

# Research Progress on Neural Mechanisms and Intervention Strategies of Cognitive Impairment Associated with Obstructive Sleep Apnea

Yejun Du <sup>1</sup>, Weikai Zhang <sup>1</sup>, Zhanfeng Yan <sup>1,\*</sup>

<sup>1</sup> Dongzhimen Hospital, Beijing University of Chinese Medicine, Beijing 100700, China

**\* Correspondence:**

Zhanfeng Yan

15210682430@163.com

*Received: 28 May 2026/ Accepted: 30 July 2026/ Published online: 19 September 2026*

## Abstract

Obstructive sleep apnea (OSA) is a prevalent sleep-related breathing disorder that is closely associated with cognitive impairment. However, the efficacy of conventional interventions remains limited, and exploring its neural mechanisms and adjunctive therapeutic strategies has become a research hotspot. This paper provides a narrative review of the research progress in neuroimaging mechanisms and intervention strategies for OSA-related cognitive impairment. Regarding neural mechanisms, this article focuses on two core mechanisms: dysfunction of the glymphatic system and unstable alterations in dynamic brain functional networks. Multimodal neuroimaging evidence demonstrates that patients with OSA exhibit distinct glymphatic system impairment and compromised dynamic reorganization ability of brain functional networks, characterized by "excessive persistence" and "abnormal transitions" of functional connectivity states. Pivotal mediation analyses have revealed for the first time the causal pathway of "glymphatic dysfunction → decreased brain network efficiency → cognitive impairment." In terms of intervention strategies, this article points out that continuous positive airway pressure (CPAP) has limited efficacy in improving cognitive function, accompanied by poor patient adherence. Non-invasive neuromodulation techniques represented by repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) show potential as adjunctive interventions due to their direct regulation of cortical excitability and neuroplasticity. Current research is limited by predominant cross-sectional designs, lack of standardized imaging biomarkers, and small sample sizes in intervention studies. Future research should focus on developing predictive models based on multimodal radiomics and artificial intelligence, exploring physical interventions targeting the glymphatic system, and conducting long-term randomized controlled trials enriched with biomarkers. This review aims to provide theoretical evidence and novel insights for the early identification and precise intervention of OSA-related cognitive impairment.

**Keywords:** Obstructive Sleep Apnea; Cognitive Impairment; Glymphatic System; Dynamic Brain Functional Networks; Non-invasive Neuromodulation; Continuous Positive Airway Pressure

## 1. Introduction

### 1.1. Clinical Association Between Obstructive Sleep Apnea and Cognitive Impairment

Obstructive Sleep Apnea (OSA) is a prevalent sleep-disordered breathing disorder characterized by recurrent upper airway collapse during sleep. It is mainly manifested as pathophysiological alterations including intermittent hypoxemia, hypercapnia, sleep fragmentation and increased sympathetic nerve activity. Epidemiological data indicate that approximately 425 million adults aged 30 to 69 worldwide suffer from moderate to severe OSA (Greenstone & Hack, 2014). The prevalence in China has also been rising year by year ("Guidelines for the diagnosis and treatment", 2012), and the country currently bears the world's heaviest disease burden of OSA. A multi-level meta-analysis reported that the overall prevalence of OSA in China is 11.8%, with a marked upward temporal trend: the figure surged from 8.1% in 2000–2005 to 26.9% in 2021–2024 (Niu et al., 2025). In terms of absolute population size, the number of OSA patients in China has exceeded 170 million (Benjafield et al., 2019). Notably, around 80% of potential OSA patients have not received timely diagnosis, resulting in a substantial gap between disease prevalence and clinical diagnosis (Yi et al., 2023).

OSA substantially elevates the risks of cardiovascular diseases, metabolic disorders and cerebrovascular events (Bradley & Floras, 2009; Coughlin et al., 2004). In recent years, its link with cognitive impairment has become a research hotspot at the intersection of sleep medicine and neuroscience. Patients with OSA present with multidimensional cognitive deficits, among which impairments in attention, executive function, visual and verbal working memory are most prominent (Zhang et al., 2025). A systematic review and meta-analysis further quantified the strength of this association, reporting that the prevalence of mild cognitive impairment (MCI) reaches 39% among OSA patients, and the prevalence of OSA is also 39% in individuals with MCI. The overall odds ratio for their correlation was 1.65, indicating a bidirectional relationship between OSA and cognitive dysfunction (Ren et al., 2025).

The biological mechanisms underlying OSA-related cognitive impairment have been extensively investigated. Intermittent hypoxia and sleep fragmentation, the hallmark pathological features of OSA, can trigger neuroinflammation, oxidative stress, neuronal damage, altered synaptic plasticity and blood-brain barrier dysfunction. These pathological cascades ultimately impair learning and memory abilities (Zhang et al., 2025). Moreover, the interplay between sleep disturbances and neurodegenerative diseases has attracted growing attention. Disordered sleep architecture is not only a common comorbidity of Alzheimer's disease (AD) and Parkinson's disease (PD), but may also be involved in their early pathogenesis (Hassan Mohammed Ahmed et al., 2025). According to an official workshop report from the American Thoracic Society (ATS), OSA acts as a risk factor for preclinical AD, and exerts adverse effects on the incidence, clinical manifestations and progression of AD and other types of dementia (Lal et al., 2022). Given the above evidence, exploring the mechanisms linking OSA to cognitive impairment is of great clinical value for the early identification and comprehensive intervention of these diseases. In this review, the terms "cognitive impairment", "cognitive dysfunction", "neurocognitive impairment", and "mild

cognitive impairment (MCI)" are used to describe different degrees of cognitive decline in OSA patients. Unless otherwise specified, "cognitive impairment" serves as the overarching term encompassing all objectively measured deficits in attention, executive function, memory, and processing speed. When referring to the specific clinical diagnosis of MCI (defined by Petersen criteria or equivalent), the term "mild cognitive impairment" is used. The occasional use of "neurocognitive damage" or "cognitive dysfunction" reflects the original authors' phrasing in cited studies, and does not imply a distinct pathophysiological entity. For clarity, all cognitive outcome measures in this review are interpreted within the framework of domain-specific performance rather than as categorical diagnoses.

## **1.2. Limitations of Current Mechanistic Understanding and Intervention Strategies**

Although numerous studies have confirmed a significant association between OSA and cognitive impairment, the underlying neural mechanisms remain incompletely elucidated, and existing intervention strategies also have evident limitations.

In terms of mechanisms, most conventional studies have focused on how OSA-related pathophysiological changes, including intermittent hypoxia and sleep fragmentation, directly induce brain tissue damage and cognitive decline. However, less attention has been paid to the systemic characteristics of OSA-associated brain injury, particularly the impaired dynamic reorganization of whole-brain networks. In recent years, dysfunction of the glymphatic system and destabilized dynamic functional brain networks have been proposed as two core neuroimaging mechanisms of OSA-related cognitive impairment. Studies have demonstrated a consistent correlation between sleep disturbances and impaired glymphatic clearance, with OSA exerting the most pronounced effect (Ghaderi et al., 2025; Xiong et al., 2024). Nevertheless, how glymphatic dysfunction specifically affects the dynamic reorganization of brain networks, as well as the temporal sequence and causal pathways between the two, remain to be further clarified. Additionally, the vast majority of relevant studies adopt a cross-sectional design, which makes it difficult to distinguish causality from mere correlation. As stated in the ATS workshop report, despite solid biological plausibility, sufficient evidence is still lacking to verify the bidirectional causal relationship between OSA and pathological brain aging (Lal et al., 2022).

