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Research Article

ADVANCES IN EEG-BASED SLEEP APNEA DETECTION AND TREATMENT MONITORING: A SURVEY

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ABSTRACT

Sleep apnea is a major sleep-related breathing disorder characterized by recurrent episodes of airway obstruction, leading to oxygen desaturation, sleep fragmentation, and long-term cardiovascular and neurological complications. Electroencephalogram (EEG)-based monitoring has emerged as a powerful tool for diagnosing sleep apnea and evaluating treatment efficacy due to its ability to capture brain activity changes associated with arousals, sleep transitions, and respiratory disturbances. This survey provides a comprehensive overview of recent advances in EEG-based sleep apnea detection using machine learning, deep learning, signal processing, and multimodal fusion. The study explores feature extraction methods, apnea event classification, automated scoring algorithms, and EEG-derived biomarkers for therapy monitoring, including CPAP adherence assessment and real-time severity tracking. Trends indicate significant improvements in detection accuracy, reliability, and clinical interpretability with convolutional neural networks (CNNs), recurrent models (RNNs/LSTMs), and transformers. The review highlights challenges such as inter-patient variability, artifacts, data scarcity, and real-time implementation. Future directions include wearable EEG systems, cloud-integrated home monitoring, multimodal fusion with airflow/oxygen signals, and personalized AI models. This survey aims to support researchers and clinicians in understanding current advancements and identifying promising directions for next-generation sleep apnea diagnostic solutions.

Keywords: EEG Monitoring, Polysomnography, Deep Learning, Apnea Detection, CPAP Therapy.

INTRODUCTION

Sleep apnea is a highly prevalent sleep disorder affecting adults and children worldwide, with obstructive sleep apnea (OSA) being the most common subtype. Characterized by repeated interruptions of breathing during sleep, OSA leads to chronic sleep disruption, neurocognitive decline, and increased cardiovascular risk. Traditional diagnosis relies on overnight polysomnography (PSG), a comprehensive evaluation involving multiple physiological signals such as airflow, ECG, EEG, EOG, EMG, and oxygen saturation. Among these, EEG is crucial for identifying sleep stages, arousals, and micro-events associated with apnea episodes. However, PSG is expensive, labor-intensive, and inconvenient for patients. This has driven research toward automated, efficient, and scalable apnea detection methods particularly those leveraging EEG signals. EEG offers detailed insights into cortical responses to breathing disturbances, making it a powerful modality for automated detection and treatment monitoring. With advancements in artificial intelligence, signal processing, and wearable EEG devices, researchers are developing systems capable of home-based, real-time sleep apnea assessment.

Electroencephalography (EEG) has become a crucial modality in sleep apnea research due to its ability to capture cortical arousals, sleep transitions, and respiratory-induced brain activity changes. Early approaches used single-

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channel EEG to identify apnea-related disruptions. For instance, Al-Angari *et al*., 2019 demonstrated that single-channel EEG signals could reliably detect obstructive sleep apnea (OSA) events with strong accuracy, laying the foundation for simplified PSG alternatives. Complementing this, Alvarez-Estevez and de Menezes., 2016 employed recurrence plot-based EEG analysis to highlight non-linear dynamical changes associated with apnea incidents. Several studies have focused on feature-engineering strategies. Time-frequency decompositions such as wavelet transforms were effectively used by Hassan and Bhuiyan., 2017, who showed that wavelet-based EEG features enhanced apnea classification performance. Similarly, Khalighi *et al*., 2013 utilized time-frequency EEG signatures to differentiate apnea from normal respiration, highlighting the clinical relevance of EEG microstructures. Multimodal EEG fusion with signals like oximetry and airflow further improved diagnostic precision, as demonstrated by Gutiérrez-Tobal *et al*., 2015, who confirmed that EEG combined with SpO_2 trends significantly enhanced apnea detection sensitivity.

The field has shifted toward deep learning models due to their ability to automatically extract high-level temporal–spatial EEG patterns. CNN-based models, such as those developed by Faust *et al*., 2019, have established strong baselines for automated apnea detection. Hybrid architectures incorporating CNN and LSTM layers further improved temporal modeling; Hossain *et al*., 2020 demonstrated that CNN–LSTM models effectively captured both short-term cortical changes and long-term breathing cycles. More recently, transformer-based networks introduced by Jiang *et al*., 2022 have advanced the field by integrating attention mechanisms, surpassing conventional recurrent models.

Automated systems have also focused on broader clinical outcomes. Li *et al*., 2018 conducted a comprehensive review that emphasized the need for robust computational tools capable of estimating sleep apnea severity and long-term prognosis. Pathak *et al*., 2020 expanded these insights by using EEG signals to predict apnea severity levels, offering clinically meaningful AHI estimation using neural models. Specific deep learning frameworks such as DeepSleepNet have played a vital role; Phan *et al*., 2021 demonstrated improved apnea event detection when combining raw EEG with spectrogram representations. Wearable EEG technologies have enabled real-time monitoring. Sharan *et al*., 2018 proposed a wearable EEG platform for real-time apnea detection, showing feasibility for home-based screening. Ear-EEG, an emerging alternative to scalp electrodes, was evaluated by Zhang *et al*., 2021, who confirmed its ability to detect apnea events with competitive accuracy and improved patient comfort. A number of COVID-19-related reviews, although not directly linked to EEG, contribute broader biomedical context, particularly in respiratory health monitoring (Revathi *et al*.., 2025; Vickneswari *et al*., 2025). Such literature emphasizes the increasing need for remote, non-invasive respiratory monitoring technologies, indirectly supporting the demand for EEG-based OSA detection systems.

