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High-Definition Electroencephalography: A New Horizon in Neurological Pathology Research

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Abstract

The advent of high-density electroencephalography (HD-EEG) has catalyzed a paradigm shift in the exploration of neurological pathologies. This editorial underscore its transformative potential in elucidating brain dynamics and refining diagnostic approaches for a spectrum of conditions, spanning from epilepsy and dementia to cognitive impairments in preterm infants. Our objective is to optimize the utility of HD-EEG by emphasizing the imperative for methodological homogenization and fostering collaborative endeavors. The remarkable spatial resolution inherent in HD-EEG enables precise mapping of aberrant neural activity, surpassing the capabilities of conventional EEG methodologies. HD-EEG has significant clinical implications, particularly for improving surgical precision in epilepsy patients. It offers deeper insights into cognitive-affecting neurological disorders by capturing brain activity during tasks, extending beyond its diagnostic role. Research discrepancies arise from data acquisition and analysis complexities, highlighting the need for standardized multicentric studies. Integrating composite connectivity indices with machine learning algorithms could enhance HD-EEG's prognostic efficacy, advancing neurological pathology understanding. Case studies illustrate its expanding applications: • Epilepsy: HD-EEG has revolutionized the localization of seizure foci, leading to more effective surgical interventions for patients with medically refractory epilepsy. • Cognitive neuroscience: HD-EEG enables researchers to explore the neural foundations of cognitive functions such as attention, memory, and decision-making more thoroughly. • Dementia: Studies are employing HD-EEG to characterize brain network alterations in dementia, paving the way for earlier diagnosis and potential interventions. • Psychiatric disorders: HD-EEG holds promise for investigating the neurophysiological basis of anxiety in Parkinson's disease and other mental health conditions. • Brain development: HD-EEG illuminates adolescent cortical development via sleep spindle dynamics. Advancements such as the Localize-MI dataset validate source localization methods. Integrating HD-EEG with fMRI and MEG offers comprehensive brain function insights: • Integration of HD-EEG with other imaging modalities (fMRI, MEG) for a comprehensive understanding of brain function. • Creation of wearable HD-EEG technology for prolonged brain activity monitoring in real-world environments. • Utilization of machine learning algorithms to enhance the predictive power of HD-EEG in neurological phenotyping. • Multicentric studies with standardized protocols to overcome data variability challenges and facilitate data sharing. HD-EEG has the potential to revolutionize neurological pathology management by overcoming methodological challenges and fostering collaborative research. Its capability to track sub-second brain dynamics and integrate with computational models promises groundbreaking discoveries in neuroscience.

Keywords: High-Definition EEG (HD-EEG), Neurological Pathologies, Biomarkers, Epilepsy Research, Cognitive Load, Source Localization, Brain Connectivity, Cognitive Neuroscience, Sleep Spindle Dynamics, Alzheimer's Disease (AD), Spatial Resolution, Neural Correlates, Parkinson's Disease (PD), Dementia Research, Human Brain Computational Model

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INTRODUCTION

The study of neurological pathologies has historically been constrained by the inherent limitations of traditional electroencephalography (EEG) methodologies. The emergence of high-density EEG (HD EEG) technology has catalyzed a paradigm shift in our approach to diagnosing and comprehending neurological conditions. Whereas conventional EEG techniques have furnished valuable insights into brain activity, their spatial resolution has been constrained, hampering the precise delineation of abnormal neural activity implicated in various pathologies. HD EEG represents a remedy to this constraint, affording researchers a more intricate and precise portrayal of brain dynamics.

Advantages compared to traditional EEG: The primary advantages of high-density electroencephalography (HD EEG) lie in its augmented spatial resolution and augmented dataset, facilitated by a substantially increased number of electrodes—typically 128 electrodes, in contrast to the customary 18 to 24 electrodes in traditional EEG setups. This elevation in electrode density yields a six-fold augmentation in data acquisition, thereby enabling a more precise scrutiny of cerebral activity. The heightened density of electrodes not only enhances the capability to pinpoint and characterize deviations in brain function but also extends coverage beyond the cranial surface to encompass subcortical regions, a feature lacking in conventional EEG systems. This expanded spatial coverage engenders a more comprehensive comprehension of cerebral function and fosters a finer localization of anomalous brain activity owing to the enhanced capacity to capture neuronal dynamics across diverse brain territories. The precise identification of pathological loci holds paramount significance for diagnostic accuracy and treatment strategizing, particularly within clinical contexts.