With regard to interventions, continuous positive airway pressure (CPAP) serves as the first-line therapy for OSA, which effectively alleviates nocturnal hypoxia and sleep fragmentation. However, available evidence reveals substantial heterogeneity in the cognitive benefits of CPAP, and its effects vary across different cognitive domains in existing studies (Lal et al., 2022). More importantly, long-term adherence to CPAP therapy is generally poor, with the non-adherence rate ranging from 30% to 60% among adult OSA patients. The adherence is even lower in children and adolescents (Rotenberg et al., 2016; Sawyer et al., 2011). This practical dilemma highlights an urgent need for alternative and adjunct therapeutic approaches. Furthermore, the ATS report indicated that current research on the cognitive effects of OSA treatments predominantly centers on CPAP, while high-quality evidence supporting other therapeutic modalities remains scarce (Lal et al., 2022).

## **1.3. Objectives and Structure of the Present Article**

This article aims to review the research progress regarding neural mechanisms and intervention strategies for cognitive impairment associated with obstructive sleep apnea (OSA). The discussion is mainly organized into three parts. First, neuroimaging mechanisms: focusing on glymphatic system dysfunction and destabilized dynamic functional brain networks, this section summarizes how multimodal imaging evidence reveals the pathological basis of OSA-related brain damage, and explores the coupling pathways between the two mechanisms as well as their correlations with cognitive deficits. Second, innovative intervention strategies: on the basis of analyzing the limitations of conventional CPAP therapy, it reviews the application prospects and working mechanisms of non-invasive neuromodulation techniques represented by repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) in the treatment of OSA-related cognitive impairment. Third, future research directions: in view of existing research gaps, this paper puts forward key research priorities including the development of multimodal radiomics models, exploration of glymphatic system-targeted interventions, and clinical trials enriched with biomarkers. It is expected to provide theoretical references for the early identification and precise intervention of OSA-related cognitive impairment.

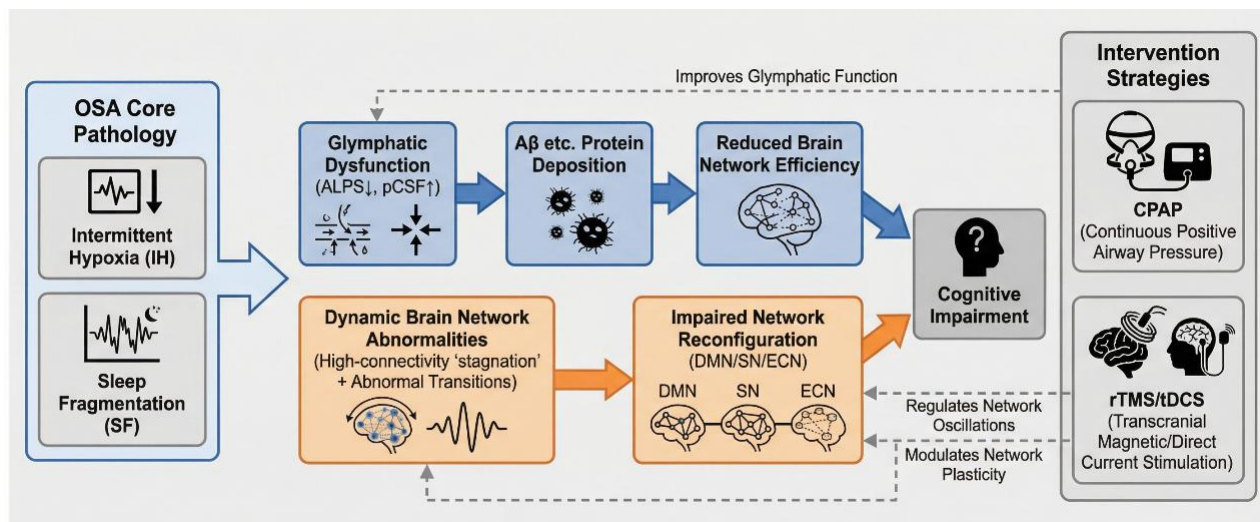


**Figure 1. Pathways underlying OSA-related cognitive impairment**

Figure 1 Schematic illustration of the two major pathways linking OSA to cognitive impairment and the potential intervention targets.

Abbreviations: pCSF, parenchymal cerebrospinal fluid; DTI-ALPS, diffusion tensor imaging-based analysis along the perivascular space; DMN, default mode network; SN, salience network; ECN, executive control network; CPAP, continuous positive airway pressure; rTMS, repetitive transcranial magnetic stimulation; tDCS, transcranial direct current stimulation.

Left panel: Core OSA pathologies (intermittent hypoxia and sleep fragmentation) drive cognitive dysfunction via two cascades. Pathway A (glymphatic dysfunction): OSA impairs glymphatic clearance, evidenced by reduced DTI-ALPS index (ALPS↓) and increased pCSF volume (pCSF↑), leading to accumulation of neurotoxic proteins (e.g., Aβ), which in turn decreases global brain network efficiency and ultimately causes cognitive decline. Pathway B (dynamic network instability): OSA disrupts the dynamic reorganization of large-scale brain networks (DMN, SN, ECN), manifesting as prolonged dwell time in high-connectivity states and aberrant state

transitions, which directly impair cognitive performance. Right panel: Potential interventions. CPAP alleviates nocturnal hypoxia and may partially restore glymphatic function. rTMS and tDCS modulate cortical excitability and network oscillations to correct aberrant dynamic connectivity. Solid arrows indicate pathological progression; dashed arrows indicate modulatory effects of interventions.

## **2. Neuroimaging Mechanisms of OSA-Related Cognitive Impairment**

In recent years, advances in neuroimaging techniques have greatly deepened the understanding of the neural mechanisms underlying OSA-related cognitive impairment. Multimodal imaging evidence, ranging from macroscopic brain networks to the microscopic glymphatic system, has gradually delineated the complex pathological profiles of OSA-associated brain damage. This section mainly elaborates on two cutting-edge mechanisms: glymphatic system dysfunction and destabilization of dynamic brain networks.

### **2.1. Glymphatic System Dysfunction**

The glymphatic system is a recently discovered pathway responsible for clearing metabolic waste in the brain, and its function largely relies on the convective exchange between cerebrospinal fluid and interstitial fluid during sleep (Yankova et al., 2021). Characterized by sleep fragmentation and intermittent hypoxia, OSA can severely impair this system and further facilitate the abnormal deposition of neurotoxic proteins (Keil et al., 2026).

