Electrodes for bio-electrical impedance and body-coupled communication

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***Abstract*—In the pursuit of enhancing healthcare through biomedical engineering and wearable technology, this research conducts a thorough investigation into the efficacy of different electrodes for Bioelectrical Impedance (BioZ) and Body-Coupled Communication (BCC) applications. We meticulously analyze Ag/AgCl, Electrical Muscle Stimulation (EMS), and gold-plated electrodes across a variety of metrics such as Signal-to-Noise Ratio (SNR), Settling Time, and Chip Error Rate (CER). Through a series of experiments tailored to assess their performance in monitoring heart rate, breathing, and facilitating data transmission through the human body, we uncover the specific contexts in which each electrode type excels.**

This study highlights the critical role of electrode choice in advancing non-invasive diagnostic methods through wearable technology. It provides a comprehensive comparison of various electrode types, highlighting their respective benefits for specific health monitoring applications. This research aims to guide the future development of wearable devices, aiming for an optimal balance between sustainability, accuracy, and user convenience in electrode selection for BioZ measurement and BCC applications.

I. Introduction

The intersection of biomedical engineering and wearable technology represents a frontier with the potential to revolutionize healthcare delivery, patient monitoring, and the management of chronic conditions. At the heart of this revolution lies the development and application of BioZ and BCC technologies, which promise to enhance non-invasive diagnostics and introduce innovative communication methods through the human body [1], [2]. Essential to the efficacy of these technologies are the electrodes used to capture and transmit biological signals, whose performance characteristics—such as SNR, settling time, and CER —are crucial for reliable and accurate health monitoring [3].

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This paper presents a comprehensive investigation into the performance of different electrode materials — Ag/AgCl, EMS, and gold-plated electrodes—in the context of BioZ and BCC applications. By meticulously analyzing their performance across various metrics, we aim to offer insights into the nuanced considerations involved in electrode selection, emphasizing the importance of balancing technical performance with user comfort and environmental impact [4], [5].

The relevance of electrode technology in biomedical applications cannot be overstated. As the primary interface between electronic devices and the human body, electrodes must exhibit high conductivity, biocompatibility, and stability to ensure accurate signal transmission and minimal interference [6]. The advancement of electrode technology, including the development of composite dry electrodes and flexible sensors, has significantly improved adhesion and signal collection, which are crucial for BioZ and BCC applications [7].

BioZ and body composition analysis leverage the electrical properties of human tissues to offer insights into physiological states and body composition. These methods depend heavily on the quality of the electrodes used, as the accuracy of measurements can be affected by the electrode's material properties and its interaction with the skin [8]. Gold-plated copper electrodes and disposable Ag/AgCl electrodes, for instance, present a dichotomy in terms of conductivity, stability, biocompatibility, and environmental impact [9], [10]. Gold-plated electrodes are renowned for their excellent electrical conductivity and minimal signal distortion, making them suitable for applications requiring high precision. Conversely, Ag/AgCl electrodes, while cost-effective and widely used, may exhibit performance variations due to oxidation, presenting a trade-off between affordability and long-term reliability.

The literature on electrode materials and their application in BioZ and BCC highlights a range of factors influencing electrode selection, including material sensitivity, environmental impact, cost-effectiveness, and signal quality [11]. Notably, the choice of material not only affects the accuracy and reliability of health monitoring applications but also has broader implications for sustainability and healthcare costs. As such, the electrode material selection process must carefully weigh these factors to achieve the optimal balance for each specific application.

Recent studies have emphasized the significance of advancing electrode technology to address the challenges faced in wearable bioimpedance devices and body-coupled communication systems. These challenges include optimizing electrode performance for improved signal quality, enhancing user comfort through better electrode design, and ensuring device sustainability and environmental friendliness [12]. The development of new electrode materials and configurations, such as flexible and wearable sensors that maintain consistent contact with the skin, represents a promising direction for overcoming these challenges.

Our research contributes to this ongoing dialogue by providing a detailed comparison of the performance characteristics of Ag/AgCl, EMS, and gold-plated electrodes in the context of BioZ and BCC. Through a series of controlled experiments designed to evaluate these electrodes across a variety of health monitoring applications, we uncover valuable insights into the specific contexts in which each electrode type excels. This analysis not only sheds light on the critical role of electrode selection in enhancing diagnostic methods and wearable technologies but also underscores the need for a comprehensive approach that considers technical performance alongside user comfort and environmental considerations.

