Benchmarking Electrodes for BioImpedance and Body-Coupled Communication

1st Juris Ormanis
Cyber-Physical Systems Laboratory
Institute of Electronics and Computer Science
Riga, Latvia
email address or ORCID

2nd Anastasija Shevchenko
Cyber-Physical Systems Laboratory
Institute of Electronics and Computer Science
Riga, Latvia
email address or ORCID

3rd Krisjanis Nesenbergs
Cyber-Physical Systems Laboratory
Institute of Electronics and Computer Science
Riga, Latvia
email address or ORCID

4th Armands Ancans
dept. name of organization (of Aff.)
Institute of Electronics and Computer Science
Riga, Latvia
email address or ORCID

5th Modris Greitans
dept. name of organization (of Aff.)
Institute of Electronics and Computer Science
Riga, Latvia
email address or ORCID

I. Introduction

In the realm of biomedical engineering and wearable technology, the quest for optimizing electrode technology plays a pivotal role in advancing non-invasive diagnostic methods and enhancing communication through the human body. This article delves into the critical evaluation of various electrodes currently available on the market, primarily used for electrocardiography (ECG) applications. However, our focus extends beyond conventional applications, aiming to ascertain the suitability of these electrodes for BioImpedance (BioZ) and Body-Coupled Communication (BCC) - two burgeoning fields with immense potential for healthcare monitoring and data transmission through the human body.

The essence of this comparative study lies in its rigorous approach to identifying electrodes that excel in performance for BioZ and BCC applications. By analyzing the frequency response of each electrode, we aim to shed light on the underlying factors that contribute to their efficacy. This analysis not only serves to benchmark current technologies but also to unravel the characteristics that make some electrodes more compatible with the specific requirements of BioZ and BCC systems. Through this exploration, the article seeks to offer insights into the material composition, design intricacies, and operational mechanisms that contribute to the superior performance of certain electrodes.

As we navigate through the comparative analysis, the article will illuminate the criteria used for evaluating electrode performance, including sensitivity, signal-to-noise ratio, and stability across a range of frequencies pertinent to BioZ and BCC. This inquiry is not just about identifying the most suitable electrodes but also understanding why they outperform others in these specific applications. By concluding with a discussion on the implications of these findings for future electrode development and application in biomedical technologies, the article aims to contribute significantly to the ongoing efforts in refining electrode technology for enhanced diagnostic capabilities and innovative communication methods through the human body.

A. What is BioZ

II. Literature Review

Cardiovascular diseases are major global health concerns, driving the need for advanced monitoring technologies. Bioimpedance measurement (BioZ) has emerged as a key technique for non-invasively monitoring heart rate, blood pressure, and other vital signs. Its integration into wearable devices offers the potential for continuous health monitoring outside clinical settings, which is vital for patient care and disease management [**?**], [**?**], [**?**].

Recent advancements in electrode technology have played a crucial role in the development of BioZ and BCC. Novel electrode materials and structures have been developed to improve adhesion to the skin and effective signal collection. These advancements include the use of composite dry electrodes and novel structures for flexible and wearable sensors, which are essential for efficient biosignal detection [**?**], [**?**].

In BCC, the focus has been on optimizing communication through the human body. Studies have explored various aspects

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such as the type of coupling (capacitive versus galvanic), the optimal frequency range, and the impact of electrode placement and shape on signal strength. For eHealth applications, galvanic coupling is often preferred due to its privacy and interference-resilience properties [?], [?]. The operational frequency range for BCC has been found to be most efficient between 1MHz and 100 MHz, with the optimal frequency varying depending on electrode placement [?], [?].

The challenges in developing bioimpedance-enabled wearable devices are multifaceted. They include selecting appropriate electrodes, their configuration, power supply, weight, and ensuring accuracy while maintaining user convenience [?], [?], [?]. The trade-off between the accuracy of tetrapolar electrode setups and the practicality of bipolar setups for wearable technology is a significant consideration in current research [?], [?].

Notable studies in the field have investigated various aspects of wearable bioimpedance devices. For instance, research has been conducted on optimizing electrode location, assessing device performance depending on electrode characteristics, and applying heart rate detection algorithms to bioimpedance measurements [?], [?], [?]. Alharbi et al.'s large-scale study with 51 test subjects is a notable example, validating multi-stage signal processing procedures for heartbeat detection [?], [?].

This work presents an experimental study examining the impact of electrode type for heart rate monitoring from bioimpedance signals obtained on the wrist. Our approach, focusing on a bipolar electrode setup, aims to strike a balance between measurement accuracy and user convenience, potentially enabling smaller and more user-friendly wearable devices [?].

III. Materials and Methods

To develop the benchmark for electrodes in BioZ and BCC application, first of all we need to identify what are the parameters we are seeking. In other words, if we have ideal signal, what are parameters of that signal, and what changes of those parameters would lead to reduction of quality of the signal.

Starting our thought experiment with pure sine wave, with zero noise, and amplitude high enought, so the smallest changes in that sine-wave would be captured by our ideal ADC.

Now lets observe real life measurements (See figures 1, 2, 3) and try to identify what are those elements that separates real world form ideal.

Looking at 1, we see that "amplitude of inhale-exhale" is about 5 ohms, the measurement drifts from 1.72KOhm to 1.695KOhms over one minute. There is insignificant noise, about 0.1 Ohm and breathing pattern is clearly visible.

Looking at 2, we see that "amplitude of inhale-exhale" is about 5 ohms, the measurement drifts from 734Ohm to 736Ohms over one minute. There is insignificant noise, about 0.1 Ohm and breathing pattern is clearly visible.

