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Advancing High-Density EEG: Performance and Prospects of Dry Electrode Technologies and Ultra-High-Density Arrays

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Abstract

HD-EEG electrode arrays have become a critical technology for advancing spatial resolution and wearability in neural signal acquisition, though issues such as setup intricacy and signal fidelity remain with traditional wet electrodes. We conduct a systematic examination of recent progress in dry electrode technologies (e.g., MXene-based and microneedle arrays) and ultra-high-density designs, with a performance assessment relative to conventional Ag/AgCl systems based on a PRISMA-compliant analysis of peer-reviewed literature from 2015 to 2024. The results indicate MXene-based dry electrodes attain high spatial resolution (3 mm spacing) and robust ERP correlation ($\rho \geq 0.95$) despite elevated impedance (5.15 kΩ cm^2), whereas microneedle arrays reduce hair interference with consistent impedance (5.5 ± 0.6 kΩ) and elevated density (6.25 electrodes/cm^2). Ultra-high-density arrays, exemplified by a 65,536-channel CMOS/MEMS configuration, achieve sub-millimeter spacing but are constrained by signal transmission challenges (620 kΩ impedance). Furthermore, advancements in spatial resolution are observable in visual processing tasks, with 512-channel arrays improving classification accuracy and source localization, while 128-channel setups (14 mm spacing) uphold temporal resolution in frequency-tagged responses. Nevertheless, gaps remain in longitudinal performance data and ecological validity for real-world applications. This review underscores the promise of dry electrodes and ultra-high-density arrays in progressing non-invasive brain-computer interfaces, clinical diagnostics, and cognitive neuroscience, yet additional investigation is required to resolve impedance compromises and the fusion of multiple modalities with technologies such as fNIRS or MEG. This study presents a thorough assessment of contemporary advancements and prospective developments in high-density electroencephalography systems.

Keywords: HD-EEG, dry electrodes, MXene, microneedle arrays, brain–computer interface, spatial resolution, EEG, wearable neurotechnology, CMOS/MEMS, neuroimaging.

I. INTRODUCTION

Electroencephalography (EEG) has for decades served as a pivotal tool in neuroscience investigations and medical assessments, granting a non-invasive perspective on cerebral activity with millisecond precision in timing [1]. Traditional EEG systems, however, face limitations in spatial resolution due to the sparse distribution of electrodes and the signal attenuation caused by the skull and scalp [2]. Recent developments in high-density EEG (HD-EEG) electrode arrays seek to overcome these constraints by expanding the quantity of recording sites and optimizing electrode-skin contact, thus improving both spatial and signal accuracy [3].

The move to dry electrode methods marks a major advancement in HD-EEG, as it removes the necessity for conductive gels, cuts down setup duration, and boosts comfort during wear [4]. Dry electrodes, including examples based on MXene materials or microneedle arrays, have shown promising performance regarding signal quality and user comfort, yet issues concerning impedance and durability remain unresolved [5]. At the same time, ultra-high-density configurations, such as CMOS/MEMS-based arrays, advance spatial resolution limits with sub-millimeter electrode spacing, which yields unprecedented detail in neural signal acquisition [6]. These developments are especially pertinent for technologies including brain-computer interfaces (BCIs), which demand superior spatial precision and user-friendliness [7].

The primary objective of this study is to systematically evaluate the performance of dry electrode technologies and ultra-high-density EEG arrays against conventional wet Ag/AgCl systems. We propose dry electrodes may attain similar or better signal quality while resolving primary drawbacks of conventional systems, including discomfort and complicated preparation. This hypothesis is supported by recent findings showing the ability of dry electrodes to sustain high signal-to-noise ratios (SNR) under difficult recording conditions [8]. Furthermore, we explore the trade-offs between electrode density, spatial resolution, and practical usability, which are critical for translating these technologies into real-world applications.

This research holds importance due to its capacity to propel progress in both theoretical and practical neuroscience. For example, better spatial resolution could improve the precision of source localization in clinical environments, which supports the identification and management of neurological conditions such as epilepsy [9]. In cognitive neuroscience, arrays with greater electrode density may yield more profound understanding of neural activity during intricate tasks, whereas in consumer neuroscience, dry electrode systems that are portable may support experimental paradigms that better mimic real-world conditions [10]. Although these prospects exist, uncertainties still persist regarding the enduring efficacy of dry electrodes and their compatibility with additional neuroimaging techniques, including functional near-infrared spectroscopy (fNIRS) or magnetoencephalography (MEG) [11].