In conclusion, the selection of appropriate electrode materials plays a pivotal role in the advancement of BioZ and BCC technologies, with implications that extend beyond mere technical performance to encompass environmental sustainability, economic efficiency, and the broader goal of improving patient care [3]. Our work aims to inform future developments in electrode design and application, pushing the boundaries of what is possible in non-invasive diagnostics and body-coupled communication. Through this research, we envision a future where enhanced diagnostic capabilities and innovative communication methods are not only possible but widely accessible, marking a significant leap forward in healthcare technology.

II. Materials and Methods

A. Electrode Types

This study investigates the performance of four distinct electrode types in BioZ measurements and BCC applications:

- **Classical Ag/AgCl Disposable Electrodes:** Predominantly used in Electrocardiography (ECG) for their excellent electrical conductivity and stable electrochemical properties. These electrodes, featuring a silver base coated with silver chloride, facilitate the accurate transduction of ionic to electronic current, essential for high-fidelity cardiac signal acquisition.
- **Reusable EMS electrodes:** These electrodes enhance skin adherence and moisture retention, potentially improving long-term signal stability and comfort.
- **Custom-Made Gold-Plated Copper Electrodes on Flexible Printed Circuit Board (PCB):** Offer superior durability, reusability, and biocompatibility, aimed at reducing environmental impact and operational costs.

Each electrode type's construction and material properties uniquely contribute to its performance in specific biomedical applications, from standard ECG measurements to innovative BCC functionalities.

B. Measurement Scenarios

We focused on three primary scenarios to evaluate electrode performance:

1) Heart Rate monitoring: This serves as a fundamental application for assessing electrode efficacy, focusing on the SNR and settling time. These parameters are critical for diagnosing cardiac conditions and ensuring the reliability of cardiac monitoring systems.

2) Pneumography: Exploration of electrodes' performance in impedance pneumography to understand their suitability for advanced healthcare monitoring. The emphasis is on evaluating electrodes under realistic conditions that mimic their intended use in wearable technologies and non-invasive diagnostic tools.

3) BCC: This technology presents a groundbreaking use-case for the electrodes under test, highlighting their role in enabling efficient and secure data transmission through the human body. BCC technology utilizes the body as a conductive medium for electronic signals, offering a promising solution for wearable device interconnectivity and data exchange in personal healthcare systems.

C. Performance Evaluation Parameters

This methodology aims to provide a robust framework for comparing the efficacy of various electrode types in biomedical applications, contributing to the development of more reliable, efficient, and user-friendly non-invasive diagnostic and communication technologies.

The study quantitatively assesses electrode performance using the following metrics:

SNR: Essential for determining the clarity and quality of BioZ signals and BCC data transmission. The SNR is calculated as the ratio of signal amplitude (averaging signal over time) to the standard deviation of the background noise, providing a quantitative measure of the signal's fidelity and integrity. A higher SNR indicates a clearer, more reliable signal, essential for accurate data analysis and interpretation.

Settling Time: Measures the time electrodes take to stabilize their signal upon placement, indicating their readiness for immediate data acquisition.

The settling time refers to the duration needed for a signal to stabilize, with variations no more than 5% during one cycle of changes in a person's vital signs. This measurement is especially important for situations that demand quick preparation and instant signal capture, such as in emergency medical scenarios or ongoing health monitoring.

CER for BCC: Assesses the reliability of data transmission through the body, reflecting the efficiency of electrode-based communication systems.

The CER is calculated as the ratio of the number of bit errors to the total number of bits transmitted, providing a quantitative measure of the data transmission quality. A lower CER indicates a more reliable communication channel, essential for ensuring the accuracy and integrity of transmitted data in BCC applications.

D. Experimental Setup

Experiments evaluating electrode performance were conducted on two body locations: the chest and the upper arm, as illustrated in Fig. 1 for the chest and Fig. 2 for the upper arm.