#### **2.1.1. Imaging Evidence of Impaired Glymphatic Function**

The primary imaging biomarkers for evaluating glymphatic function include the diffusion tensor imaging-based analysis along the perivascular space (DTI-ALPS) index and parenchymal cerebrospinal fluid (pCSF) mapping derived from multi-echo T2 imaging. A systematic review and meta-analysis conducted by Ghaderi demonstrated that patients with severe OSA exhibited a markedly reduced DTI-ALPS index compared with healthy controls, with a pooled effect size of -0.95, confirming substantial glymphatic system impairment in this population. Meta-regression analysis further identified the apnea-hypopnea index (AHI) and Epworth Sleepiness Scale (ESS) score as major sources of heterogeneity, indicating that hypoxia burden and daytime sleepiness are closely linked to impaired glymphatic function (Ghaderi et al., 2025). Xiong et al. (2024) also reported a significantly lower ALPS index in OSA patients relative to controls, and this index was positively correlated with cognitive performance scores. Zhou et al. adopted multi-echo FAST-T2 MRI to compare untreated OSA patients, CPAP-treated OSA patients and healthy individuals. The results showed that untreated OSA patients had remarkably larger pCSF volume in the whole-brain gray matter, white matter and Alzheimer's disease (AD)-vulnerable brain regions. By contrast, pCSF levels in the CPAP group were comparable to those in healthy controls. Notably, pCSF burden was positively correlated with cortical amyloid- $\beta$  ( $A\beta$ ) deposition, suggesting that glymphatic dysfunction may mediate impaired  $A\beta$  clearance in OSA. This finding provides a mechanistic explanation for the epidemiological association between OSA and AD (Keil et al., 2026). In studies on Parkinson's disease (PD) complicated with OSA, Nepozitek et al. (2025) found that the ALPS index in newly diagnosed, treatment-naïve PD patients was significantly negatively

correlated with AHI, oxygen desaturation index and the proportion of stage N1 sleep. Such correlations were not observed in PD patients without OSA. This evidence suggests that OSA may accelerate the pathological progression of neurodegenerative diseases by disrupting glymphatic function.

### 2.1.2. Correlation with Cognitive-Related Brain Regions

Glymphatic dysfunction is anatomically associated with structural and functional alterations in cognition-related brain regions. Xiong et al. (2024) found that the ALPS index was moderately positively correlated with the Montreal Cognitive Assessment (MoCA) scores in OSA patients. More importantly, mediation analysis conducted by Xiong et al. revealed that the global efficiency of brain networks exerted a partial mediating effect between glymphatic dysfunction and cognitive impairment, with an indirect effect value of 4.58 and a mediating effect proportion of 26.9%. This finding firstly established the causal chain of *glymphatic dysfunction* → *decreased brain network efficiency* → *cognitive impairment* in patients with OSA.

In terms of regional specificity, Keil et al. (2026) demonstrated that elevated pCSF was particularly prominent in AD-vulnerable brain regions of untreated OSA patients, including the posterior cingulate cortex, precuneus and medial temporal lobe. These areas are not only early-affected sites of AD pathology, but also core nodes of the default mode network (DMN), which play pivotal roles in episodic memory and self-referential processing. Impaired A $\beta$  clearance resulting from glymphatic dysfunction may initially manifest in these regions, offering a mechanistic interpretation for the regional specificity of OSA-related cognitive impairment.

### 2.1.3. Technical Limitations and Confounding Factors of Glymphatic Imaging Biomarkers

It is important to recognize that both the DTI-ALPS index and parenchymal cerebrospinal fluid (pCSF) mapping are indirect surrogate markers of glymphatic function, rather than direct measures of CSF-interstitial fluid exchange. The DTI-ALPS index, derived from diffusion tensor imaging along the perivascular space, can be influenced by multiple confounders including cerebral small vessel disease, white matter hyperintensities, and age-related microstructural changes, all of which are common in OSA populations. Furthermore, the ALPS index assumes a specific orientation of perivascular diffusion, which may not hold true in regions with complex fiber crossings or in the presence of substantial motion artifacts. Similarly, pCSF elevation, as quantified by multi-echo T2 imaging, reflects the volumetric expansion of CSF spaces within the parenchyma; however, this increase is not specific to impaired clearance function. It can also result from brain atrophy, age-related sulcal widening, small vessel disease, or altered intracranial pressure dynamics. Thus, interpreting pCSF burden solely as a marker of metabolic waste clearance requires caution. The reproducibility of both biomarkers across different MRI scanners, field strengths, and post-processing pipelines remains to be systematically evaluated. Future studies should incorporate complementary techniques (e.g., contrast-enhanced MRI or PET tracers) to validate these imaging surrogates and should adjust for vascular and neurodegenerative confounders in statistical analyses.

## 2.2. Destabilization of Dynamic Functional Brain Networks

Traditional resting-state functional magnetic resonance imaging (rs-fMRI) studies generally assume that functional brain connectivity remains stable during scanning. However, recent research

has revealed the time-varying characteristics of functional brain networks. Due to intermittent hypoxia and disrupted sleep architecture, patients with OSA exhibit impaired capacity for dynamic network reorganization, presenting with unstable network states.

### **2.2.1. Application of Dynamic Functional Connectivity Analysis**

Dynamic functional connectivity (dFC) analysis adopts the sliding-window approach to capture time-varying patterns of functional connections (Allen et al., 2014; Calhoun et al., 2014). Widely used analytical frameworks include independent component analysis (ICA)-based time-varying functional network connectivity (FNC), multiplier temporal derivative (MTD)-based state transition analysis, and graph theory-based dynamic network metrics (Preti et al., 2017; Shine et al., 2016; Zalesky et al., 2014). Yu et al. (2025) combined ICA with the sliding-window method and identified two reproducible functional connectivity states among 82 male OSA patients and 48 healthy controls. State I was characterized by strong functional connectivity with a low occurrence frequency, while State II showed weak functional connectivity and occurred more frequently. The results indicated that OSA patients with mild cognitive impairment (OSA-MCI) had longer dwell time and higher occupancy rate in the strong-connectivity state, alongside shorter dwell time and lower occupancy rate in the weak-connectivity state. The number of state transitions tended to rise in the patient group and was positively correlated with cognitive scores. These findings suggest that the prolonged retention of brain functional networks in the strong-connectivity state may reflect compensatory neural recruitment, yet persistent activation of this state could eventually deplete the reserve of network plasticity. Wang et al. (2025) applied the MTD method to analyze dFC features in 111 OSA patients and distinguished five connectivity states, consisting of four high-connectivity states and one low-connectivity state. Significant alterations in fractional time (FT) and mean dwell time (MDT) of State 1, State 3 and State 4 were observed in patients with moderate to severe OSA. Specifically, FT and MDT of State 1 were negatively correlated with hypoxia-related parameters, whereas those of State 3 were positively correlated with total sleep time. Notably, FT of State 3 was inversely associated with the visuospatial and executive function subscores of the Montreal Cognitive Assessment (MoCA), indicating that aberrations in specific dynamic connectivity states may be directly linked to executive dysfunction.

### **2.2.2. Dynamic Functional States and Cognitive Impairment**

The aforementioned studies reveal two predominant patterns of aberrant dynamic functional states in OSA patients: excessive dwell time in high-connectivity states, indicating impaired network flexibility, and abnormal transitions between low- and high-connectivity states, which reflects disrupted network stability. Collectively, these two patterns hinder the brain from efficiently reorganizing network resources when confronted with cognitive demands.