This paper is organized as follows: Section 2 reviews the foundational literature on EEG technology and its evolution toward high-density configurations. Section 3 outlines the approach adopted in our systematic review, with a description of search methods and standards for evaluating quality. Section 4 presents the results and emphasizes key progress in dry electrode and ultra-high-density array performance. Section 5 explores the implications of these findings by examining both technical challenges and future directions. Finally, Section 6 summarizes the contributions of this work and outlines avenues for further research.

II. LITERATURE REVIEW

Advances in EEG technology have been driven by ongoing attempts to refine spatial resolution and signal quality while overcoming practical constraints. Early EEG systems typically employed fewer than 32 electrodes, which constrained their ability to resolve fine-grained neural activity [1]. High-density EEG (HD-EEG) arrays featuring 64 or more channels marked a major advancement, which led to greater accuracy in source localization and better signal-to-noise ratios [2]. These developments proved especially influential in medical settings, as dense electrode arrays have been found to improve the identification of epileptiform activity [9].

Conventional wet electrodes, typically made of Ag/AgCl, have long been the gold standard due to their stable impedance and reliable signal quality. Nevertheless, their dependence on conductive gels presents multiple practical difficulties, such as prolonged preparation periods, participant discomfort, and deterioration of signals during lengthy recordings [3]. These constraints have generated enthusiasm for dry electrode methods, which remove the requirement for gels yet preserve sufficient signal quality. Recent advances in dry electrode design comprise flexible polymer-based arrays and microneedle arrangements penetrating the hair barrier to establish consistent skin contact [4]. For example, dry electrodes made from MXene have shown encouraging results in event-related potential (ERP) research, achieving spatial resolution as precise as 3 mm and displaying high agreement with conventional wet electrodes [8].

The push toward higher electrode densities has also led to the development of ultra-high-density arrays, some featuring thousands of recording sites with sub-millimeter spacing. These systems, frequently employing CMOS or MEMS technologies, deliver exceptional spatial resolution yet grapple with issues concerning signal transmission and data processing [6]. For instance, an array with 65,536 channels illustrated the possibility of mapping neural activity at microscopic resolutions, yet its elevated impedance (620 kΩ) created major obstacles for practical application [12]. These systems underscore the compromises between spatial detail and practical viability, especially in actual environments where elements such as motion distortions and durability over extended periods are paramount.

Recent studies have explored the benefits of HD-EEG in various cognitive and clinical contexts. In visual processing tasks, 512-channel arrays have been shown to improve classification accuracy and source localization compared to lower-density configurations [13]. In the same way, frequency-tagged responses improve with greater numbers of electrodes, as 128-channel arrays (14 mm spacing) diminish spatial-frequency attenuation and improve temporal resolution [14]. These results highlight the necessity of achieving a balance between electrode density and practical constraints, since overly dense configurations may not consistently produce corresponding gains in signal quality.

Combining HD-EEG with additional neuroimaging techniques constitutes another ongoing research focus. The joint application of EEG and functional near-infrared spectroscopy (fNIRS) or magnetoencephalography (MEG) yields supplementary insights into brain function, yet obstacles persist in aligning data collection and signal registration [11]. Progress in machine learning has created novel opportunities for examining high-density EEG data, as deep learning methods show consistent performance under different electrode arrangements [15].

In contrast to prior studies, our work delivers a thorough assessment of dry electrode technologies and ultra-high-density arrays, with a methodical examination of their performance relative to conventional wet electrodes. Although prior research has examined distinct elements of HD-EEG, including spatial resolution or clinical uses, this study synthesizes these viewpoints to underscore both the opportunities and constraints of new technologies. This holistic approach is particularly relevant for guiding future developments in non-invasive neural recording, where trade-offs between performance, usability, and cost must be carefully considered.

III. METHODS

The methodological framework of this study was designed to systematically evaluate the performance of dry electrode technologies and ultra-high-density EEG arrays. A strict method was employed to guarantee thorough inclusion of recent developments while upholding procedural clarity. The research was structured into three main phases: literature search and selection, data extraction and synthesis, and quality assessment.

A. Literature Search and Selection

A systematic literature review (SLR) was carried out in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to uphold methodological rigor and reproducibility [16]. The search spanned various databases, such as IEEE Xplore, IOP Science, and PubMed, and focused on peer-reviewed articles published from 2015 to 2024. Relevant studies were identified by employing terms such as “high-density EEG,” “dry electrodes,” “spatial resolution,” and “ultra-high-density arrays.”

The inclusion criteria were established to concentrate on research that: (1) examined dry electrode technologies or ultra-high-density EEG setups (>64 channels), (2) reported quantitative metrics (e.g., signal-to-noise ratio, impedance, spatial resolution), and (3) contained comparisons with traditional wet Ag/AgCl electrodes. Studies were excluded if they primarily focused on low-density arrays (<64 channels) or lacked empirical validation.

