electrodes.

Electrode distances were measured, and in average outer electrode distance for along the forearm tetrapolar measurements were calculated as 20.33 cm. Across the wrist the distances of opposing electrodes were calculated as 4.64 cm on average across 10 participants (measured from the electrode center to electrode center). Furthermore, the ECG measurements were performed with electrodes placed in a 3-electrode configuration on the chest, 2 electrodes placed under right and left clavicle, whereas the third electrode was placed under the left side of the chest below pectoral muscles, right under the last left rib bone. The EEG-2R module used for ECG measurements has a wireless data transfer unit thus providing totally floating measurement for avoiding potential interference with the EIP measurements.

B. Data Processing

Sampling frequency of the acquired EIP and ECG data was 2 kHz. A single recording included at least one minute of data. Raw data matrix formed by the gathered information included three columns: the ECG signal [µV], the impedance magnitude signal [ohm], and the impedance phase signal [degree]. In the preprocessing, the raw impedance magnitude and ECG data were detrended and further filtered using a Butterworth-type IIR and Savitzky-Golay filters. The SNR of the data was examined through MATLAB based on the method described in [25]. In essence, the ECG-signal is used to segment the EIP signal and extract a pulse template. Next, a noise-free EIP signal is reconstructed using the pulse template and the ECG-based segmentation. The residual noise signal is calculated by subtracting the reconstruction from the original EIP signal. SNR is then calculated from reconstruction (signal) and residual (noise), see also Fig. 2.

III. Results and Discussion

During the preliminary examination, it was observed that the data gathered from subject 4 was inconclusive due to technical problems in the measurement. Hence six measurements linked to the subject 4 were excluded and are presented in the results of the study. The remaining 54 measurements will be summarized through the results. As mentioned earlier, SNR analysis has been completed to observe the signal quality and noise level changes across electrode configurations and subject behavior (moving or resting condition).

Fig. 2 illustrates the operation of the SNR estimation method [27] for one recording. Fig. 3 shows an example of a high SNR and low SNR signal cases recorded during stationary phase and movement phase, respectively.

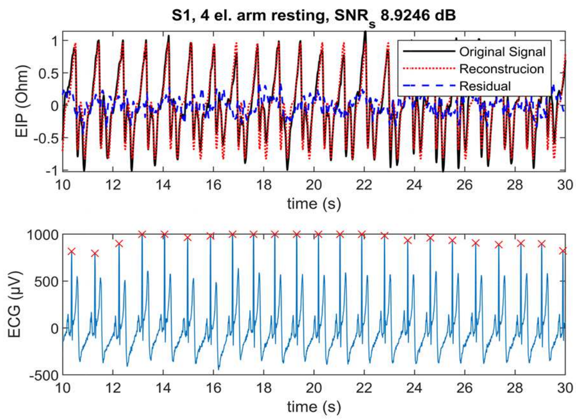

Fig. 2. Example SNRs calculation for an EIP signal (top) using the reference ECG for segmentation (bottom). The detected QRS complexes are marked in red.

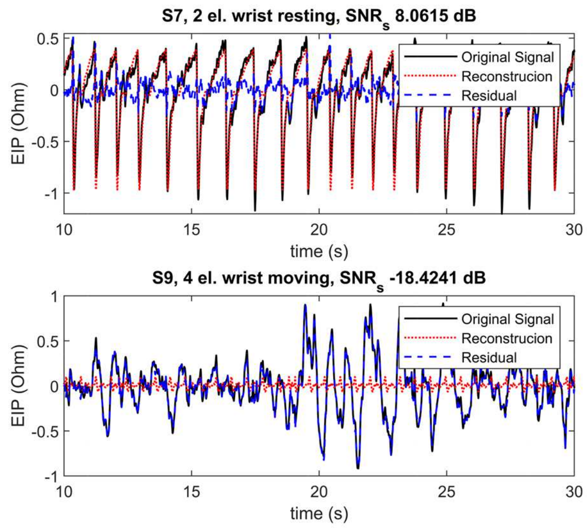

Fig. 3. Example of a high SNRs case (top) and a low SNRs case (bottom).

Fig. 4 summarizes the results of the SNR analysis showing boxplots of the average 1-minute SNR readings of the subjects with the three evaluated electrode configurations during both resting and mild movements conditions. 4 el. wrist refers to tetrapolar electrode configuration around the wrist, 4 el. arm refers to the tetrapolar electrode configuration along the forearm, and 2 el. wrist refers to the bipolar electrode configuration around the wrist. As it can be observed, the conventionally used tetrapolar electrode setup along the arm produces the highest SNR when there is no movement present. However, the median SNR with bipolar electrode configuration is only 2.1 dB lower indicating its potential in the wrist based EIP pulse wave measurements. Surprisingly, the tetrapolar configuration around the wrist performed inferior compared with the bipolar configuration. This could be explained by the bipolar setup having the voltage measurement at the same locations than the current excitation thus maximizing the measurement sensitivity.

There was significant SNR decrease across the measurements with the presence of the finger movement. Hence, one can conclude that even with the randomized and small finger movements the movement artefacts reduce signal quality considerably. However, with frequency domain HR estimation methods, the average HR could likely be obtained even in these cases [26].

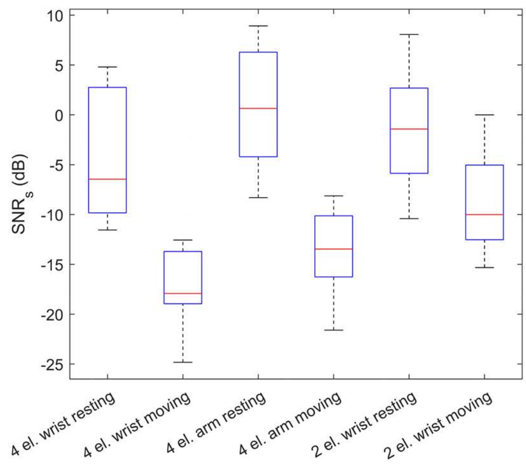

Fig. 4. SNRs across the electrode configuration and measurement type (stationary resting and finger movement).

IV. Conclusion

Three electrode configurations were evaluated and compared for forearm EIP measurement for pulse wave extraction. The results show that wrist area electrode configuration, which would enable integrating the electrodes into a wrist strap produces almost comparable SNR with the conventionally used configuration along the limb. EIP technology could thus offer a supplementary method along PPG or even substitute PPG in wrist-worn HR and heart rate variability monitoring. More investigations with varying movement conditions and with dry measurement electrodes as well as the evaluation of the actual HR and beat-to-beat heartbeat interval estimation performance are however needed.

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