Advantages of HD-EEG compared to MEG (Magneto Encephalography High-density electroencephalography (HD-EEG) systems typically offer greater portability compared to magnetoencephalography (MEG) machines and can be utilized in non-traditional settings, including intraoperative environments. The portable nature of HD-EEG expands its potential applications, particularly in scenarios necessitating mobility. To enhance the depth of information regarding brain function, HD-EEG can be complementarily employed with other techniques such as EEG-fMRI. Simultaneous recording capabilities augment the versatility of HD-EEG, enabling researchers to acquire more comprehensive datasets within a single session.

MEG systems entail significantly higher costs than HD-EEG setups, thereby limiting their utilization in clinical and research settings, especially those constrained by budgetary considerations. Moreover, susceptibility to magnetic interference within the environment poses challenges to MEG recordings. The necessity for a meticulously shielded room to ensure accuracy further exacerbates the logistical and financial burdens associated with MEG studies. Additionally, the requirement for patients to remain motionless within a helmet during MEG recordings can induce discomfort, potentially compromising data quality, particularly in cases involving individuals unable to sustain stillness for extended periods.

For investigations necessitating the capture of rapid brain activity, such as epilepsy studies, HD-EEG may present a more suitable option. Conversely, MEG is preferred when precise localization of deep brain activity sources, such as tumor locations, (Klamer et al. 2015; Malmivuo 2012) is imperative, owing to its superior spatial resolution. In summary, both HD-EEG and MEG serve as invaluable tools for studying brain function, each offering distinct advantages and disadvantages that warrant consideration in research and clinical applications [1].

Clinical applications: The localization of seizure foci in epilepsy research has been completely transformed by HD EEG, allowing researchers to pinpoint the specific brain regions that contribute to seizure initiation and propagation with unparalleled precision. This advancement is crucial for surgical planning in patients with medically refractory epilepsy, as locating the seizure focus accurately is essential for successful intervention. (Yi Li et al 2022). Moreover, HD EEG has opened up new frontiers in cognitive neuroscience, enabling the examination of the neural traces of cognitive processes similar to attention, memory, and decision-making [2].

*Cognitive neuroscien*ce: HD EEG has expanded cognitive neuroscience and allowed researchers to explore the neural correlates of cognitive processes in new ways beyond clinical diagnosis. The identification of neural signatures associated with various cognitive functions, such as attention, memory, and decision-making, can be achieved by recording brain activity during cognitive tasks. This data not only broadens our understanding of normal brain functioning but also sheds light on the neural origins of cognitive impairment in neurological disorders.

Future Directions: The range of applications for HD EEG is extensive and constantly expanding. In future research, it could be important to incorporate HD EEG with other imaging modalities, such as fMRI and MEG, to obtain a complete understanding of brain function. Furthermore, advancements in wearable EEG technology show potential for extended monitoring of brain activity in real-world settings, providing insights into brain function dynamics outside the laboratory. As technology evolves, HD EEG remains a cornerstone technology in the study of neurological pathologies, offering invaluable insights into brain function and dysfunction.

Challenges and Opportunities: Despite its potential, the application of HD EEG in neurological research faces challenges related to variability in data acquisition and processing. Harmonization of experimental protocols and preprocessing steps is essential to ensure the reliability and replicability of findings across studies. Multicentric studies employing standardized protocols are crucial for overcoming variability challenges and facilitating data sharing and integration. Moreover, employing composite connectivity metrics and machine learning algorithms shows potential for improving the predictive accuracy of HD-EEG in neurological phenotyping.

Multicentric protocol harmonization: To overcome the challenges posed by variability, multicentric studies employing standardized protocols are crucial. Harmonization efforts should focus on establishing consensus guidelines for data acquisition, preprocessing, and connectivity analysis. This will facilitate data sharing and integration, enabling the accumulation of large-scale datasets necessary for robust scientific conclusions.

Composite metrics and machine learning approaches: In addition to methodological harmonization, the use of composite connectivity metrics and machine learning algorithms holds promise for enhancing the predictive power of HD EEG in neurological phenotyping. By combining multiple connectivity measures and integrating EEG data with other modalities, such as clinical, genetic, and neuroimaging data, comprehensive models can be developed for a multidimensional characterization of neurological disorders.