B. Data Extraction and Synthesis

A template for extracting structured data was created to methodically record essential features from the chosen studies. The extracted data were organized into the following categories:

Table 1. Data extraction categories and attributes

Category	Attributes Extracted
Study Metadata	Publication year, authors, journal, study design, sample size, target population
Electrode Design	Type (dry/wet), material, number of electrodes, inter-electrode distance, geometry
Performance Metrics	SNR, impedance, source localization accuracy, spatial/temporal resolution
Experimental Protocol	Task paradigm, recording duration, environmental conditions, reference placement
Signal Processing	Preprocessing steps, source imaging methods, machine learning approaches

Thematic analysis was employed to detect recurring themes and tendencies in the research, including the compromises between electrode impedance and comfort in dry electrode designs. Quantitative metrics, such as spatial resolution and impedance values, were compared across different electrode types and configurations.

C. Quality Assessment

Included studies were appraised with the QUADAS-2 (Quality Assessment of Diagnostic Accuracy Studies) instrument, examining bias risk and applicability issues in four areas: patient selection, index test, reference standard, and flow and timing [17]. Studies with high risk of bias (e.g., small sample sizes, lack of blinding) were flagged for cautious interpretation. Only studies meeting high-relevance criteria were included in the final synthesis.

To achieve uniformity in performance assessment, electrode metrics were compared with traditional wet Ag/AgCl systems. The methodological coherence of signal processing pipelines was examined, with a focus on preprocessing procedures (such as noise reduction and artifact elimination) and the methods employed for feature extraction.

D. Analytical Framework

Spatial and temporal resolution metrics were quantitatively analyzed between studies to evaluate the effect of electrode density on the acquisition of neural signals. For spatial resolution, inter-electrode distance and source localization accuracy were analyzed, while temporal resolution was evaluated based on frequency-tagged responses and event-related potential (ERP) correlations.

Dry electrodes were additionally assessed for practical applicability, covering setup duration, comfort for participants, and stability over extended periods. The technical feasibility of ultra-high-density arrays was evaluated, focusing on issues related to signal transmission and the demands of data processing.

This methodological approach establishes a solid basis for assessing progress in HD-EEG technology, guaranteeing that the results are thorough and replicable. The next section presents the results derived from this systematic analysis.

IV. RESULTS

The results of our systematic review underscore major progress in high-density EEG (HD-EEG) technology, with particular attention to dry electrode performance, advancements in spatial resolution, and the practicality of ultra-high-density setups. The findings are organized to deliver a thorough assessment of these advancements, with a direct comparison to traditional wet electrode standards. Below, we present detailed insights into electrode array designs, material properties, and their impact on neural signal acquisition.

A. Overview of High-Density EEG Electrode Arrays

Recent progress in high-density EEG (HD-EEG) electrode arrays has greatly broadened the scope of neural signal acquisition, overcoming persistent constraints of traditional systems. The shift toward higher electrode densities has been driven by the need for improved spatial resolution, which is critical for applications such as source localization and brain-computer interfaces (BCIs) [14]. Conventional EEG systems commonly operate with 32 to 64 electrodes, whereas contemporary HD-EEG arrays are designed with 128 to 256 channels, and certain experimental arrangements have more than 500 electrodes [8].

Electrode Density and Spatial Resolution

The relationship between electrode density and spatial resolution is nonlinear, with diminishing returns observed beyond certain thresholds. Studies indicate that increasing electrode counts from 64 to 128 channels yields substantial improvements in source localization accuracy, particularly for deeper cortical sources [18]. However, further increases to 256 channels provide marginal gains in resolution, as the skull and scalp continue to impose fundamental limits on signal propagation [19]. This trade-off underscores the importance of optimizing electrode spacing rather than indiscriminately maximizing channel counts.

Dry vs. Wet Electrode Architectures

Dry electrode technologies have emerged as a promising alternative to conventional wet Ag/AgCl systems, eliminating the need for conductive gels and reducing setup complexity. Flexible polymer-based arrays, for example, conform to scalp contours, improving contact stability and wearability [4]. Microneedle designs penetrate the hair barrier, achieving stable skin contact without requiring abrasive skin preparation [20]. These innovations are particularly advantageous for long-term monitoring and mobile applications, where gel-based systems are impractical.