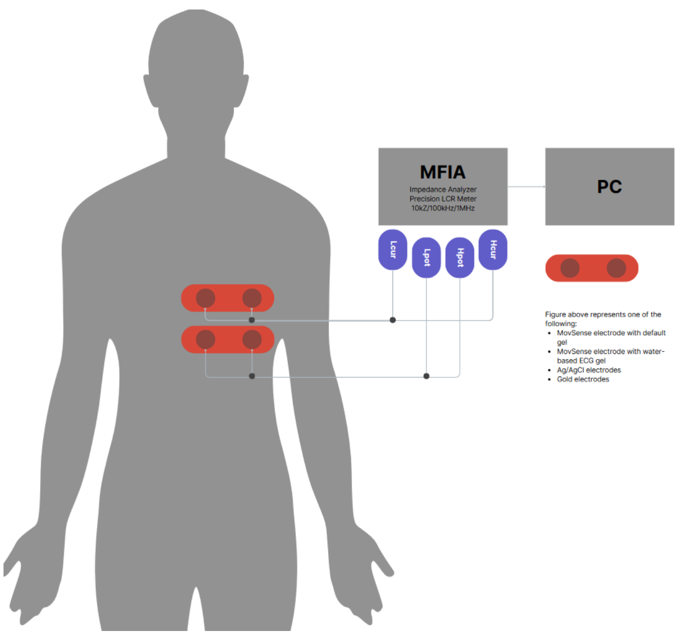

Fig. 1. Electrode placement in the experimental setup for evaluating the electrode performance on chest.

The study employs an MFIA Impedance Analyzer for BioZ signal measurement and Software Defined Radio (SDR) for evaluating BCC communication quality. Data acquisition and analysis were facilitated through custom scripts in Python, enabling the extraction of SNR, settling time, and CER metrics from the collected data.

Electrodes were tested under controlled conditions to simulate their application in BPG recording, BioZ pneumography, and BCC scenarios.

E. Equipment and Materials

- Electrode connectros that would allow to plug them to MFIA analyzer and SDR
- MFIA impedance analyzer

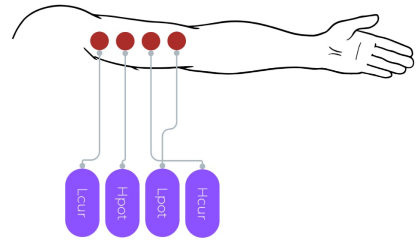

Fig. 2. Electrode placement in the experimental setup for evaluating the electrode performance on the upper arm.

- SDR
- Ag/AgCl electrodes
- Gold plated electrodes
- EMS electrodes

F. Experiment Procedure

Each experiment will follow the steps outlined below, to be repeated for each type of electrode:

1) **Preparation:** Ensure all equipment is calibrated according to the manufacturer's instructions. Prepare the subject by cleaning the skin area near the left side of the body near the last rib and upper arm for electrode placement.
2) **Electrode Placement:** Apply one type of electrodes to the prepared skin area.
3) **Measurement:**
   a) **Heart Rate Measurement:** Instruct the subject to hold their breath. Measure the heart rate using the MFIA impedance analyzer. Record the data.
   b) **Breathing Measurement:** Without altering the electrode placement, measure the subject's breathing using the MFIA impedance analyzer. Record the data.
4) **Repeat:** Repeat steps 1, 2 and 3 for each type of electrode and each skin area.
5) **Electrode Placement:** Apply one pair of electrodes to chest area and another pair to the upper arm.
6) **Data Transmission:** Utilize the SDR to measure the data transmission capabilities of the electrodes. Record the data.
7) **Repeat:** Repeat steps 5 and 6 for each type of electrode.

Data were collected across static conditions to assess each electrode type's performance.

III. Results

In this section, we outline the experimental outcomes from comparison among Ag/AgCl electrodes, EMS electrodes, and gold-plated electrodes. The evaluation metrics included SNR for both breathing and pulse signals, Settling Time for signal stabilization, and CER for BCC. The summary of experimental results is shown in Table I. Instances where signal quality was insufficient for measurement are denoted by "-".

A. Signal-to-Noise Ratio

Breathing (Upper Arm): The SNR values for Ag/AgCl and EMS electrodes were 10 and 12, respectively, with gold-plated electrodes at a lower SNR of 5.

Breathing (Chest): Gold-plated electrodes significantly outperformed with an SNR of 30, against 10 for Ag/AgCl and 15 for EMS electrodes.