Yu et al. (2025) further identified the core brain networks affected by dynamic functional abnormalities. Compared with healthy controls, OSA patients exhibited widespread aberrant functional connectivity within the high-connectivity state, mainly involving the salience network (SN), default mode network (DMN) and executive control network (ECN), along with reduced connectivity in the low-connectivity state. These networks undertake core roles in attentional orientation, introspective monitoring and cognitive control during cognitive processing.

Progressive deterioration of dFC was observed during the transition from OSA with normal cognition (OSA-NC) to OSA with mild cognitive impairment (OSA-MCI), suggesting that dynamic network metrics may serve as early imaging biomarkers for OSA-related cognitive impairment.

As summarized in the review by Rosenzweig et al. (2015), OSA patients present with abnormal or diminished blood oxygen level-dependent (BOLD) activation in specific brain regions including the hippocampus and prefrontal cortex during cognitive tasks. Such alterations in neurovascular coupling are likely associated with disturbed dynamic networks. Intermittent hypoxia impairs cerebrovascular reactivity, while sleep fragmentation disrupts synaptic homeostasis. The combined effects of these two factors ultimately undermine the dynamic reorganization capacity of functional brain networks.

The dynamic functional connectivity (dFC) metrics discussed above are derived from resting-state BOLD fMRI, which is inherently sensitive to physiological noise and motion artifacts. Patients with OSA often present with intermittent hypoxia, abnormal cerebrovascular reactivity, sleep deprivation, and relatively large head movements during scanning, all of which can confound BOLD signal fluctuations. In particular, changes in respiration and heart rate can induce low-frequency oscillations that mimic or contaminate neural connectivity patterns. Notably, none of the primary studies included in this review explicitly reported the use of physiological monitoring (e.g., simultaneous recording of cardiac and respiratory signals) or retrospective correction methods (e.g., RETROICOR, RVHRCOR) to remove such artifacts. Head motion parameters were generally matched between groups, but the potential residual effects of motion on dynamic state transitions were not systematically quantified. Furthermore, the risk of patients falling asleep during the scan is seldom addressed, which could dramatically alter connectivity states. Therefore, while the observed aberrant dFC patterns are consistent with the hypothesis of network instability, caution is warranted in attributing these findings solely to neuronal dysfunction; vascular and non-neuronal physiological contributions cannot be excluded. Future dFC studies in OSA should adopt rigorous artifact control strategies and report detailed procedures for handling physiological noise and motion.

### **2.3. Coupling Between Glymphatic Dysfunction and Brain Network Inefficiency**

The two mechanisms described above are not independent but are linked in a sequential causal chain. Glymphatic dysfunction, by impairing the clearance of neurotoxic metabolites such as amyloid- $\beta$ , creates a hostile microenvironment that undermines synaptic efficacy and the stability of large-scale functional connections (Benveniste et al., 2019; He & Sun, 2025; Yankova et al., 2021). The spatial overlap between regions of elevated pCSF (e.g., posterior cingulate cortex, precuneus, medial temporal lobe) and the core nodes of the default mode network provides anatomical support for this coupling. Mediation analyses (as detailed in Section 2.1.2) have quantitatively established that reduced global network efficiency partially mediates the relationship between glymphatic impairment and cognitive deficits. Thus, the pathway of glymphatic dysfunction  $\rightarrow$  decreased brain network efficiency  $\rightarrow$  cognitive impairment represents a unifying framework that integrates micro- and macro-level imaging findings.

### **3. Limitations of Conventional Interventions and Innovations in Non-Invasive Neuromodulation Techniques**

Continuous positive airway pressure (CPAP) serves as the mainstay of conventional treatment for OSA. Although it effectively relieves nocturnal hypoxia and sleep fragmentation, it suffers from poor long-term patient adherence and shows limited efficacy in reversing established damage to brain functional networks (Gurbani et al., 2025). In recent years, non-invasive brain stimulation (NIBS) techniques, represented by repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS), have emerged as a cutting-edge research direction for intervening in OSA-related cognitive impairment. These techniques enable targeted regulation of activities in specific brain regions and facilitate neural plasticity.

#### **3.1. Efficacy and Limitations of Continuous Positive Airway Pressure**

A meta-analysis revealed that CPAP treatment yielded significant improvements only in the Trail Making Test Part B, which reflects cognitive flexibility, whereas no robust overall effects were observed on other cognitive domains including information processing speed, executive function and working memory (Durtette et al., 2024). Another study similarly indicated that CPAP mainly alleviated daytime sleepiness and improved processing speed and visual search ability, with insufficient evidence supporting its benefits for higher-order cognitive functions such as executive function and memory (Durtette et al., 2024). Therefore, merely relieving upper airway obstruction is inadequate to reverse established brain network damage, highlighting the necessity to develop adjunctive therapeutic strategies.

#### **3.2. Application Prospects of Non-Invasive Neuromodulation Techniques**

Non-invasive brain stimulation (NIBS) modulates the excitability of cortical neurons via externally applied electric or magnetic fields, thereby altering the functional states of distant brain networks. Unlike CPAP, which improves brain function indirectly by relieving upper airway obstruction, NIBS enables direct targeting of cognition-related neural circuits. It offers an alternative therapeutic option for OSA patients who cannot tolerate CPAP or continue to suffer from persistent cognitive impairment after CPAP treatment (Yao et al., 2023; Yu et al., 2024; Zhao et al., 2024).

##### **3.2.1. Clinical Evidence of rTMS and tDCS**

Direct evidence of TMS in patients with OSA: Han et al. (2023) conducted a randomized controlled trial (RCT) to explore the effects of transcranial magnetic stimulation (TMS) on cognitive function in OSA patients. A total of 42 patients diagnosed with OSA via polysomnography were enrolled. Intermittent theta burst stimulation (iTBS) was delivered over the left dorsolateral prefrontal cortex (DLPFC), with parameters set as 2-second stimulation followed by an 8-second interval. Each session consisted of three trains of 600 pulses, with a 15-minute break between trains. The results demonstrated significant improvements in visual memory, sustained attention and working memory in the active stimulation group. Quantitative electroencephalography (EEG) recordings acquired before and after intervention revealed that TMS markedly increased the relative power spectral density of theta and beta bands in the parietal,

temporal and anterior brain regions, indicating that TMS ameliorates cognitive function by regulating cortical neural oscillations.

Indirect evidence from cross-diagnostic meta-analyses: Although studies focusing specifically on NIBS for OSA remain limited, high-quality meta-analyses on other neurological disorders provide valuable references. A meta-analysis by Begemann et al. (2020) including 82 RCTs found that both TMS and tDCS yielded small yet statistically significant improvements in working memory, and tDCS also exerted notable benefits on attention and alertness. A key finding was that the pro-cognitive effects of NIBS were consistent across diagnoses. Similar effect sizes were observed in various brain disorders such as dementia, Parkinson's disease and schizophrenia, suggesting that NIBS acts by modulating general brain network states rather than targeting disease-specific pathways. This conclusion is highly generalizable to patients with OSA.