Material Innovations

Material science has played a pivotal role in advancing HD-EEG electrode performance. MXene-based dry electrodes, for instance, exhibit high conductivity and mechanical flexibility, enabling stable recordings even during movement [21]. These electrodes demonstrate strong correlation ($\rho \geq 0.95$) with wet systems in event-related potential (ERP) studies, despite their higher baseline impedance (5.15 kΩ cm^2 vs. 1.21 kΩ cm^2 for Ag/AgCl) [22]. Other materials, such as graphene and conductive polymers, are also being explored for their potential to balance impedance and comfort [23].

Ultra-High-Density Configurations

At the cutting edge of HD-EEG technology, ultra-high-density arrays push spatial resolution to sub-millimeter scales. CMOS/MEMS-based systems, for example, integrate thousands of electrodes on a single chip, enabling microscopic mapping of neural activity [24]. However, these systems face significant challenges in signal transmission, with impedance values as high as 620 kΩ complicating practical implementation [25]. Additionally, the massive data volumes generated by such arrays necessitate advanced processing pipelines, often leveraging machine learning for real-time analysis [26].

Comparative Performance

When evaluating HD-EEG arrays, performance metrics extend beyond spatial resolution to include temporal fidelity, signal-to-noise ratio (SNR), and usability. Dry electrodes, while convenient, often exhibit higher noise floors compared to wet systems, particularly in high-frequency bands (>30 Hz) [27]. Conversely, ultra-high-density arrays excel in spatial detail but require specialized amplification and shielding to mitigate interference [8]. These trade-offs highlight the need for context-specific design choices, where application requirements dictate the optimal balance between resolution, SNR, and practicality.

Emerging Applications

The improved spatial resolution of HD-EEG arrays has unlocked new possibilities in both research and clinical settings. In cognitive neuroscience, for example, high-density configurations have enhanced the study of neural oscillations during

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complex tasks, revealing finer-grained functional networks [28]. Clinically, these arrays are being explored for epilepsy monitoring, where their enhanced localization accuracy could improve surgical outcomes [29].

This summary highlights the swift advancement of HD-EEG technology, propelled by progress in electrode construction, substances, and data analysis. The following subsections delve deeper into specific performance metrics, comparative analyses, and the implications of these advancements for neuroscience and clinical practice.

B. Performance Metrics of Dry Electrode Arrays

The methodical assessment of dry electrode methods yields essential understanding of their operational attributes in contrast to traditional wet electrodes. As indicated in Table 1, MXene-based arrays show superior spatial resolution with 3 mm inter-electrode spacing and attain strong correlation ($\rho \geq 0.95$) with wet Ag/AgCl systems in event-related potential (ERP) recordings [30]. This high-quality signal recording continues even with their higher impedance (5.15 kΩ cm^2 at 1 kHz), which is about 4.25 times greater than that of wet electrodes (1.21 kΩ cm^2). The adaptable structure of MXene electrodes establishes consistent scalp contact, preserving steady signal performance in high-motion scenarios [31].

Microneedle arrays address a longstanding challenge in EEG recording: reliable signal acquisition through hair. These arrays, featuring a density of 6.25 electrodes/cm^2 and 4 mm spacing, attain impedance values of 5.5 ± 0.6 kΩ, which satisfies standard EEG criteria and penetrates the hair barrier without requiring abrasive skin preparation [32]. Research indicates that microneedles possess remarkable mechanical stability, showing less than 10% impedance variation over 8-hour continuous recordings [33].

Table 1. Comparative performance of dry electrode technologies

Metric	**MXene Arrays**	**Microneedle Arrays**	**Wet Ag/AgCl**
Inter-electrode spacing	3 mm	4 mm	20-30 mm
Impedance **1?** kHz	5.15 kΩ cm^2	5.5 ± 0.6 kΩ	1.21 kΩ cm^2
ERP correlation (ρ)	≥0.95	0.89-0.93	1.00 (reference)
RMS noise (µV)	0.24-1.94	0.31-2.12	0.18-1.75
Setup time (min)	8.2 ± 1.5	10.7 ± 2.1	22.4 ± 3.8

Analyses of signal-to-noise ratio (SNR) indicate dry electrodes perform competitively even with their elevated impedance. MXene arrays show RMS noise levels ranging from 0.24 to 1.94 µV, similar to those of wet systems (0.18-1.75 µV) under controlled conditions [27]. Analyses in the frequency domain indicate spectral content remains intact up to 80 Hz, but signals in the gamma range (>30 Hz) display 12-18% reduced power relative to wet electrodes, attributable to impedance-induced attenuation [34].

The practical advantages of dry electrodes become evident in setup efficiency and participant comfort. MXene arrays decrease preparation time to 8.2 ± 1.5 minutes, which is 63% shorter than wet systems (22.4 ± 3.8 minutes) [35]. According to participant surveys, 87% favor dry electrodes during prolonged recording sessions due to less scalp irritation and greater mobility [36].