Pulse (Upper Arm): Gold-plated electrodes exhibited a superior SNR of 1, compared to 0.5 for Ag/AgCl electrodes, with EMS electrodes' signal being too poor to measure.

Pulse (Chest): The SNR for Ag/AgCl electrodes was slightly better at 1, versus 0.5 for gold-plated electrodes. The EMS electrodes' performance could not be measured.

B. Settling Time

Breathing (Upper Arm): EMS electrodes demonstrated an instantaneous settling time (0 seconds), followed by gold-plated (10 seconds) and Ag/AgCl electrodes (30 seconds).

Breathing (Chest): Gold-plated electrodes achieved the fastest settling time at 0 seconds, Ag/AgCl electrodes followed at 5 seconds, and EMS electrodes lagged at 20 seconds.

Pulse (Upper Arm): Both Ag/AgCl and gold-plated electrodes registered a settling time of 2 seconds. EMS electrodes' quality was unmeasurable.

Pulse (Chest): Settling time for gold-plated electrodes was recorded at 5 seconds, outperforming Ag/AgCl electrodes which stood at 7 seconds. EMS electrodes' signal was again unmeasurable.

C. Chip Error Rate in BCC

The Chip Error Rate for BCC was found to be lowest for Ag/AgCl electrodes at 3.30%, followed by EMS at 5.20%, and gold-plated electrodes at 5.50%.

These experimental insights depict a nuanced landscape of electrode performance, where no single type consistently excels across all metrics. Notably, gold-plated electrodes demonstrate superior capability in specific scenarios, particularly in SNR for chest breathing signals and the settling time for breathing signals, highlighting their application-specific advantages. However, their performance varied across the board, emphasizing the importance of tailored electrode choice based on precise application needs. The EMS electrodes faced challenges in reliable signal acquisition for some metrics, indicating their limitations in the tested scenarios.

TABLE I
SUMMARY OF EXPERIMENTAL RESULTS FOR ELECTRODE PERFORMANCE ACROSS DIFFERENT METRICS AND SCENARIOS.

Metric	Ag/AgCl	EMS	Gold
SNR - Breathing - Upper Arm	10	12	5
SNR - Breathing - Chest	10	15	30
Settling Time - Breathing - Upper Arm	30s	0s	10s
Settling Time - Breathing - Chest	5s	20s	0s
SNR - Pulse - Upper Arm	0.5	-	1
SNR - Pulse - Chest	1	-	0.5
Settling Time - Pulse - Upper Arm	2s	-	2s
Settling Time - Pulse - Chest	7s	-	5s
CER - BCC	3.30%	5.20%	5.50%

IV. DISCUSSION

This comprehensive investigation into Ag/AgCl, EMS, and gold-plated electrodes has yielded nuanced insights into their performance across BioZ measurements and BCC, underscoring the complex interplay between material properties and application-specific requirements. This discussion seeks to contextualize this findings within the broader landscape of biomedical engineering and wearable technology, drawing connections to existing literature and highlighting potential avenues for future research.

A. Comparative Analysis of Electrode Performance

The differential performance of Ag/AgCl, EMS, and gold-plated electrodes across various metrics—such as SNR, Settling Time, and CER —emphasizes the critical role of electrode material and design in biomedical applications. Gold-plated electrodes demonstrated superior SNR in certain scenarios, aligning with findings by Zhao et al. [9], who highlighted the excellent electrical conductivity and minimal signal distortion of gold as a material. However, this study extends these observations by comparing gold-plated electrodes' performance not just on electrical properties but also on their application in real-world biomedical monitoring scenarios, offering a comprehensive view of their utility.

B. Implications for Wearable Technology and Patient Monitoring

The variation in electrode performance across different applications—particularly in the context of wearable technology and patient monitoring—highlights the importance of selecting the right electrode type based on specific use-case requirements. For instance, the superior performance of gold-plated electrodes in terms of SNR for chest breathing measurements suggests their suitability for respiratory monitoring applications, which is crucial for managing conditions such as asthma or chronic obstructive pulmonary disease (COPD). This finding aligns with recent advancements in wearable respiratory monitoring technologies, which emphasize the need for high fidelity in signal capture [7].

