Advancements in Wearable EEG Technology: Electrode Characterization and Signal Quality Assessment

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Abstract: This research contributes to the advancement of practical, user-friendly EEG devices for both research and real-world applications. The paper presents a comprehensive study on the development and characterization of wearable electroencephalography (EEG) recording in non-traditional electrode locations. In particular, we focus on optimizing electrode placement, material selection, and signal quality assessment. Our investigation includes impedance testing of various electrode materials, comparative analysis of dry versus wet electrodes, and validation through standard EEG protocols. Results demonstrate the feasibility of acquiring high-quality EEG signals from over-the-ear locations where using gold-plated brush electrodes with retractile pins, show superior impedance characteristics ($10^5\Omega$) compared to other tested materials. We also validate and compare dry electrodes by means of an eyes-open/eyes-closed protocol, confirming the ability to detect alpha rhythm modulation in non-traditional electrode placements.

1 INTRODUCTION

Electroencephalography (EEG) has been a fundamental tool in neuroscience and clinical practice (Berger, 1929). This non-invasive technique measures the electrical activity of the brain by recording voltage fluctuations resulting from ionic current flows within neurons (Teplan, 2002) and emerging to the scalp. EEG provides excellent temporal resolution and has a variety of application such as cognitive processes, diagnosing neurological disorders, and developing brain-computer interfaces (Lotte et al., 2018).

Traditional EEG systems typically utilize the international 10-20 system for electrode placement (Klem et al., 1999), which yields comprehensive spatial information, but presents significant limitations for its use outside controlled laboratory or clinical environments. The complexity of setup, need for skin preparation, and use of conductive gels make traditional EEG systems impractical for long-term or everyday use (Casson et al., 2010).

Recent advancements in miniaturized electronics, sensor technologies, and signal processing algorithms have sparked interest in developing more portable and user-friendly EEG acquisition devices (Mihajlovic et al., 2015). These wearable EEG systems aim to enable continuous, high-quality brain monitoring in real-world settings, potentially expanding the applications of EEG in fields such as personalized medicine, cognitive monitoring, and human-computer interaction (Lin et al., 2014).

The development of wearable EEG technology faces several significant challenges due to the difficulty in measuring high quality EEG signal using small devices. These include optimizing electrode placement for non-traditional locations, improving signal quality from dry electrodes, ensuring user comfort and social acceptability, managing power consumption for continuous recording, and developing robust algorithms for real-time signal processing in noisy environments (Mullen et al., 2015). Additionally, wearable EEG systems often employ a reduced number of channels compared to traditional setups, which further complicates the issue of optimal elec-

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trode placement (Debener et al., 2015). The use of dry electrode designs is also affected by the presence of hair which can substantially increase the impedance potentially comprommising the measured EEG signal quality(Lopez-Gordo et al., 2014).

In this study we chose over-the-ear locations for EEG electrodes as it is justified by different factors. Firstly, this area offers a balance between signal quality and user comfort, as it is less obtrusive than traditional scalp placements (Bleichner and Debener, 2017). Secondly, the proximity to temporal and parietal lobes provides access to relevant brain activity (Mikkelsen et al., 2015) while maintaining a socially acceptable form factor (Norton et al., 2015).

This paper presents a comprehensive study addressing several key aspects of electrodes employed in EEG enabled devices, with a specific focus on over-the-ear electrode placement. Our research tackles three areas of interest: i) evaluating different electrode materials and designs to enhance signal acquisition in this unique anatomical region; ii) comparing dry and wet electrodes for over-the-ear placement; and iii) assessing the quality of EEG signals obtained from our over-the-ear prototype system through standard EEG protocols and comparing them with traditional setups.

By addressing these crucial aspects in the context of over-the-ear placement, our study aims to contribute to the advancement of practical, user-friendly EEG devices suitable for both research and real-world applications.

The following sections detail our methods for electrode characterization and signal quality assessment specific to over-the-ear placement, present our findings, and discuss their implications for the future of wearable EEG technology.

2 METHODS

In the next sections, three data acquisitions protocols are described and then the resulting data are later analized.

All the data acquisition on subjects was performed according to the descriptive rules reported in the experimental protocol (Opinion 46/2023, dated December 18^{th}, 2023) that received approval from the Politecnico di Milano Ethical Committee.