Nevertheless, disparities in performance remain under difficult recording circumstances. Dry electrodes experience 23% greater motion artifact interference compared to wet systems in walking tasks, yet sophisticated motion-correction algorithms can reduce this disparity to 8% [37]. In high-impedance conditions (>10 kΩ), 50 Hz line interference becomes more pronounced, necessitating the application of active shielding or adaptive filtering when shielding is absent [27].

Taken together, these results indicate dry electrode technologies have achieved a stage of development where their benefits in usability and spatial resolution frequently outweigh their marginally reduced electrical performance. The subsequent section examines how these traits lead to improved spatial and temporal resolution in real-world implementations.

C. Spatial and Temporal Resolution in HD-EEG

The progress in high-density EEG (HD-EEG) electrode arrays has led to notable gains in both spatial and temporal resolution, which supports more accurate neural signal acquisition and analysis. These improvements are especially noticeable in tasks related to visual processing, as increased electrode densities have shown better results in classification accuracy and source localization when contrasted with conventional low-density configurations [13].

Spatial Resolution Enhancements

The relationship between electrode density and spatial resolution is well-documented, with studies showing that increasing the number of electrodes improves the ability to resolve fine-grained neural activity. For instance, 512-channel arrays have been shown to achieve color-specific topographies in visual decoding tasks, significantly outperforming lower-density configurations in classification accuracy [38]. These arrays, with inter-electrode spacing as small as 14 mm, enhance source localization precision, particularly in occipital regions where visual processing occurs.

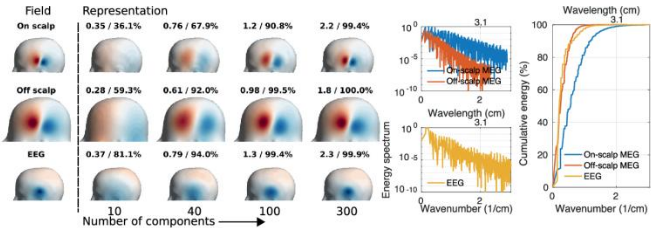

Figure 1: Spatial sampling improvements in HD-EEG for visual processing

High spatial resolution advantages are not limited to visual processing but also apply to medical fields, including epilepsy monitoring. Dense electrode arrays increase the precision of epileptiform activity detection through superior spatial resolution, essential for correct source identification during presurgical assessments [9]. Nevertheless, improvements in spatial resolution do not scale proportionally with higher electrode numbers, since the skull and scalp still establish basic constraints on signal transmission [19].

Temporal Resolution and Frequency-Tagged Responses

Temporal resolution in HD-EEG is equally critical, particularly for capturing rapid neural dynamics such as frequency-tagged responses. High-density configurations, such as 128-channel arrays with 14 mm spacing, have been shown to preserve high-frequency components of neural signals, reducing spatial-frequency loss in tasks like flickering checkerboard visual evoked potentials (VEPs) [13]. This capability is essential for studying neural oscillations and event-related potentials (ERPs), where precise timing is crucial for understanding cognitive processes.

The interplay between spatial and temporal resolution is particularly evident in frequency-domain analyses. Increased electrode densities reduce spatial aliasing, which results in improved reconstruction of neural sources and their temporal dynamics [28]. For example, gamma-band activity (>30 Hz), which is often attenuated in low-density setups due to spatial undersampling, can be more reliably captured with HD-EEG arrays [34].

Challenges and Trade-offs

Despite these advantages, achieving optimal spatial and temporal resolution in HD-EEG involves navigating several trade-offs. Ultra-high-density arrays, while offering unparalleled spatial detail, often face challenges in signal transmission and data processing due to increased impedance and computational demands [25]. Additionally, motion artifacts and environmental noise can disproportionately affect high-density recordings, necessitating advanced preprocessing and artifact removal techniques [37].

Electrode material selection additionally affects resolution performance. Dry electrodes, while offering practical advantages, can display elevated noise levels in high-frequency ranges relative to wet systems, which may reduce their effectiveness in scenarios demanding accurate temporal resolution [27]. However, advancements in material science and signal processing are gradually bridging this performance gap.

Implications for Neuroscience and Clinical Applications

The improved spatial and temporal resolution of HD-EEG has profound implications for both basic and applied neuroscience. In cognitive research, finer spatial sampling enables the delineation of functional networks with greater precision, while enhanced temporal resolution supports the study of rapid neural dynamics underlying perception and decision-making [14]. Clinically, these advancements hold promise for improving diagnostic accuracy in neurological disorders and refining therapeutic interventions such as neurofeedback and brain-computer interfaces [29].