Exploration of tDCS application: To date, no RCTs have reported the direct use of tDCS in OSA patients. Nevertheless, studies on Alzheimer's disease (AD) and mild cognitive impairment (MCI) have shown that anodal tDCS applied to the left DLPFC or parietal cortex can enhance episodic memory and executive function (Rektorová et al., 2025). Given the overlapping neuropathological mechanisms between OSA and AD, including impaired amyloid- $\beta$  clearance and glymphatic dysfunction, tDCS possesses considerable translational potential for clinical use in OSA populations.

### **3.2.2. Potential Neural Mechanisms: From Neural Oscillations to Brain Network Remodeling and Glymphatic Modulation**

The mechanisms by which non-invasive brain stimulation (NIBS) alleviates OSA-related cognitive impairment can be elaborated from three aspects: neural oscillations, brain network remodeling and glymphatic system regulation.

Modulation of cortical neural oscillations: Han et al. (2023) firstly verified in OSA patients that TMS significantly elevated the power spectral density of theta and beta bands after intervention. Theta oscillations are closely implicated in the encoding and retrieval of working memory, while beta oscillations participate in sustained attention and cognitive control. TMS-induced alterations in oscillatory rhythms serve as electrophysiological markers of neural plasticity, reflecting persistent enhancement of cortical excitability following stimulation.

Remodeling of unstable functional brain networks: Neuroimaging-based mechanistic studies indicate that NIBS may exert therapeutic effects by regulating dynamic connectivity patterns of large-scale brain networks. A recent review in *Nature Reviews Neurology* noted that advances in NIBS, including state-dependent protocols, network-based strategies, multifocal and subcortical paradigms, personalized electric field modeling and accelerated stimulation regimens, offer great promise for the diagnosis and management of neurological disorders (Rektorová et al., 2025).

Indirect regulation of glymphatic function: Impaired amyloid- $\beta$  ( $A\beta$ ) clearance resulting from glymphatic dysfunction is one of the core mechanisms underlying OSA-related cognitive impairment (Liu et al., 2023). Whether NIBS can indirectly improve glymphatic function by adjusting sleep architecture or cerebral hemodynamics has become a major research focus. Latest evidence suggests that accelerated iTBS is well tolerated and yields clinically meaningful cognitive

benefits in patients with Alzheimer's disease, which may be linked to the modulation of A $\beta$  deposition (Rektorová et al., 2025). For OSA populations, exploring the synergistic effects of TMS and CPAP — whereby TMS restores cortical excitability and CPAP relieves nocturnal hypoxia — represents a key direction for future investigations.

## **4. Limitations of Current Studies and Key Directions for Future Research**

### **4.1. Limitations of Existing Studies**

Despite remarkable progress in the research on OSA-related cognitive impairment in recent years, several critical limitations remain, hindering the translation of basic research findings into clinical practice.

First, most studies adopt a cross-sectional design, resulting in a lack of longitudinal evidence to confirm causality. The vast majority of current investigations into the association between OSA and cognitive impairment are cross-sectional, which cannot distinguish causal relationships from mere correlations. A bidirectional interaction may exist between the two conditions: OSA impairs cognitive function via intermittent hypoxia and sleep fragmentation, while cognitive decline may in turn disrupt sleep architecture, thus forming a vicious cycle. Large-sample and long-term longitudinal cohort studies are urgently required to clarify this complex interplay.

Second, imaging biomarkers lack standardization and external validation. Although emerging imaging biomarkers have shown promising application prospects, substantial variations in imaging parameters, analytical pipelines and threshold settings across studies reduce the comparability of results. To date, there are no unified operational specifications for these biomarkers, nor replications in independent external cohorts, which limits their clinical application.

Third, intervention studies are plagued by small sample sizes and inconsistent treatment adherence. Conventional therapies represented by CPAP can effectively alleviate nocturnal hypoxia and sleep fragmentation, yet the long-term adherence rate among patients is generally below 50%. A multicenter randomized controlled trial demonstrated that 12-month CPAP treatment significantly improved functional connectivity of the default mode network and cortical thickness, but failed to produce notable changes in Montreal Cognitive Assessment scores. This indicates that relieving upper airway obstruction alone may be insufficient to reverse established brain network damage, and a longer intervention period may be necessary. For non-invasive neuromodulation techniques, high-quality randomized controlled trials specifically targeting OSA patients are still scarce. Major shortcomings include small sample sizes, inconsistent stimulation parameters and a lack of long-term follow-up data.

Fourth, the causal relationship between the glymphatic system and brain networks remains unclear. Multiple studies have confirmed glymphatic dysfunction and aberrant brain networks in OSA patients, both of which are correlated with cognitive performance. However, how glymphatic dysfunction specifically affects the dynamic reorganization of brain networks, as well as the temporal sequence and causal pathways linking the two, needs to be further elucidated through longitudinal imaging studies and animal experiments.

## 4.2. Key Priorities for Future Research

This section proposes major research directions from three perspectives: the development of multimodal radiomics models, exploration of glymphatic system-targeted interventions, and implementation of relevant clinical trials.

### 4.2.1. Multimodal Radiomics Models and AI-Based Prediction

Transition from unimodal to multimodal integration: Most current studies evaluate OSA-related brain damage using a single imaging modality. Nevertheless, glymphatic dysfunction, abnormal dynamic brain networks and cerebral structural changes interact intricately, so a single modality cannot fully characterize the overall pathological features. Future research should integrate multimodal data including structural MRI, functional MRI and angiography to establish combined radiomics models. As commented by Jackson and Rosenzweig in *AJRCCM*, integrating high-density polysomnography with perivascular imaging enables direct verification of the arousal-vascular uncoupling hypothesis. Repeated respiratory event-related microarousals in OSA patients may impair norepinephrine-mediated slow vascular pulsation, thereby disrupting glymphatic function (Jackson & Rosenzweig, 2025).

Artificial intelligence-driven predictive models: The Sleep-Brain-Aging Vulnerability (SBAV) framework proposed by Sheikh Ibrahim further demonstrates the potential of multi-omics integration. This hierarchical model incorporates genomics, proteomics, endocrine biomarkers, EEG sleep microarchitecture and neuroimaging features. It improves the accuracy of identifying cognitive risks associated with OSA in female patients by 35%–42% compared with traditional AHI stratification. This paradigm indicates that future model development should fully account for heterogeneity in gender, age and genetic background (Sheikh Ibrahim, 2025).

### 4.2.2. Exploration of Glymphatic System-Targeted Interventions

Protective effects of CPAP on glymphatic function: Recent longitudinal studies have yielded compelling evidence that CPAP can ameliorate glymphatic function. A 4-year follow-up study by Jackson and Rosenzweig (2025) involving over 1,000 community participants demonstrated a dose-response relationship between OSA severity and reduced DTI-ALPS index. Patients with alleviated OSA presented a relative increase in ALPS index, and changes in this index mediated the association between AHI variations and alterations in visual memory. Additionally, Keil et al. (2026) reported that pCSF levels in CPAP-treated patients were comparable to those in healthy controls, while untreated patients had markedly elevated pCSF, which was positively correlated with A $\beta$  deposition. Another study found that the volume of perivascular spaces in the basal ganglia remained stable among OSA patients with persistent CPAP adherence, whereas a significant progression was observed in the non-adherent group (Sommer et al., 2025). Collectively, these findings suggest that CPAP may slow the progression of cerebral small vessel disease by restoring glymphatic function.