2.1 Dry Impedance Testing

The study involved a set of 6 gender-balanced healthy subjects (age: 28 ± 1.73). Four different dryelectrode types were tested: conductive elastomer (CE), PLA+carbon, TPU+carbon, and gold-plated with retractile pins brush (GPR) electrodes (Brainbit Inc., New York, NY, USA). Each electrode material was tested three times per subject.

The impedance was measured using a PalmSens EmStat 4S potentiostat (PalmSens BV, Houten, Netherlands) in a two-electrode configuration. We positioned the test electrode (serving as the working electrode) behind the left ear, while a gel electrode, acting as the reference and counter electrode, was placed below the working electrode (see Figure 1 for reference). This placement mimics the intended configuration for an around-the-ear wearable EEG system.

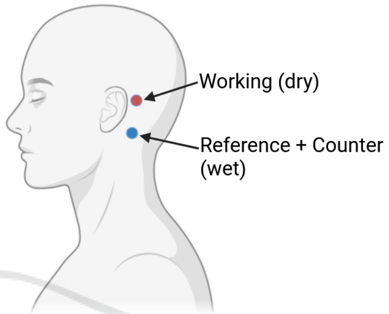

Figure 1: Positioning of the electrodes in the skin-electrode impedance test.

The potentiostat generated a sine wave with an amplitude of $100mV_{rms}$ and $0V$ bias, sweeping frequencies between $0.5Hz$ and $10kHz$.

2.2 Dry vs. Wet Electrode Comparison

A set of five healthy participants (2 females, age: 28.6 ± 4.84,) were recruited for a comparative study of dry and wet electrodes during baseline recordings. For dry electrodes, we used both brush CE and GPR electrodes in occipital area. For wet electrode recordings, we utilized an EBNeuro BEPlus LTM amplifier with a 61-electrode cuff and gel was applied under the examined electrodes (i.e., the ones placed in the same locations of the dry configuration).

Each subject underwent 1 minute of baseline recording in a resting state with eyes open for each electrode configuration.

2.3 Eyes Open/Closed Experiment

The study involved 10 healthy subjects (age: 27.2 ± 1.8, gender-balanced). We used GPR electrodes connected to a MAX30001 evaluation kit (Analog Devices Inc., Wilmington, MA, USA), recording EEG signals at 512Hz. Flat CE electrodes were used for ground (GND) and reference, placed at the nasion.

The EOEC serves as an excellent initial test for new EEG systems due to its simplicity and reliability (Barry et al., 2007). The primary objectives were to validate the ability of our chosen electrode configurations to capture meaningful EEG signals in both traditional and non-traditional scalp locations, to assess the sensitivity of our setup in detecting the well-known alpha rhythm (i.e, activity in the $8-12Hz$ frequency band) modulation associated with eye closure, and to evaluate the overall signal quality and reliability of EEG recordings obtained from our prototype system.

Each subject participated in two recording sessions:

1. GPR electrode placed in the occipital zone (serving as a ground truth for eyes-closed alpha activity)
2. GPR electrode placed over the ear (our prototype configuration)

In each session, subjects followed a protocol alternating between eyes open and eyes closed states. The protocol consisted of two minutes with eyes open, followed by two minutes with eyes closed. This cycle was repeated twice, resulting in a total recording duration of eight minutes per session. The recorded signal was then filtered between 1-30 Hz to mitigate artifacts and line interference effects.

3 RESULTS

3.1 Impedance Testing

The impedance tests revealed significant differences among the tested electrodes. GPR electrodes demonstrated substantially lower impedance in the band of interest ($1-100$ Hz), approximately $10^5\Omega$, compared to the other electrode types, which exhibited impedance around $10^7\Omega$. See Figure 2 for details on impedance response of the materials tested.

3.2 Dry vs. Wet Electrode Comparison

In the comparison of dry and wet electrodes, we focused on the high-frequency components (above 55 Hz) of the Power Spectral Density (PSD), where noise components are dominant. CE electrodes exhibited the highest PSD values in this high-frequency range (see Figure 3 for reference), indicating greater susceptibility to noise. The GPR electrodes showed intermediate PSD values, while wet electrodes demonstrated the lowest PSD values, confirming their superior performance in noise rejection.