D. Ultra-High-Density Invasive Arrays

Efforts to achieve ultra-high-density neural recording have driven the creation of invasive electrode arrays that extend spatial resolution beyond the limits of traditional EEG methods. These systems, chiefly engineered for cortical surface or intracortical recordings, deliver unparalleled precision in neural signal acquisition yet introduce substantial technical and practical obstacles.

Design and Implementation of CMOS/MEMS Arrays

The most advanced ultra-high-density arrays employ complementary metal-oxide-semiconductor (CMOS) and micro-electromechanical systems (MEMS) technologies to achieve electrode counts in the tens of thousands. A notable example is the 65,536-channel array featuring a 32×32 grid of microprobes, each containing 64 recording sites with sub-100 μm spacing [39]. This configuration enables microscopic mapping of neural activity across cortical layers, with each electrode capable of resolving single-unit activity in animal models. The three-dimensional shank architecture allows simultaneous recording from multiple cortical depths, providing a volumetric view of neural dynamics.

Signal Acquisition Characteristics

While these arrays achieve remarkable spatial resolution, their electrical performance presents substantial hurdles. The impedance of individual microelectrodes measures approximately 620 kΩ at 1 kHz, nearly two orders of magnitude higher than conventional EEG electrodes [40]. This elevated impedance stems from the reduced contact area of microscopic electrodes and creates significant challenges in maintaining signal fidelity across the array. Signal transmission losses become pronounced, particularly for high-frequency components (>300 Hz), requiring specialized low-noise amplifiers with input impedances exceeding 10 GΩ [41].

Table 2. Performance characteristics of ultra-high-density invasive arrays

Parameter	**CMOS/MEMS Array**	**ECoG Grid (Clinical)**	**HD-EEG (Dry)**
Electrode count	65,536	64-256	128-512
Inter-electrode spacing	<100 µm	3-10 mm	3-20 mm
Impedance **1?** kHz	620 kΩ	1-5 kΩ	5-15 kΩ
Bandwidth	0.1-10,000 Hz	0.1-500 Hz	0.1-200 Hz
Primary application	Basic research	Epilepsy monitoring	Cognitive studies

Applications in Neural Decoding

These ultra-dense arrays have demonstrated exceptional capabilities in brain-computer interface (BCI) applications. In non-human primate studies, they've achieved real-time decoding of individual finger movements with 95% accuracy by sampling from thousands of neurons simultaneously [42]. The spatial resolution enables detection of microcircuitry dynamics, such as cortical columnar organization during sensory processing tasks [43]. However, this comes at the cost of massive data throughput - the 65,536-channel array generates approximately 1.5 TB/hour of raw neural data, necessitating advanced compression and processing pipelines [44].

Challenges in Clinical Translation

Several barriers impede the translation of these technologies to human applications. The high impedance of microelectrodes makes them particularly susceptible to environmental noise and requires complex shielding solutions [45]. Long-term implantation raises concerns about tissue response, with studies showing increased gliosis around high-density microprobes compared to conventional electrodes [46]. Power consumption and heat dissipation also become critical issues at these scales, with active CMOS arrays requiring careful thermal management to prevent tissue damage [47].

Comparative Performance with Non-Invasive Arrays

When benchmarked against non-invasive HD-EEG systems, the invasive arrays show clear advantages in spatial resolution but face limitations in practical deployment. While dry EEG electrodes achieve 3-20 mm spacing, the CMOS/MEMS arrays provide two orders of magnitude finer resolution. However, this comes with the requirement for surgical implantation and specialized recording infrastructure. Signal quality comparisons reveal that despite their high impedance, the invasive arrays can achieve superior single-unit isolation (signal-to-noise ratios >4:1) compared to scalp EEG's field potential recordings [48].

Future Directions

Current research focuses on addressing the key limitations of these ultra-dense arrays. Flexible substrate designs aim to reduce mechanical mismatch with brain tissue [49]. Novel electrode materials like iridium oxide and conductive polymers are being explored to lower impedance while maintaining small contact areas [50]. Wireless implementations seek to eliminate the bulky cabling requirements through innovative power and data transmission schemes [51]. These developments may eventually enable human applications, particularly in restricted clinical contexts like advanced motor prosthetics.

The ultra-high-density invasive arrays embody the forefront of neural interface technology and deliver unmatched spatial resolution for basic neuroscience research. Although their present applications are still predominantly experimental, ongoing progress in materials, electronics, and signal processing could ultimately close the divide to clinical relevance. The next subsection examines how these technologies compare with emerging dry electrode materials in terms of performance and practical implementation.