Direct modulation techniques for glymphatic function: Conventional interventions act on the glymphatic system indirectly by relieving nocturnal hypoxia, while physical therapies targeting this system are emerging. An ongoing open-label study conducted at the Mayo Clinic (Mayo Clinic, n.d.) is the first to evaluate the efficacy of the Automated Manual Lymph Drainage Device

(AMLDT, Neuroglide) on glymphatic function in OSA patients. Primary outcome measures include changes in plasma A $\beta$ 42, A $\beta$ 40, A $\beta$ 42/A $\beta$ 40 ratio, phosphorylated tau 217 (p-tau-217), neurofilament light chain and glial fibrillary acidic protein. Eligible participants are required to have received stable CPAP treatment for no less than six months. This study aims to assess the incremental benefits of combining lymph drainage therapy with CPAP, and provide evidence for the "CPAP-plus" combined intervention strategy.

#### **4.2.3. Biomarker Enrichment and Long-Term Follow-Up Clinical Trials**

Biomarker enrichment strategies: A 12-month follow-up study by Frias et al. on patients with Alzheimer's disease comorbid with OSA found that cognitive decline progressed more slowly in individuals with good CPAP adherence compared with those with poor adherence. Baseline sleep architecture, sleep efficiency and sleeping posture were predictive of cognitive outcomes, indicating these parameters can serve as enrichment biomarkers to identify patients most likely to benefit from treatment (Frias et al., 2025). Ma et al. further demonstrated that plasma neurofilament light chain (NfL) outperformed A $\beta$ -related biomarkers in distinguishing OSA patients with concomitant mild cognitive impairment (MCI). When combined with conventional indicators, its area under the curve (AUC) reached 0.907 (Ma et al., 2026). In future clinical trials, plasma NfL, glial fibrillary acidic protein (GFAP) and p-tau-217 can be incorporated into enrollment criteria or stratified randomization design to enhance statistical power.

Long-term follow-up and real-world evidence: Most existing intervention studies adopt a follow-up period of 3 to 12 months. However, the development and progression of OSA-related cognitive impairment is a chronic process. Randomized controlled trials with a follow-up duration of at least 2 to 3 years are warranted to clarify whether interventions can prevent progression to dementia. Meanwhile, pragmatic clinical trials based on real-world data should be conducted to evaluate long-term adherence and therapeutic effects of interventions under routine clinical settings.

### **5. Discussion and Conclusions**

Research on the mechanisms and innovative interventions for cognitive impairment associated with obstructive sleep apnea has become a cutting-edge hotspot at the intersection of sleep medicine and neuroscience. This article reviews recent advances in this field, and the main conclusions are summarized as follows. First, glymphatic dysfunction and destabilization of dynamic functional brain networks are two core neuroimaging mechanisms underlying OSA-related cognitive impairment, with a well-established mediating coupling pathway between them. At the micro level, multimodal imaging evidence based on the DTI-ALPS index and pCSF mapping consistently confirms evident glymphatic impairment in OSA patients. A systematic review and meta-analysis by Ghaderi et al. reported a significant reduction in the DTI-ALPS index among patients with severe OSA relative to healthy controls, verifying substantial glymphatic dysfunction in this population (Ghaderi et al., 2025). Li et al. further found that patients with severe OSA exhibited markedly attenuated global and anterior BOLD-CSF coupling, which was closely correlated with cognitive decline. Notably, both cognitive function and cortical glymphatic function were significantly improved after effective treatment (Li et al., 2025). At the macro level, dynamic functional network

analyses have identified two unstable patterns in OSA patients: excessive dwell time in specific connectivity states and abnormal state transitions, accompanied by impaired dynamic reorganization of the default mode network, salience network and executive control network (Huang et al., 2023; Li et al., 2022; Wang et al., 2025). Mediation analyses have established a causal chain from glymphatic dysfunction to reduced network efficiency and subsequently to cognitive impairment (Xiong et al., 2024).

It is worth emphasizing that the association between glymphatic dysfunction and cognitive impairment is not unique to OSA. Recent systematic reviews and meta-analyses have demonstrated a consistent link between sleep disorders and impaired glymphatic clearance, with OSA exerting the strongest effect, which supports the dose-response relationship and relevant cognitive analyses (De la Herrán-Arita, 2026; Ghaderi et al., 2025; Wostyn & Nedergaard, 2026). A review by De la Herrán-Arita further regarded the glymphatic system as a key physiological bridge connecting sleep disturbances and the molecular pathogenesis of neurodegenerative diseases. Common clinical conditions including OSA, chronic insomnia and circadian rhythm disorders can fundamentally disrupt glymphatic clearance (De la Herrán-Arita, 2026). Collectively, the above evidence indicates that OSA-related glymphatic dysfunction ultimately leads to multidimensional cognitive deficits by compromising global brain network efficiency.

Second, continuous positive airway pressure (CPAP) yields limited and highly heterogeneous effects on cognitive function in OSA patients, while non-invasive neuromodulation techniques show promising potential as adjunct interventions. Although CPAP effectively corrects nocturnal hypoxia and sleep fragmentation, meta-analyses have revealed inconsistent cognitive improvements across studies (Lal et al., 2022). Simply alleviating upper airway obstruction is insufficient to reverse established brain network damage, creating an urgent need for complementary therapeutic approaches.

Represented by repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS), non-invasive brain stimulation (NIBS) can directly modulate neuronal excitability in targeted brain regions, enhance neural plasticity and regulate dynamic connectivity of large-scale brain networks. It provides a novel treatment option for OSA patients who are intolerant to CPAP or suffer from persistent cognitive impairment after CPAP therapy. A high-quality umbrella review by Wu et al. confirmed that NIBS, particularly rTMS and tDCS, significantly improves overall cognition, language ability, executive function and memory in patients with Alzheimer's disease and mild cognitive impairment (Wu et al., 2025).

In direct evidence from OSA populations, a randomized controlled trial by Han et al. demonstrated that iTBS applied over the left dorsolateral prefrontal cortex remarkably improved visual memory, sustained attention and working memory in OSA patients. The intervention also increased the relative power spectral density of theta and beta bands in the parietal, temporal and anterior brain regions, indicating that TMS ameliorates cognition by regulating cortical neural oscillations (Han et al., 2023). Future research should further explore the synergistic effects of NIBS combined with CPAP, as well as the potential mechanisms whereby NIBS restores glymphatic function indirectly via modulating sleep architecture.