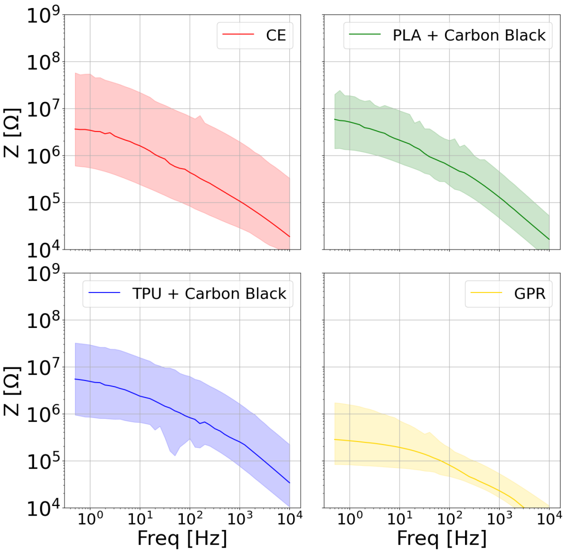

Figure 2: Electrode-skin impedance for the tested materials.

To further assess the signal quality, we computed the signal prevalence for each electrode type as the ratio of the power in each traditional brain activity bands (delta, theta, alpha, and beta) to the power in the high-frequency band (> 55 Hz), which we consider representative of noise. Table 1 presents these ratios, reported as median ± interquantile range (IQR).

Table 1: Median and IQR of brainwave band power ratios normalized by the power in the > 55 Hz band (associated with noise) for wet, CE, and GPR electrode types. Values represent the relative strength of each brainwave band compared to the high-frequency noise component.

Band	WET	GOLD	DRY
delta (1-4Hz)	30.02 ± 17.07	8.49 ± 3.51	6.04 ± 5.59
theta (4-8Hz)	7.03 ± 12.33	1.52 ± 2.59	0.83 ± 1.80
alpha (8-12Hz)	2.87 ± 1.96	1.00 ± 1.29	0.36 ± 0.18
beta (12-30Hz)	2.18 ± 1.86	0.85 ± 0.99	0.61 ± 0.27

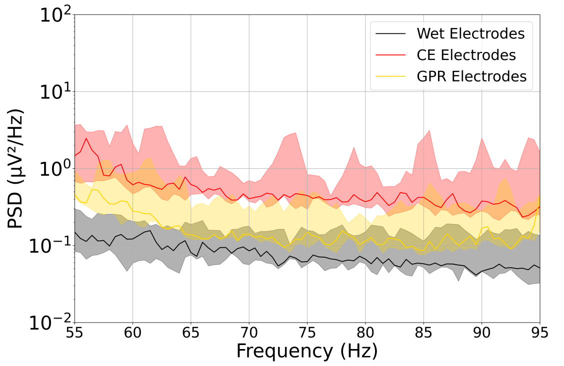

Figure 3: Comparison of Power Spectral Density (PSD) for frequencies above $55Hz$ between CE, GPR, and wet electrodes. PSD is reported on a logarithmic scale, with median IQR shown for each electrode type.

In this analysis, higher values correspond to more reliable and robust signals. Consistent with the PSD results, wet electrodes achieved the highest ratios across all frequency bands, indicating the best signal quality. The GPR electrodes showed intermediate performance, while the CE electrodes yielded the lowest ratios, suggesting they are more susceptible to noise interference. Due to the superior impedance characteristics demonstrated by GPR electrodes, the subsequent EOEC experimental results will focus exclusively on this electrode type

3.3 Eyes Open/Closed Experiment

Both electrode placements (occipital and over-ear) captured clear modulation of alpha activity corresponding to the eyes open/closed cycles. The spectrograms (see Figures 4 and 5) showed increased power in the alpha frequency band (8-12 Hz) during eyes-closed periods as expected (Barry et al., 2007). This effect was more pronounced in the occipital electrode placement (as expected from the literature), but was also clearly visible in the over-the-ear configuration.

The alpha ratio (power in alpha normalized by broadband power) analysis revealed significantly higher values during the eyes-closed phases in both recording setups (see Table 2).

Table 2: Distribution of Alpha ratio recorded in the occipital and over-the-ear locations in the different phases of the protocols (EO: eyes open, EC: eyes closed) along the examined population (median ± IQR).

Location	EO 1	EC 1	EO 2	EC 2
Occipital	0.76 ± 0.21	3.88 ± 0.74	0.81 ± 0.17	4.21 ± 0.60
Over-the-ear	0.62 ± 0.13	3.31 ± 0.67	0.92 ± 0.20	3.54 ± 0.59

The results show that both electrode placements successfully captured the expected alpha rhythm modulation between eyes-open and eyes-closed conditions. As anticipated, the occipital placement showed the strongest effect, with the highest alpha ratios during eyes-closed periods. The over-the-ear placement demonstrated a robust ability to detect the alpha rhythm modulation, with alpha ratios comparable to those observed in the occipital placement.