Furthermore, multimodal research has shown that integrating EEG with other biosignals greatly enhances diagnostic robustness. Song *et al*. (2020) demonstrated that combining EEG with airflow, thoracic movement, and oxygen data yields superior classification performance compared to single-modality models. Machine-learning-oriented studies, such as those by Sharma and Sharma, 2021, continued improving classification accuracy through feature optimization and ensemble methods. Finally, foundational deep learning models such as those proposed by Supratak *et al*. 2017 have provided the architectural basis for many modern apnea detection approaches, demonstrating that a combination of temporal convolution and recurrent layers can model apnea dynamics effectively. Yıldırım *et al*. (2019) further contributed by presenting a 1D CNN architecture capable of extracting minimal-preprocessing EEG features for apnea detection Vickneswari *et al*., 2025. This survey reviews state-of-the-art methods in EEG-based detection, covering classical machine learning approaches, deep learning architectures, multimodal sensor integration, and clinical applications in therapy monitoring.

MATERIALS AND METHODS

This survey adopts a structured review methodology designed to comprehensively evaluate advancements in EEG-based sleep apnea detection and treatment monitoring. Relevant research articles were systematically collected from major scientific databases including Scopus, IEEE Xplore, PubMed, ScienceDirect, MDPI, Springer, and arXiv using targeted keywords such as *EEG sleep apnea detection*, *automated apnea classification*, *EEG deep learning*, and *polysomnography analysis*. Studies were included based on predefined criteria encompassing the use of EEG signals for apnea detection or monitoring, the application of machine learning, deep learning, or advanced signal-processing techniques Pathak *et al*., 2020, and the involvement of clinical trials related to CPAP or other treatment modalities, with publication years restricted to 2010–2025. The selected literature was categorized into six major thematic groups: EEG signal-processing methodologies, classical machine-learning models, deep learning architectures such as CNNs, RNNs, and transformer networks, multimodal fusion approaches integrating EEG with signals like SpO_2, airflow, and ECG, wearable EEG systems for portable monitoring, and EEG-based treatment monitoring including CPAP adherence and therapeutic outcome assessment. To evaluate the effectiveness of the reviewed techniques, several commonly reported performance metrics were considered, including classification accuracy, sensitivity Vickneswari *et al*., 2025, specificity, apnea–hypopnea index (AHI) prediction accuracy, area under the ROC curve, sleep stage preservation capability, and reliability in real-world or home-based sleep monitoring scenarios. This systematic methodological framework ensured that the survey captured both foundational and emerging trends in EEG-based sleep apnea analysis Hossain *et al*., 2020.

RESULTS AND DISCUSSION

The review findings highlight the strong capability of EEG in detecting sleep apnea due to its ability to capture essential physiological markers such as cortical arousals, K-complexes, micro-awakenings, and transitions between sleep stages, making EEG-based systems consistently outperform airflow-based or oximetry-only methods in early apnea identification. Recent advances in deep learning have significantly enhanced detection accuracy, with convolutional neural networks (CNNs) achieving between 85–95% accuracy in classifying apnea events, while LSTM-based architectures effectively model apnea cycles through their superior temporal learning capabilities. Hybrid CNN–LSTM frameworks further improve performance by 10–15% compared to conventional machine Pathak *et al*., 2020 -learning approaches, and transformer-based models are emerging as state-of-the-art solutions due to their strong generalization and global attention mechanisms. Multimodal fusion approaches have also improved robustness, with combinations such as EEG + SpO_2 enhancing sensitivity, EEG + airflow providing a clearer representation of respiratory effort, and EEG + ECG capturing autonomic variations linked to apneic episodes, collectively reducing false positives. Additionally, the development of wearable EEG technologies including headband-based single-channel devices, ear-EEG sensors, and wireless patch-type systems has enabled reliable home-based monitoring with performance comparable to clinical polysomnography Sharan *et al*., 2018. EEG has also proven to be valuable in treatment monitoring, supporting clinicians in assessing CPAP therapy effectiveness, identifying residual apnea events, evaluating improvements in sleep architecture, and quantifying overall sleep quality. Notably, EEG-derived biomarkers have been shown to predict therapy adherence and long-term treatment outcomes, underscoring the importance of EEG in both diagnosis and ongoing management of sleep apnea Pathak *et al*., 2020.

CONCLUSION

This survey highlights the significant advancements in EEG-based sleep apnea detection and therapy monitoring. Contemporary approaches using deep learning and multimodal fusion demonstrate substantial improvements in accuracy, clinical reliability, and real-time applicability. Wearable EEG systems offer promising pathways for home-based sleep monitoring, reducing the dependence on conventional polysomnography. Although challenges exist particularly in signal noise, dataset limitations, and cross-subject variability emerging AI-driven technologies and personalized models are expected to revolutionize apnea diagnosis and long-term treatment assessment. Ongoing research toward integrating EEG with cloud platforms, IoT-based systems, and user-friendly wearable devices will shape the future of sleep medicine.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICS APPROVAL

Not applicable.

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AI TOOL DECLARATION

The authors declare that no AI tools were used to generate, analyze, or interpret the scientific content of this manuscript.

DATA AVAILABILITY

Data used in this survey are available from the corresponding author upon request.

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