

Role of Electroencephalographic Biomarkers as Predictors of Post-Stroke Cognitive Outcomes in Patients with Cerebral Infarction: Literature Review

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Abstract: Cerebral infarction (ischemic stroke) is a leading cause of long-term disability. It is often associated with cognitive impairment that has a significant impact on quality of life. Predicting biomarkers is necessary, and electroencephalographic (EEG) biomarkers have emerged as promising tools to predict cognitive outcomes in these patients. To conduct this literature review, a comprehensive search was performed in different databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar from inception to 2025, focusing on biomarkers and the role of ECG in predicting cognitive outcomes. In addition, recent clinical trials were also reviewed and assessed for the role of biomarkers in predicting cognitive outcomes. This literature review suggests that specific EEG abnormalities, including generalized slowing or altered power in alpha, delta, beta, gamma, and theta bands, as well as disrupted functional connectivity, consistently correlate with deficits in memory, attention, and executive functioning. In addition, the ability to assess the effectiveness of cognitive rehabilitation interventions has also been demonstrated. It provides non-invasive, cost-effective, and accessible insights into brain function and event-related ability to assess cognitive prognosis after stroke. EEG biomarkers can be used as a predictor for cognitive impairments in patients with cerebral infarction (ischemic stroke).

Keywords: electroencephalographic biomarkers, ischemic stroke, cognitive impairments, memory loss

Introduction

Stroke, a second leading cause of mortality, has a significant contribution to disability worldwide, with the highest prevalence in developing countries, and among strokes, ischemic stroke is the most common type.¹ Fifteen million people reportedly suffer from stroke annually, among these, 5 million die, and 5 million patients are reported as permanently disabled.² Moreover, 8 out of every 10 strokes are due to cerebral infarction (cerebral ischemia), and 2 from cerebral hemorrhage.³ Patients who survive stroke often face a range of challenges like physical, cognitive, and emotional, with cognitive impairment considered as one of the most prevalent and debilitating outcomes.⁴ Cognitive impairment has direct implications for patients' post-stroke quality of life (QoL) and functioning, including living independently, ability to maintain job, interpersonal relationships, and other tasks related to life.⁵ Therefore, predicting cognitive outcomes in patients with cerebral infarction is essential for timely treatment and maintaining better QoL.

There are different modalities used for the prediction of cognitive outcomes after stroke, such as transcranial doppler ultrasonography,⁶ and computed tomography (CT) brain scans.⁷ However, these modalities have limitations and outcomes depend on various factors, like age, gender, skull bone thickness, variation in CO₂ partial pressure in the blood, and haematocrit value.⁸ Furthermore, pre-existing cerebral atrophy is another most important and consistent predictor of cognitive impairment,⁹ and markers including fluid markers (ubiquitin C hydrolase L1, glial fibrillary acidic protein, and

S100) and imaging markers (CT scores, pathological observations, magnetic resonance imaging (MRI) classification.¹⁰ However, there are two types utilized for the assessment of post-stroke cognitive impairments. One is a neuropsychological assessment, which uses questionnaires, such as the Montreal Cognitive Assessment Scale (MoCA) and Mini-Mental Status Examination (MMSE). However, the reliability and validity of this type of assessment are questionable.¹¹ In contrast, biomarkers like electroencephalographic (EEG) are used as predictors of cognitive recovery and outcomes in stroke patients and can classify different groups of cognitive impairment after stroke.¹²

Electroencephalography (EEG) is a non-invasive technique for measuring the electric field or activity in the brain through electrodes placed on the scalp, which observes and measures the voltage potentials in the neurons' circumference,¹³ and it has a long history of utilization in clinical settings to diagnose and monitor various neurological conditions.¹⁴ Most recently, it has gained attention for its potential role in the assessment of brain function after stroke. This may be due to its ability for detection of specific patterns associated with brain injury and recovery.¹⁵ In addition, EEG biomarkers can also provide valuable insights into acute and chronic cognitive impairment.¹⁶ Using EEG biomarkers to predict cognitive outcomes is based on the understanding that certain patterns of brain wave activity correspond to specific cognitive functions and can determine nerve recovery or damage after a stroke.¹² One of the key aspects is the analysis of frequency bands, including alpha, beta, delta, theta, and gamma waves. Each frequency band is associated with a different state of brain activity and cognitive processes.^{12,17} In addition to spectral power analysis, coherence measures in the EEG also provide insight into the connectivity between different regions of the brain. Coherence reflects the synchronization of oscillatory activity across the EEG and is particularly useful in evaluating network connections within the brain.^{18,19} Whereas reduced coherence in the right central parietal area is considered an early EEG biomarker in patients with cognitive impairment.²⁰ By using EEG, researchers can identify how the brain responds to stimuli and engages in learning and working memory, which can influence a person's performance in performing decision-making tasks.²¹ In addition, different lobes in the brain have different brain functions, like the temporal lobe associated with the recognition and perception of language and auditory stimuli; the parietal lobe is related to hearing, sensory, vision, memory, and motor function; the frontal lobe is associated with voluntary movement, planning, emotions, reasoning, and problem solving.²²