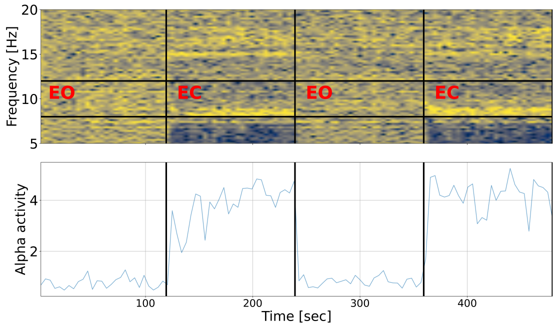

Figure 4: Spectrogram (top) and alpha ratio (bottom) for the occipital electrode placement during eyes open/closed cycles. The spectrogram show power across frequencies over time, while the alpha ratio plot displays the ratio of alpha band power to total power. EO = Eye-Open period; EC = Eye-Closed period.

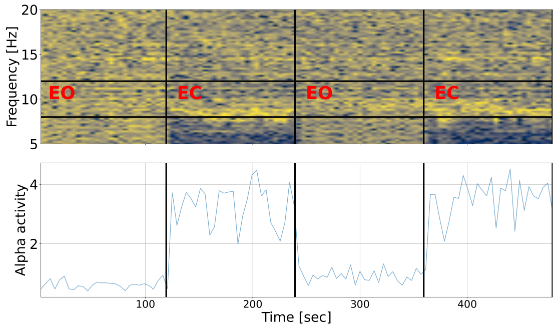

Figure 5: Spectrogram (top) and alpha ratio (bottom) for the over-ear electrode placement during eyes open/closed cycles. The spectrogram shows power across frequencies over time, while the alpha ratio plot displays the ratio of alpha band power to total power. EO = Eye-Open period; EC = Eye-Closed period.

These findings suggest that the over-the-ear electrode placement, using GPR electrodes, is capable of reliably detecting fundamental EEG phenomena such as alpha rhythm modulation. This supports the potential of this configuration for use in wearable EEG devices.

4 DISCUSSION

Our study on wearable over-the-ear EEG technology revealed several significant findings. GPR electrodes demonstrated superior impedance characteristics ($10^5\Omega$ compared to $10^7\Omega$ for other types), suggesting better electrode-skin interface performance. While wet electrodes showed the best signal quality, GPR electrodes provided a practical alternative balancing signal quality and user convenience.

The EOEC experiments validated the feasibility of acquiring meaningful EEG signals from over-the-ear locations, with alpha activity modulation comparable to traditional occipital placements. This suggests over-the-ear placement could be viable for certain EEG applications, offering advantages in user comfort and social acceptability. The ability to capture meaningful EEG data from this location is particularly significant for developing wearable devices that could be worn for extended periods in everyday settings.

The combination of over-the-ear electrode placement and GPR electrodes offers a promising configuration for wearable EEG devices, providing an optimal balance of signal quality, potential user comfort, and practical applicability. This addresses key challenges in developing wearable EEG technology for everyday use. However, while our results are promising for short-term recordings, the long-term stability and comfort of the proposed configurations require further investigation. Additionally, performance during physical activity or in noisy environments needs to be assessed.

Future work should focus on increasing sample size, assessing long-term stability and comfort, investigating performance during complex cognitive tasks beyond the EOEC paradigm, and developing specialized signal processing algorithms for over-the-ear recordings. These investigations will provide a more comprehensive understanding of the capabilities and limitations of over-the-ear EEG recordings.

5 CONCLUSION

Our research demonstrated that GPR electrodes achieve superior impedance characteristics for over-the-ear EEG signal acquisition. The successful detection of alpha rhythm modulation in over-the-ear locations, comparable to traditional occipital placement, validates this approach for EEG recording. The combination of over-the-ear placement and GPR electrodes provides a promising configuration for wearable EEG devices, effectively balancing signal quality and user comfort. Future studies investigating more complex cognitive tasks beyond EOEC paradigms would further validate and strengthen these findings, potentially expanding the applications of this wearable EEG technology.

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