Third, research on OSA-related cognitive impairment is evolving from the traditional hypoxia-brain injury paradigm toward an integrated diagnosis and treatment model featuring multimodal mechanism interpretation, targeted intervention and precise patient stratification. This paradigm shift is mainly driven by three factors. First, the rapid advancement of multimodal neuroimaging techniques enables systematic exploration of mechanisms ranging from glymphatic function to dynamic brain networks, and provides objective biomarkers for accurate identification of individuals at high risk of cognitive decline. Second, interventions targeting the glymphatic system and dynamic brain networks are progressing from theoretical research to clinical validation. Third, biomarker enrichment strategies are expected to enhance the statistical power and clinical translation efficiency of clinical trials. Future studies should prioritize large-sample, multicenter randomized controlled trials with a follow-up period of no less than 2 to 3 years, to clarify the efficacy of different interventions in preventing progression to dementia. Additionally, it is essential to develop multimodal radiomics prediction models integrating structural MRI, functional MRI and angiography, so as to facilitate precise stratified management of OSA-related cognitive impairment. The establishment of this new paradigm will lay a more solid theoretical foundation and offer practical approaches for the early identification and effective intervention of OSA-associated cognitive deficits.

#### **Author Contributions:**

Conceptualization, Z.F.Y.; methodology, Y.J.D.; resources, Z.F.Y.; data curation, Y.J.D. and W.K.Z.; writing — original draft preparation, Y.J.D. and W.K.Z.; writing — review and editing, Z.F.Y.; visualization, Y.J.D.; supervision, Z.F.Y.; project administration, Z.F.Y.; funding acquisition, Z.F.Y. All authors have read and agreed to the published version of the manuscript.

#### **Funding:**

The project is supported by the following grants: National Population Health Science Data Center, Chinese Academy of Medical Sciences (Grant No. NCMI202409A08).

#### **Institutional Review Board Statement:**

Not applicable.

#### **Informed Consent Statement:**

Not applicable.

#### **Data Availability Statement:**

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

#### **Acknowledgments:**

The authors would like to thank all participants and staff who contributed to this study.

#### **Conflict of Interest:**

The authors declare no conflict of interest.

## References

- Allen, E. A., Damaraju, E., Plis, S. M., et al. (2014). Tracking whole-brain connectivity dynamics in the resting state. *Cerebral Cortex*, 24(3), 663–676.
- Begemann, M. J., Brand, B. A., Ćurčić-Blake, B., et al. (2020). Efficacy of non-invasive brain stimulation on cognitive functioning in brain disorders: A meta-analysis. *Psychological Medicine*, 50(15), 2465–2486.
- Benjafield, A. V., Ayas, N. T., Eastwood, P. R., et al. (2019). Estimation of the global prevalence and burden of obstructive sleep apnoea: A literature-based analysis. *The Lancet Respiratory Medicine*, 7(8), 687–698.
- Benveniste, H., Liu, X., Koundal, S., et al. (2019). The glymphatic system and waste clearance with brain aging: A review. *Gerontology*, 65(2), 106–119.
- Bradley, T. D., & Floras, J. S. (2009). Obstructive sleep apnoea and its cardiovascular consequences. *The Lancet*, 373(9657), 82–93.
- Calhoun, V. D., Miller, R., Pearlson, G., et al. (2014). The chronnectome: Time-varying connectivity networks as the next frontier in fMRI data discovery. *Neuron*, 84(2), 262–274.
- Coughlin, S. R., Mawdsley, L., Mugarza, J. A., et al. (2004). Obstructive sleep apnoea is independently associated with an increased prevalence of metabolic syndrome. *European Heart Journal*, 25(9), 735–741.
- De la Herrán-Arita, A. K. (2026). When sleep fails, brain clearance suffers: The role of glymphatic impairment in clinical neurology. *Acta Neurologica Belgica*, 126(3), 783–792.  
<https://doi.org/10.1007/s13760-025-02959-w>
- Durtette, A., Dargent, B., Gierski, F., et al. (2024). Impact of continuous positive airway pressure on cognitive functions in adult patients with obstructive sleep apnea: A systematic review and meta-analysis. *Sleep Medicine*, 123, 7–21.
- Frias, C. L., Almeria, M., Castejon, J., Artero, C., Caruana, G., Elias-Mas, A., Uscamaita, K., Hawkins, V., Ray, N. J., Buongiorno, M., Cullell, N., & Krupinski, J. (2025). A pilot study: The effect of CPAP intervention on sleep architecture and cognition in Alzheimer's disease patients with obstructive sleep apnea. *Neurology International*, 17(9), Article 147.  
<https://doi.org/10.3390/neurolint17090147>
- Ghaderi, S., Mohammadi, S., & Fatehi, F. (2025). Glymphatic pathway dysfunction in severe obstructive sleep apnea: A meta-analysis. *Sleep Medicine*, 131, 106528.
- Greenstone, M., & Hack, M. (2014). Obstructive sleep apnoea. *BMJ*, 348, g3745.
- Guidelines for the diagnosis and treatment of obstructive sleep apnea hypopnea syndrome (revised 2011). (2012). In *Proceedings of the 4th Northeast China Academic Conference on Respiratory Diseases & the 11th Annual Conference of Jilin Society of Respiratory Diseases* (pp. 67–70).
- Gurbani, N., Naismith, S., Rosenzweig, I., et al. (2025). Should we treat sleep apnoea to prevent dementia? *Current Treatment Options in Neurology*, 27(1), 26.
- Han, X., Cai, S., Gui, H., et al. (2023). Transcranial magnetic stimulation cortical oscillations and improve cognition in obstructive sleep apnea patients. *Brain and Behavior*, 13(4), e2958.

- Hassan Mohmmmed Ahmed, A. F., Emam Mohamed Ahmed, N. M. A., Abdulwahid Elsamany, A. A., et al. (2025). The role of sleep disturbances in Alzheimer's disease progression: A systematic review. *Cureus*, 17(6), e86450.
- He, Z., & Sun, J. (2025). Clearance mechanisms of the glymphatic/lymphatic system in the brain: New therapeutic perspectives for cognitive impairment. *Cognitive Neurodynamics*, 19(1), 111.
- Huang, Y., Shen, C., Zhao, W., et al. (2023). Multilayer network analysis of dynamic network reconfiguration in patients with moderate-to-severe obstructive sleep apnea and its association with neurocognitive function. *Sleep Medicine*, 112, 333–341.
- Jackson, M. L., & Rosenzweig, I. (2025). Perivascular dynamics, sleep apnea, and memory: Interpreting a moving target. *American Journal of Respiratory and Critical Care Medicine*, 211(12), 2244–2246.
- Keil, S. A., Li, Y., Krieger, A. C., et al. (2026). Increased MRI-derived parenchymal cerebral spinal fluid mapping in untreated obstructive sleep apnea patients. *Neurobiology of Disease*, 221, 107325.
- Lal, C., Ayappa, I., Ayas, N., et al. (2022). The link between obstructive sleep apnea and neurocognitive impairment: An official American thoracic society workshop report. *Annals of the American Thoracic Society*, 19(8), 1245–1256.
- Li, H., Li, L., Li, K., et al. (2022). Abnormal dynamic functional network connectivity in male obstructive sleep apnea with mild cognitive impairment: A data-driven functional magnetic resonance imaging study. *Frontiers in Aging Neuroscience*, 14, 977917.
- Li, Y., Lin, S., Guo, Z., et al. (2025). Decoupling of global signal and cerebrospinal fluid inflow is associated with cognitive decline in patients with obstructive sleep apnoea. *Sleep Medicine*, 129, 330–338.
- Liu, G., Yang, C., Wang, X., et al. (2023). Oxygen metabolism abnormality and Alzheimer's disease: An update. *Redox Biology*, 68, 102955.
- Ma, L., Liu, N., Feng, Y., et al. (2026). Exploration of plasma biomarkers of neurodegeneration in obstructive sleep apnea-related mild cognitive impairment. *Clinical Otolaryngology*, 51(1), 92–100.
- Mayo Clinic. (n.d.). A study of automated manual lymphatic drainage therapy for obstructive sleep apnea. <https://www.mayo.edu/research/clinical-trials/cls-20597241>
- Nepozitek, J., Marecek, S., Rottova, V., et al. (2025). Glymphatic dysfunction evidenced by DTI-ALPS is related to obstructive sleep apnea intensity in newly diagnosed Parkinson's disease. *npj Parkinson's Disease*, 11(1), 160.
- Niu, Y., Sun, S., Wang, Y., et al. (2025). Spatiotemporal trends in the prevalence of obstructive sleep apnoea across China: A multilevel meta-analysis incorporating geographic and demographic stratification (2000-2024). *Nature and Science of Sleep*, 17, 879–903.
- Preti, M. G., Bolton, T. A., & Van De Ville, D. (2017). The dynamic functional connectome: State-of-the-art and perspectives. *NeuroImage*, 160, 41–54.
- Rektorová, I., Pupíková, M., Fleury, L., et al. (2025). Non-invasive brain stimulation: Current and future applications in neurology. *Nature Reviews Neurology*, 21(12), 669–686.

