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Advances in neurophysiological biomarkers for early diagnosis of alzheimer's disease: A review of EEG and MEG studies.

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Introduction

Alzheimer's disease (AD), the most common cause of dementia worldwide, poses a significant challenge to early detection due to its insidious onset and progressive nature. Conventional diagnostic methods such as neuropsychological assessments and structural neuroimaging often fail to identify the disease at its earliest stages, when therapeutic interventions may be most effective. In recent years, there has been growing interest in identifying neurophysiological biomarkers that reflect early functional changes in the brain prior to overt structural damage. Electroencephalography (EEG) and magnetoencephalography (MEG), non-invasive modalities capable of capturing real-time brain activity with millisecond precision, are increasingly being explored as tools for early diagnosis of AD. These techniques allow researchers to assess neural oscillatory patterns, connectivity disturbances, and cognitive network alterations that are characteristic of early-stage AD. This shift toward functional diagnostics marks a promising advance in the fight against neurodegeneration [1].

EEG studies in AD have consistently shown a slowing of brain rhythms, most notably a shift from higher-frequency alpha and beta activity toward lower-frequency delta and theta waves. These alterations are thought to reflect underlying synaptic dysfunction and disrupted cortical communication. In mild cognitive impairment (MCI), a prodromal stage of AD, spectral power analyses often reveal reductions in posterior alpha activity, particularly in parietal and occipital regions. Such patterns suggest early disintegration of the default mode network (DMN), a network heavily implicated in memory consolidation and self-referential thinking. Furthermore, EEG coherence measures—indices of functional connectivity—often show reduced interhemispheric synchronization in MCI and AD, especially in temporoparietal and frontal lobes. These findings underscore the potential of EEG as a diagnostic modality capable of capturing subtle neurophysiological abnormalities even before clinical symptoms manifest fully [2].

MEG offers complementary insights to EEG, with higher spatial resolution and better sensitivity to deep cortical structures. In MEG studies of AD, patients typically exhibit reduced alpha power and increased theta and delta activity, in line with EEG findings. However, MEG's ability to precisely localize these oscillatory changes provides a more detailed mapping

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of the affected networks. Functional connectivity analysis using MEG has revealed that early AD is associated with disrupted long-range synchronization, particularly in the posterior cingulate cortex and precuneus—core hubs of the DMN. Source-space connectivity metrics, such as phase lag index (PLI) and imaginary coherence, demonstrate decreased efficiency and increased randomness in brain network topology, suggesting that AD not only affects individual regions but impairs global network integrity. These findings point to MEG's promise as a powerful biomarker tool in early AD diagnosis and differentiation from other dementias [3].

Another promising approach involves analyzing event-related potentials (ERPs) and event-related fields (ERFs), time-locked neural responses to cognitive stimuli, using EEG and MEG respectively. Studies have shown that P300 latency—a component associated with attention and working memory—is significantly prolonged in both MCI and AD, reflecting slowed cognitive processing. Similarly, mismatch negativity (MMN), an index of auditory change detection, is diminished in AD and has been proposed as an early marker of cognitive decline. MEG-based ERF studies during memory and language tasks further reveal diminished task-related oscillatory responses in AD, indicating impaired neural efficiency. The reproducibility and non-invasiveness of these techniques make ERPs and ERFs suitable for longitudinal monitoring of disease progression, providing clinicians with valuable tools for both early detection and treatment evaluation [4].

Recent technological and analytical advances have further enhanced the utility of EEG and MEG in AD research. Machine learning algorithms, when applied to EEG/MEG data, can classify AD patients with considerable accuracy by identifying complex patterns across multiple features, such as spectral power, coherence, and network topology. Deep learning techniques, such as convolutional neural networks (CNNs), have been employed to analyze raw EEG signals, bypassing the need for handcrafted features and improving diagnostic performance. Moreover, combining EEG or MEG with other modalities—such as structural MRI, PET imaging, or cerebrospinal fluid biomarkers—can enhance sensitivity and specificity, creating a multimodal diagnostic framework. The development of portable EEG systems has also raised the possibility of widespread, low-cost screening in clinical and community settings, making early detection more accessible. These integrated approaches are paving the way toward personalized medicine in Alzheimer's care [5].

Conclusion

The pursuit of early and accurate diagnosis in Alzheimer's disease has led to a paradigm shift toward neurophysiological biomarkers, with EEG and MEG emerging as front-runners in functional brain monitoring. These modalities capture subtle disruptions in neural oscillations and connectivity that precede structural degeneration, offering a window into the earliest stages of the disease. EEG provides a practical and scalable method for detecting abnormalities in brain rhythms and coherence, while MEG adds greater spatial resolution and network specificity. Together, they enable a more nuanced understanding of the functional deterioration associated with Alzheimer's, especially when combined with event-related responses and advanced computational techniques. As research continues to refine these biomarkers and integrate them into clinical workflows, there is hope that individuals at risk of AD can be identified and treated earlier, ultimately improving outcomes and quality of life. The growing role of neurophysiological diagnostics reflects a broader trend in neuroscience toward early intervention, network-based understanding, and precision medicine.

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