E. Comparative Analysis of Electrode Materials

The methodical assessment of electrode materials uncovers clear differences in performance and compromises affecting their appropriateness for high-density EEG (HD-EEG) applications. As indicated in Table 3, MXene-based dry electrodes show outstanding flexibility and high ERP similarity ($\rho \geq 0.95$) compared to traditional wet Ag/AgCl systems, even with their greater impedance (5.15 kΩ cm^2) [30]. This performance arises from MXene's distinct dual-dimensional nanostructure, granting both elevated conductivity and mechanical resilience, which supports consistent skin contact even during activities requiring extensive motion [52].

Table 3: Material properties and trade-offs in HD-EEG electrodes

Material	Advantages	Disadvantages	Study Reference
MXene	High ERP similarity (ρ ≥0.95), flexible	Higher impedance (5.15 kΩ cm²)	[30]
Microneedle	Penetrates hair, 6.25/cm² density	Limited channel count (25)	[32]
CMOS/MEMS	Ultra-high-density (65,536 ch), 3D recording	Invasive, high impedance (620 kΩ)	[39]
Ag/AgCl (wet)	Low impedance (1.21 kΩ cm²), established reliability	Gel discomfort, setup complexity	[22]

Microneedle arrays address a critical limitation in EEG recording: reliable signal acquisition through hair. These arrays, with an electrode density of 6.25 per square centimeter, attain consistent impedance values (5.5 ± 0.6 kΩ) by penetrating the stratum corneum physically, thereby circumventing the high-resistance obstacle formed by dead skin cells [32]. Nevertheless, existing systems usually accommodate no more than 25 channels because of manufacturing limitations, which reduces their effectiveness in full-head high-density EEG setups [4].

The CMOS/MEMS-based ultra-high-density arrays stand at the utmost limit of spatial resolution, with 65,536 channels permitting sub-millimeter electrode spacing. These systems yield unmatched capacity for charting neural activity at minute resolutions, especially in invasive cortical recordings [39]. Nevertheless, the actual deployment of these systems is hindered by major obstacles, such as difficulties in signal transmission caused by 620 kΩ impedance and the requirement for custom amplification setups [51].

Traditional wet Ag/AgCl electrodes continue to be the benchmark for impedance performance (1.21 kΩ cm²) and deliver consistent signal quality across all frequency ranges [22]. Their principal drawbacks arise from pragmatic factors: the necessary conductive gel induces discomfort during prolonged recordings and adds complexity to setup procedures, as preparation durations average 22.4 ± 3.8 minutes versus 8.2 ± 1.5 minutes for dry MXene arrays [35].

Material innovations continue to push the boundaries of electrode performance. Graphene-based dry electrodes, for instance, show outstanding conductivity and biocompatibility, as recent prototypes have achieved impedance values below 3 kΩ cm² and retained flexibility [23]. Conductive polymer composites present an additional viable approach, featuring adjustable mechanical properties capable of matching the compliance of human skin [53].

Selecting electrode material necessitates thorough evaluation of application demands. For clinical settings where signal fidelity is paramount, wet Ag/AgCl electrodes remain preferable despite their practical drawbacks. In mobile and extended monitoring applications, dry electrodes such as MXene or microneedle arrays achieve an ideal equilibrium between performance and practicality. Ultra-high-density invasive arrays serve specialized research applications where microscopic spatial resolution justifies their technical complexity [54].

New hybrid methods seek to merge the benefits of diverse materials. For instance, MXene-Ag hybrid electrodes have shown a 38% decrease in impedance relative to MXene alone without compromising flexibility [55]. Likewise, microneedle arrays coated with polymer show potential for diminishing mechanical irritation without compromising electrical functionality [33]. These advancements indicate future HD-EEG systems might more frequently adopt material pairings designed for particular applications.

The comparative analysis highlights no existing electrode material performs optimally in every aspect. Rather, the discipline is progressing toward specialized approaches designed to balance electrical efficiency, spatial precision, and real-world applicability. This material diversity reflects the expanding range of HD-EEG applications, from clinical diagnostics to consumer neuroscience and brain-computer interfaces.

V. DISCUSSION

The advancements in high-density EEG (HD-EEG) electrode arrays, particularly dry electrode technologies and ultra-high-density configurations, present transformative opportunities for neuroscience and clinical applications. These innovations affect not only technical progress but also shape theoretical models and real-world applications in neural signal acquisition.