Case studies and groundbreaking research: Illustrative examples from recent studies highlight the diverse applications of HD EEG in neurological research. From characterizing brain network alterations in dementia to guiding surgical planning in epilepsy, HD EEG has demonstrated its utility across various clinical contexts. Seminal works exemplify the transformative impact of HD EEG in elucidating post-stroke neuroplasticity, enhancing presurgical planning for epilepsy patients, and advancing our understanding of cognitive domains affected by neurological disorders.

The groundbreaking study by *(Mammone et al. 2018)* exemplifies the transformative impact of HD-EEG in elucidating post-stroke neuroplasticity. By leveraging the high spatial resolution of HD-EEG, the researchers uncovered asymmetries in brain activity following unilateral stroke events, shedding light on the brain's adaptive mechanisms in response to injury. Their findings underscore the importance of understanding post-stroke brain reorganization to optimize rehabilitation strategies and improve patient outcomes [3].

The utilization of HD-EEG in presurgical planning for epilepsy patients exemplifies its clinical relevance *(Ching-Chang Kuo et al., 2018).* The localization of the seizure onset zone (SOZ) using HD-

EEG offers a noninvasive yet accurate method for guiding surgical interventions, enhancing patient outcomes, and exemplifying the translational potential of HD-EEG research in clinical practice [4].

Expanding applications of HD EEG: Recent research has expanded HD-EEG applications to explore cognitive changes associated with deep brain stimulation (DBS) surgery in Parkinson's disease (PD). Studies have shown that HD-EEG can effectively investigate changes in bioelectric potentials during various protocols, including motor tasks and auditory stimuli, in PD patients undergoing DBS therapy *(Buril et al., 2020).* This highlights the versatility of HD EEG in capturing dynamic neural activity and its potential to elucidate the effects of therapeutic interventions on brain connectivity [5].

Ground-truth for source localization methods: Precisely localizing brain activity recorded by EEG is essential yet challenging.

The Localize-MI dataset is a groundbreaking resource that includes EEG-recorded electrical activity from precisely known brain locations in living humans. Collected during the pre-surgical evaluation of patients with drug-resistant epilepsy, this dataset provides a unique opportunity to accurately validate and test source localization methods. The applications of this dataset range from estimating in vivo tissue conductivity to developing and validating forward and inverse solution methods, significantly advancing our understanding of EEG source localization *(Mikulan et al., 2020) [6].*

Cognitive domains: Temporal lobe epilepsy (TLE) is now recognized as a network disorder affecting various cognitive domains. In their study, Duma et al. (2022) examined the differences in dynamic network reconfiguration between patients with unilateral TLE and a healthy control group, focusing on two connectivity indices: flexibility and integration. Using HD-EEG source-based functional connectivity, they found that TLE patients had significantly lower flexibility in brain networks related to cognitive control and attention, along with higher integration values in resting-state networks. Additionally, higher integration indices were linked to poorer cognitive performance, suggesting a mechanism for specific neuropsychological alterations in TLE patients [7].

Expanding applications of HD EEG: Recent advancements, such as the development of a high-density 256-channel cap for dry electroencephalography *(Fiedler et al., 2022),* have enhanced the accessibility and applicability of HD-EEG, opening up new possibilities for its use in various settings and applications [8].

Recent advancements in multimodal brain imaging techniques have significantly contributed to our understanding of neurological pathologies. For example, dynamic causal modeling (DCM) has been employed to assess effective connectivity between brain regions, allowing researchers to investigate the spread of epileptic activity and characterize underlying epileptic networks. A notable application of this approach is the study of "musicogenic epilepsy," a rare reflex epilepsy syndrome triggered by musical stimuli. *(Klamer et al. 2015)* utilized DCM for fMRI, HD EEG, and MEG to localize the seizure focus and propagation effects in a patient with musicogenic epilepsy, validating results with invasive EEG recordings [9]. Their findings demonstrated concordance between functional modalities, highlighting the potential of multimodal approaches in characterizing neurological disorders.

Emotion regulation: Emotion regulation (ER) strategies can affect how the brain constructs affective predictions at various stages. Del Popolo Cristaldi et al. (2022) explored the impact of different ER strategies (expressive suppression vs. cognitive reappraisal) on event-related potentials (ERPs) and brain source activity during affective prediction stages using HD-EEG. They found that ER strategies interacted with contextual uncertainty levels, modulating ERPs and source activity differently across prediction stages. These findings highlight the role of ER strategies in affective prediction processing and its implications for understanding cognitive and emotional functioning [10].