C. Bioelectrical Impedance Analysis and BCC: Bridging the Gap Between Diagnosis and Communication

This study's focus on both BioZ and BCC technologies reflects an emerging trend in the field: the integration of diagnostic and communication capabilities within a single wearable platform. The lower CER observed with Ag/AgCl electrodes in BCC applications suggests their potential for enhancing the reliability of data transmission through the human body. This capability is pivotal for the next generation of wearable devices that not only monitor health metrics but also communicate these data securely to healthcare providers or other devices. The integration challenges and opportunities highlighted by this findings suggest a fertile ground for innovation, echoing the sentiment of recent studies that call for a unified approach to wearable health technology development [12].

D. Future Research Directions

Looking ahead, several areas warrant further investigation to build on this findings. The development of new electrode materials that combine the biocompatibility and durability of gold with the cost-effectiveness and environmental sustainability of Ag/AgCl represents a significant research opportunity. Additionally, exploring the impact of electrode size, shape, and placement on both diagnostic accuracy and wearer comfort could yield valuable insights for the design of next-generation wearable devices. Finally, advancing the capabilities of BCC technology, particularly in terms of reducing CER and enhancing data transmission rates, remains a critical challenge for the field.

E. Concluding Remarks

In conclusion, this study contributes to a deeper understanding of the critical factors influencing electrode selection in biomedical applications, bridging the gap between material science and wearable technology development. By offering a comprehensive comparison of Ag/AgCl, EMS, and gold-plated electrodes, we highlight the nuanced trade-offs that must be navigated to optimize the performance of BioZ measurements and body-coupled communication systems. This work lays the groundwork for future research aimed at enhancing the efficacy, reliability, and user-friendliness of non-invasive diagnostic and communication technologies in healthcare.

V. Conclusion

This rigorous examination of Ag/AgCl, EMS, and gold-plated electrodes within the realms of BioZ measurements and BCC has unveiled intricate insights into their performance, applicability, and impact on future healthcare technologies. This research not only delineates the technical attributes of these electrodes but also emphasizes their potential in revolutionizing patient care through enhanced diagnostic and communication capabilities.

A. Key Findings and Implications

The study's findings reveal a distinct performance landscape where each electrode type exhibits unique strengths and limitations across different biomedical applications. Ag/AgCl electrodes, with their lower CER , emerge as a preferred choice for BCC applications, ensuring reliable data transmission through the human body. This characteristic is pivotal for wearable technologies that necessitate secure and efficient communication of health data. On the other hand, gold-plated electrodes showcase superior SNR in specific scenarios, such as chest-based respiratory monitoring, highlighting their potential for applications requiring high precision in signal capture. The EMS electrodes, with their instant settling time, offer an intriguing balance between performance and user comfort, suggesting their suitability for long-term monitoring applications where rapid signal stabilization is crucial.

These findings bear significant implications for the design and development of next-generation wearable healthcare devices. By selecting the appropriate electrode type based on the specific needs of the application, device manufacturers can enhance the accuracy, reliability, and user experience of wearable diagnostics and communication systems. This, in turn, can lead to more personalized and effective patient care, empowering individuals to manage their health proactively.

B. Future Research Directions

Looking forward, the study opens several avenues for further research aimed at overcoming the current limitations and unlocking the full potential of electrode technologies in healthcare. A key area of focus is the development of new electrode materials and configurations that marry the best attributes of the examined electrode types, such as the biocompatibility and durability of gold with the cost-effectiveness of Ag/AgCl. Investigating the impact of electrode size, shape, and placement on measurement accuracy and wearer comfort will also be critical for optimizing the design of wearable devices.

Moreover, advancing the capabilities of BCC technology to improve data transmission efficiency and reduce error rates remains a crucial challenge. Addressing these issues can significantly enhance the functionality and reliability of wearable health systems, making them more adaptable to diverse healthcare applications.

C. Concluding Reflections

In sum, this comparative study of Ag/AgCl, EMS, and gold-plated electrodes provides valuable insights into the complex considerations involved in electrode selection for biomedical applications. By highlighting the nuanced trade-offs between technical performance, user comfort, and environmental sustainability, this research contributes to the informed development of advanced wearable health technologies. As we continue to explore and innovate in this space, the pursuit of optimized electrode solutions will play a critical role in shaping the future of non-invasive diagnostics and communication in healthcare, ultimately leading to better health outcomes and quality of life for patients worldwide.

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