Fig. 1. AgAgCl electrodes capturing breathing

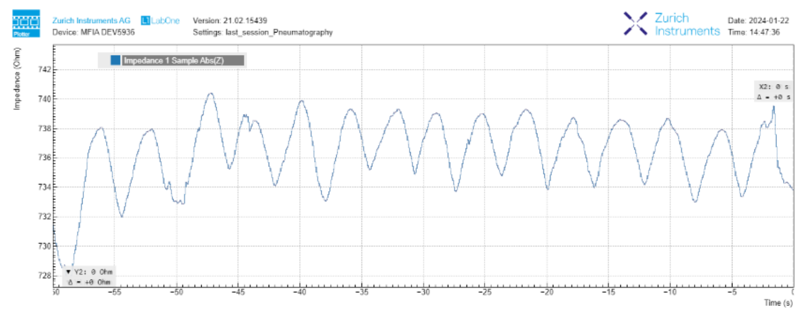

Fig. 2. Custom, gold plated electrodes capturing breathing

- MovSense our gel

- MovSense original gel

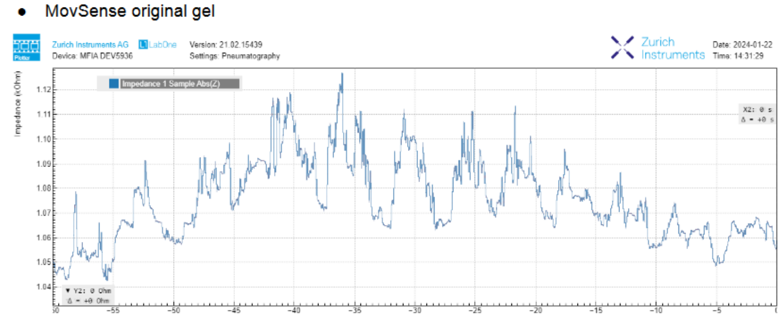

Fig. 3. Unknown electrodes from our shelf, we completely have no idea who is the manufacturer of those electrodes

Looking at 3, we are unable to see ”amplitude of inhale-exhale”, the measurement have no significant drift. There is drastic noise and artifacts, breathing pattern is not visible.

From those observations we can conclude that we are looking for electrodes that provides stable, low-noise, high amplitude signal.

So, to evaluate the electrodes, we will need to move from qualitative to quantitative analysis. firs of all we need to define the parameters that we are going to measure.

our proposal is to measure:

- Amplitude of inhale-exhale
- Drift of the measurement
- Noise
- SNR
- Artifacts
- Breathing pattern visibility
- Heartbeat pattern visibility
- Muscle activity pattern visibility
- Skin impedance (atkartojamība)

IV. Experimental Design

This section outlines the experimental procedures utilized to evaluate the performance of three distinct types of electrodes under various test conditions. The aim was to assess the electrodes’ impedance characteristics and their suitability for BioImpedance (BioZ) and Body Coupled Communication (BCC) applications. Experiments were systematically conducted across six different scenarios, employing both four-terminal and two-terminal connection methods.

A. Experimental Conditions

The electrodes were evaluated under the following test conditions:

1) Open Circuit - The electrodes were not connected to any medium or each other, serving as a control setup to measure the open-circuit impedance.
2) Copper Foil - Electrodes were placed on a conductive copper foil to simulate a uniform conductive environment.
3) Short Circuit/Flop - The electrodes were directly connected to each other, providing a zero impedance reference.
4) Fake Skin (Phantom) - The electrodes were placed on a synthetic skin substitute that had been moistened, mimicking the electrical properties of human skin.
5) Gel Bath - A bath of ultrasound gel served as another phantom medium, representing a different set of electrical properties for comparison.
6) Calf Placement - Electrodes were applied to the calf of human participants. This phase of the experiment is planned for future execution.

B. Connection Methods

Each of the above conditions was tested using the following electrode connection configurations:

1) Four-Terminal Parallel - The potential (voltage) terminals were attached to one electrode, while the current terminals were attached to a separate electrode. This setup aimed to minimize the impact of electrode impedance on the potential measurement.
2) Four-Terminal Series - The potential and current terminals on one side (Lpot and Lcur) were connected to the first electrode, whereas the potential and current terminals on the other side (Hpot and Hcur) were connected to the second electrode. This method allows for the evaluation of the combined impedance of the electrode-skin interface and the electrode itself.
3) Two-Terminal Bipolar - A straightforward bipolar measurement was conducted by using only two terminals, which combined the current and potential measurement through the same electrodes. This configuration is commonly used in simpler impedance measurement devices but is susceptible to electrode polarization effects.

C. Procedure

The experimental procedure for each test condition and connection method was as follows:

- Setup the impedance analyzer with the appropriate connection method.
- Calibrate the analyzer using the open and short circuit conditions.
- Apply the electrodes to the medium as specified by the test condition.
- Perform impedance measurements across a defined frequency range.
- Record the impedance values and any observed anomalies.
- Ensure environmental conditions such as temperature and humidity are consistent throughout the experiments.

D. Data Analysis

Data collected from the impedance measurements will be analyzed to determine the performance characteristics of each electrode type. The analysis will include:

- A comparison of impedance values under different test conditions.
- Assessment of the repeatability and reliability of the measurements.
- Statistical analysis to evaluate the significance of the observed differences.

E. Future Work

The upcoming calf placement experiments will involve:

- Applying electrodes to the calves of human participants after obtaining ethical approval and informed consent.
- Repeating the impedance measurements and comparing them with the phantom models.
- Analyzing the in vivo data in the context of the previous phantom experiments.

The results from these comprehensive experiments will inform the development of optimized electrodes for BioZ and BCC applications.