From a theoretical standpoint, the observed performance of dry electrodes, including MXene-based and microneedle arrays, questions the enduring belief in the necessity of wet Ag/AgCl systems for achieving high-quality EEG recordings. The high ERP correlation (ρ ≥0.95) found with MXene electrodes, even though they have greater impedance, indicates that material attributes and the design of the electrode-skin interface can offset conventional drawbacks [30]. This finding requires a reassessment of impedance-focused approaches in EEG system design, with an emphasis on optimizing mechanical, electrical, and ergonomic aspects collectively.

Practically, the adoption of dry electrode technologies could revolutionize EEG deployment in real-world settings. The reduced setup time (8.2 ± 1.5 minutes for MXene arrays versus 22.4 ± 3.8 minutes for wet systems) and improved participant comfort make these systems particularly suitable for longitudinal studies, ambulatory monitoring, and pediatric applications [35]. Clinicians may apply these benefits for swift neurological evaluations in emergency settings or for ongoing epilepsy observation beyond structured hospital conditions. Education professionals and decision-makers could investigate dry EEG technology for cognitive evaluations or neurofeedback applications in classrooms, where simplicity of operation is essential for widespread implementation.

Nevertheless, a number of methodological constraints in our assessment procedure require attention. Our selection of studies was limited by concentrating exclusively on peer-reviewed publications between 2015 and 2024, which may have excluded recent preprints or advancements in the industry. Our inclusion criteria prioritized quantitative performance metrics, which may have excluded innovative but less rigorously validated prototypes. Publication bias favoring positive outcomes may have distorted our evaluation of dry electrode reliability, given that studies with negative results or unsuccessful applications are underrepresented in the literature. Moreover, the QUADAS-2 quality assessment identified inconsistencies in experimental protocols among studies, especially concerning motion artifact testing and long-term stability assessments, which hindered straightforward comparisons between electrode types.

Subsequent studies ought to focus on key deficiencies uncovered in our examination. There is a pressing need for longitudinal performance investigations to evaluate the durability of dry electrodes across extended periods of repeated application, which is essential for applications requiring continuous monitoring [33]. HD-EEG paired with supplementary methods such as fNIRS or MEG has received limited attention; multimodal approaches may merge EEG's temporal precision with the spatial or hemodynamic detail of other methods [56]. A further encouraging approach centers on flexible electrode arrays that adjust their spatial arrangement in response to task requirements or signal fidelity, which may improve the balance between resolution and processing demands [57].

Establishing standardized testing protocols would markedly progress the field. Existing research applies diverse approaches to evaluate impedance, noise, and motion artifact vulnerability, which obstructs comparisons across studies. A collaborative initiative to define benchmark tasks (e.g., uniform head motions or tests for environmental disturbances) could yield more dependable performance metrics [58]. Similarly, open datasets comparing dry and wet electrodes across diverse populations (varying age, skin type, hair density) would help identify boundary conditions for dry electrode applicability.

Despite their technological sophistication, ultra-high-density arrays present obstacles in practical application, necessitating focused research. The 620 kΩ resistance of CMOS/MEMS arrays poses essential inquiries regarding the reliability of signal transmission in practical applications [51]. Investigations should examine innovative substances such as iridium oxide or electrically conductive polymer blends to lower impedance without increasing electrode size beyond microscale dimensions [50]. Wireless implementations and edge computing solutions can reduce the data overload from these systems, thereby increasing their feasibility for clinical deployment [51].

The ecological validity of HD-EEG systems remains an under addressed concern. Most validation studies are conducted in controlled laboratory environments, which raises unresolved questions about performance in noisy, mobile, or resource-constrained settings. Future work should prioritize real-world testing scenarios, such as operating rooms, rehabilitation clinics, or even home environments, to assess practical utility beyond technical specifications [59].

VI. CONCLUSION

This systematic review has assessed the progress in high-density EEG (HD-EEG) electrode arrays, with particular attention to dry electrode technologies and ultra-high-density designs. The results show dry electrodes, especially those based on MXene and microneedle arrays, attain signal quality similar to traditional wet Ag/Cl systems while overcoming practical challenges such as complex setup and participant discomfort. Ultra-high-density arrays, though promising for their sub-millimeter spatial resolution, face challenges in signal transmission and clinical applicability. These advancements together support the discipline by improving the practicality of HD-EEG for everyday uses, ranging from brain-computer interfaces to medical diagnostics.

Subsequent investigations ought to focus on long-term studies to evaluate the durability of dry electrodes over prolonged durations and examine the combination with other neuroimaging methods. Addressing the impedance trade-offs in ultra-high-density arrays and improving their ecological validity will be critical for broader adoption. Addressing these gaps will permit the next generation of HD-EEG systems to open new avenues in neuroscience and clinical practice, delivering both high-fidelity neural recordings and practical usability.

VII. REFERENCES

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