(Gábor Bocskai et al. 2023) seminal work represents a significant step forward in unraveling the complexities of adolescent cortical development through the lens of sleep spindle dynamics. By elucidating the distinct developmental trajectories of slow and fast spindles and advocating for a more targeted approach to EEG analysis, their study lays the groundwork for future investigations into the neurobiological underpinnings of sleep and cognition during adolescence [11].

Longitudinal monitoring of MCI to AD conversion: (morabito et al. 2023) proposed an explainable artificial intelligence approach to longitudinally monitor subjects affected by Mild Cognitive Impairment (MCI) using HD-EEG. This methodology demonstrates high intra-subject classification performance and explores the progression from MCI to Alzheimer's Disease (AD) [12].

The exploratory hd-EEG study (Paola Polverino et al, 2022) provides valuable insights into brain cortical activity alterations in MCI due to AD and PD. The observed correlations between EEG parameters and global cognitive status underscore the potential of EEG as a non-invasive tool for assessing cognitive function in neurodegenerative diseases. Further research incorporating longitudinal assessments and larger sample sizes is warranted to validate these findings and elucidate their clinical implications [13].

(Mento et al. 2022) epitomizes the transformative potential of HD EEG in unraveling the complexities of brain function and pathology. As we continue to harness the power of this cutting-edge technology, the horizon of neurological research beckons with new possibilities, paving the way for unprecedented advancements in diagnosis, treatment, and beyond [14].

Overall, (Betrouni et al. 2022) contributes to our understanding of anxiety in PD and underscores the importance of considering both motor and non-motor symptoms in disease management. By identifying specific markers of PD-related anxiety using hd-EEG, we can potentially improve early detection, develop targeted interventions, and enhance the overall quality of life for patients with PD [15].

Tracking sub-second brain dynamics during cognitive tasks, Mheich et al. (2021) provide high-density EEG datasets collected during both task-free and task-related paradigms. These include visual naming and spelling tasks, visual and auditory naming tasks, a visual working memory task, and resting state. These datasets enable the tracking of brain network dynamics and rapid reconfigurations at a sub-second timescale, allowing for the development of new methods to estimate brain cortical networks and better understand brain functioning during rest and task [16].

The proposal by (Prado et al. 2022) heralds a new era of multidimensional dementia research, propelled by the integration of high-density EEG connectivity analyses within multicentric frameworks. By addressing variability challenges and embracing innovative methodologies, the field stands poised to revolutionize our understanding of dementia and pave the way for more targeted interventions and personalized care [17].

(Sonal Bhatia et al. 2024) pioneering work heralds a new era in BCECTS research, leveraging the capabilities of HD-EEG to unmask the intricacies of this intriguing epilepsy syndrome. By harnessing the enhanced spatial resolution of HD-EEG, researchers can decipher the neural networks underpinning BCECTS and pave the way for more effective diagnostic and therapeutic strategies [18].

In a recent study by *(Tabbal et al. 2022*), HD-EEG functional connectivity states were assessed using a human brain computational model. This study provides a quantitative assessment of various pipeline steps involved in EEG source-space network analysis, offering insights into the advantages and limitations of different techniques. The findings emphasize the importance of rigorous evaluation and optimization of EEG/MEG source connectivity analysis methods to enhance the accuracy and reliability of results in neurological research [19].

The work by (Stoyell et al. 2021) underscores the transformative impact of HD-EEG on epilepsy care and highlights the need for continued innovation and collaboration to maximize its clinical utility. By embracing HD-EEG as a valuable tool in the neurology armamentarium, we can advance our understanding of epilepsy pathophysiology and improve patient outcomes in the years to come [20].

(Holler et al. 2018) has explored the potential of HD-EEG in motor imagery classification in patients with spinal cord injury, suggesting promising results for the use of HD-EEG in neuroprostheses or brain-computer interface systems [21].

CONCLUSION

HD EEG stands at the forefront of a new era in the study of neurological pathologies. Its ability to provide detailed neural maps has already yielded significant advancements in our understanding of brain function and dysfunction. By combining high spatial resolution with advanced signal processing techniques, HD EEG offers a powerful tool for diagnosing and treating neurological disorders, as well as for advancing our knowledge of the underlying neural mechanisms. As technology continues to evolve, the future of HD EEG holds promise for further breakthroughs in the field of neuroscience.

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