- Ren, Y., Chen, S., Wang, H., et al. (2025). Unraveling the bidirectional links between obstructive sleep apnea and mild cognitive impairment: A systematic review and meta-analysis. *Sleep Medicine*, 132, 106562.
- Rosenzweig, I., Glasser, M., Polsek, D., et al. (2015). Sleep apnoea and the brain: A complex relationship. *The Lancet Respiratory Medicine*, 3(5), 404–414.
- Rotenberg, B. W., Murariu, D., & Pang, K. P. (2016). Trends in CPAP adherence over twenty years of data collection: A flattened curve. *Journal of Otolaryngology - Head & Neck Surgery*, 45(1), 43.
- Sawyer, A. M., Gooneratne, N. S., Marcus, C. L., et al. (2011). A systematic review of CPAP adherence across age groups: Clinical and empiric insights for developing CPAP adherence interventions. *Sleep Medicine Reviews*, 15(6), 343–356.
- Sheikh Ibrahim, H. (2025). SBAV: A sex-stratified precision framework for predicting sleep apnea-driven neurodegeneration in aging women [Conference abstract]. *Innovation in Aging*, 9(Suppl. 2), igaf122.4257. <https://doi.org/10.1093/geroni/igaf122.4257>
- Shine, J. M., Bissett, P. G., Bell, P. T., et al. (2016). The dynamics of functional brain networks: Integrated network states during cognitive task performance. *Neuron*, 92(2), 544–554.
- Sommer, R., Hill, E. A., Ramirez, J., et al. (2025). Continuous positive airway pressure and progression of enlarged perivascular spaces in adults with obstructive sleep apnea. *Neurology*, 105(8), e213955.
- Wang, J., Wang, Z., Wang, X., et al. (2025). Altered brain dynamic functional connectivity in patients with obstructive sleep apnea and its association with cognitive performance. *Sleep Medicine*, 128, 174–182.
- Wostyn, P., & Nedergaard, M. (2026). Ocular glymphatic dysfunction as a potential link between obstructive sleep apnea and retinal structural changes. Comment on Pusic Sesar et al. Multimodal assessment of ocular parameters in patients with severe obstructive sleep apnea with emphasis on retinal structural changes. *Life* 2025, 15, 1307. *Life*, 16(2), Article 214. <https://doi.org/10.3390/life16020214>
- Wu, M., Song, W., Wang, X., et al. (2025). Efficacy of non-invasive brain stimulation interventions on cognitive impairment: An umbrella review of meta-analyses of randomized controlled trials. *Journal of NeuroEngineering and Rehabilitation*, 22(1), 22.
- Xiong, Z., Bai, M., Wang, Z., et al. (2024). Resting-state fMRI network efficiency as a mediator in the relationship between the glymphatic system and cognitive function in obstructive sleep apnea hypopnea syndrome: Insights from a DTI-ALPS investigation. *Sleep Medicine*, 119, 250–257.
- Yankova, G., Bogomyakova, O., & Tulupov, A. (2021). The glymphatic system and meningeal lymphatics of the brain: New understanding of brain clearance. *Reviews in the Neurosciences*, 32(7), 693–705.
- Yao, L., Wang, Y., Gao, Y., Gao, H., & Guo, X. (2023). The role of the fronto-parietal network in modulating sustained attention under sleep deprivation: An functional magnetic resonance imaging study. *Frontiers in Psychiatry*, 14, Article 1289300. <https://doi.org/10.3389/fpsy.2023.1289300>

- Yi, H. J., Liao, X. Y., Pi, M. Y., et al. (2023). Establishment of a new telemedicine-based model for the diagnosis and treatment of obstructive sleep apnea: Study protocol for a non-inferiority randomized controlled trial. *Chinese General Practice*, 26(3), 380–385.
- Yu, R., Li, Y., Zhao, K., et al. (2025). The contributions of resting-state functional-MRI studies to our understanding of male patients with obstructive sleep apnea: A systematic review. *Frontiers in Neurology*, 16, 1532037.
- Yu, S., Wang, S., & Sun, H. (2024). Effects of repetitive transcranial magnetic stimulation on inhibitory control in first-episode schizophrenia: Behavioral and neural mechanisms. *Frontiers in Psychiatry*, 15, Article 1496562. <https://doi.org/10.3389/fpsy.2024.1496562>
- Zalesky, A., Fornito, A., Cocchi, L., et al. (2014). Time-resolved resting-state brain networks. *Proceedings of the National Academy of Sciences of the United States of America*, 111(28), 10341–10346.
- Zhang, X., Xu, H., Yin, S., et al. (2025). Obstructive sleep apnea and memory impairments: Clinical characterization, treatment strategies, and mechanisms. *Sleep Medicine Reviews*, 81, 102092.
- Zhao, X., Liu, J., Shao, Z., Liu, X., Wang, Z., Yuan, K., Zhang, B., Li, Y., Sheng, X., Zhu, Y., & Guo, Y. (2024). Restoration of abnormal sleep EEG power in patients with insomnia disorder after 1Hz rTMS over left DLPFC. *Frontiers in Psychiatry*, 15, Article 1431837. <https://doi.org/10.3389/fpsy.2024.1431837>

**License:** Copyright (c) 2026 Author.

All articles published in this journal are licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). This license permits unrestricted use, distribution, and reproduction in any medium, provided the original author(s) and source are properly credited. Authors retain copyright of their work, and readers are free to copy, share, adapt, and build upon the material for any purpose, including commercial use, as long as appropriate attribution is given.