Contact Impedance Characterization of a 3D-Printed Dry EEG Electrode

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***Abstract*—Dry electroencephalography (EEG) electrodes represent a promising alternative to conventional gel-based Ag/AgCl systems, particularly for mobile and long-term monitoring. However, their performance is strongly governed by the electrode–skin interface impedance, which directly affects signal attenuation, noise susceptibility, and overall signal fidelity. In this study, a custom dry EEG electrode was designed and fabricated using additive manufacturing with an electrically conductive Filaflex filament. The objective was to experimentally characterize its complex contact impedance and evaluate its suitability for biopotential sensing. The complex contact impedance was evaluated on an agar-based phantom using a three-electrode configuration over a frequency range of 0.5 Hz to 1.1 kHz. Particular attention was given to the EEG-relevant band (0.5–60 Hz). The results demonstrate frequency-dependent impedance with predominantly capacitive behavior and values compatible with modern high-input-impedance amplifiers. Compared with a reference dry electrode, the proposed design achieved comparable, and in some regions lower, impedance magnitude. The developed electrode represents a low-cost and customizable alternative to commercially available dry EEG electrodes, with potential for application-specific optimization in wearable neurophysiological systems.**

***Index Terms*—agar phantom, conductive filament, dry electrode, electrical impedance**

I. Introduction

Electroencephalography (EEG) serves as a critical modality in neuroscience and clinical diagnostics, offering superior temporal resolution for non-invasive neural monitoring [1]. Central to applications ranging from brain-computer interfaces (BCIs) to cognitive analysis is the electrode-skin interface, which governs the transduction of physiological ionic currents into electronic signals [2]. The conventional gold standard for signal acquisition remains the wet Ag/AgCl electrode; this configuration necessitates conductive electrolytes to establish low interfacial impedance (< 40 kΩ), a prerequisite for minimizing thermal noise and securing a high signal-to-noise ratio (SNR) [3]. Despite their prevalence, wet EEG electrodes present significant operational challenges, particularly outside controlled environments. The necessity for skin abrasion and gel application renders the setup time-consuming and technician-dependent, while potentially inducing dermatological irritation [4]. Moreover, signal stability degrades during long-term recordings due to gel dehydration [5], with contact impedance demonstrated to triple over a five-hour period [6]. Finally, in high-density EEG electrodes arrays, the fluidity of the gel or paste introduces the risk of conductive bridging between adjacent channels, resulting in short circuits and compromised spatial resolution.

In response to these drawbacks of wet EEG electrodes, dry EEG electrodes have emerged as a promising alternative, eliminating the need for conductive gels and complex skin preparation. By streamlining preparation and enhancing comfort, these dry electrodes-based systems facilitate long-term and mobile EEG monitoring. Predominant designs utilize pin- or comb-like geometries to penetrate hair, employing materials ranging from Ag/AgCl-coated thermoplastic polyurethane (TPU) [7] and carbon fiber [8] to conductive textiles [9]. Although specific iterations, such as the active claw-shaped sensor by Wang et al. [7], show promise, dry electrodes typically exhibit elevated interfacial impedance (¿50 kΩ). This characteristic renders them susceptible to motion artifacts, primarily due to mechanical decoupling between the rigid electrode structure and the scalp during subject movement [9].

Ongoing discourse questions whether dry EEG electrodes can achieve signal fidelity comparable to traditional wet EEG systems. Signal integrity is intrinsically governed by the electrode-tissue interface, with contact impedance acting as the definitive performance metric; elevated impedance correlates directly with signal attenuation and noise susceptibility [10]. The standard protocol for characterizing this interface involves measuring the impedance spectrum via a small-amplitude frequency sweep (0.1 Hz – 1 kHz), a non-destructive method that elucidates both resistive and capacitive components [11]. For comparative standardization, impedance is frequently reported at 10 Hz, aligning with the spectral dominance of the neural alpha band. However, single-point characterization offers an incomplete assessment of electrode performance. Neural activity spans a broad spectral range - from delta (0.5–4 Hz) to gamma (¿30 Hz) - with each band underpinning distinct cognitive and clinical phenomena. Detailed spectral analysis is particularly critical for dry electrodes, which typically exhibit pronounced capacitive behavior.

Recent advances in electrically conductive filaments for additive manufacturing have expanded opportunities for rapid prototyping of biomedical sensing components [12], [13]. In EEG applications, 3D printing with conductive materials en-