Post-stroke cognitive outcomes affect a large number of survivors, and face difficulty in performing functions, memory loss, and other issues. Therefore, it is important for timely intervention and rehabilitation to optimize recovery and improve stroke survivors' QoL. Traditional imaging methods such as CT and MRI scans provide valuable insights into the structural changes in the brain. However, there is limited information on real-time brain activity and connectivity related to cognitive impairment. Brain EEG biomarkers are considered a viable tool to predict cognitive outcomes in ischemic stroke (cerebral infarction) patients. Therefore, this literature review aims to compile current findings on the predictive value of EEG biomarkers. It provides a comprehensive understanding of their role and potential as a standard component of cognitive outcome assessment in stroke rehabilitation.

For literature search, different electronic databases, such as PubMed, Scopus, Web of Sciences, ScienceDirect, Google Scholar, and grey literature, were searched using keywords, like "ischemic stroke", "cerebral infarction", "cognitive outcomes", "electroencephalographic biomarkers". Studies focusing on the role of EEG biomarkers in predicting cognitive outcomes in patients with cerebral infarction were analyzed and critically evaluated for their limitations and research gaps.

Pathophysiology of Stroke (Cerebral Infarction) and Cognitive Outcomes

Pathophysiology of stroke, particularly cerebral infarction (ischemic stroke), involves a complex mechanism that blocks blood flow to the brain and leads to nerve death and multiple functional impairments, including cognitive outcomes.²³ In addition, ischemia also disrupts local excitatory-inhibitory balance, long-range connectivity, and thalamocortical drive. Thus, understanding the pathophysiology of cerebral infarction helps clarify how ischemic events can have acute and chronic cognitive consequences. It also explores possible treatments that can mitigate these consequences.

Cerebral infarction primarily occurs when cerebral blood flow is interrupted, which can induce severe neural injuries.²⁴ Moreover, the immune mediators pro-inflammatory signals rapidly influence the infiltration of a wide range of inflammatory cells (monocytes, neutrophils, macrophages, T cells subtypes, and other inflammatory cells) and activate

resident cells into the ischemic region, resulting in brain damage.²⁵ Recently, to understand the cerebral infarction (ischemic stroke) pathophysiology, efforts have been made, including oxidative stress, cellular excitotoxicology, neuro-inflammation, and cell death processes.²⁴ Meanwhile, inflammatory cells release free oxidants/radicals and reactive oxygen species (ROS), which can threaten tissue viability in the ischemic core vicinity because brain tissue is not well equipped with antioxidant defences.²⁶ Similarly, a plethora of signaling pathways either neuroprotective or detrimental, are also considered and involved in pathophysiology.²⁴

Mechanism of Cerebral Infarction (Stroke)

The initial blockage of blood flow triggers a series of biochemical and molecular events that lead to the death of neurons, glial cells, and other supportive brain cells. Proper regulation of brain energy metabolism is important for maintaining brain function in various pathophysiological conditions. In case of cerebral infarction (ischemic stroke), which has complex pathophysiological conditions, including disrupting the brain energy metabolism, which can worsen the brain injury and stroke outcomes.²⁷ Moreover, energy failure involves the decline of glucose neuronal metabolism, resulting in a deficit of adenosine triphosphate (ATP) production, which ultimately limits glucose access.^{28,29} This energy metabolism vicious circle is evoked by the nicotinamide adenine dinucleotide (NAD) deficiency in the mitochondrial salvage pathway and subsequently results in the Krebs cycle impairment.²⁸ In the decreasing level of NAD, the activity of enzymes dependent on the NAD also declined and influences the genetic error, which initiates the neuronal degradation and death process.²⁸

With the energy failure, the excitotoxicity process occurred when oxygen and glucose deficiency disrupted the oxidative phosphorylation process and resulted in energy depletion and imbalance in ions, followed by depolarization of the cell membrane, extracellular accumulation of the excitatory amino acid glutamate, and calcium overload.^{30,31} Sometimes due to the severity of energy deprivation, cells in the ischemic core often lead to necrosis, and cells in the penumbra may also undergo apoptosis, a more controlled form of cell death. It depends on the severity of the ischemia and the energy state of the cells.^{32,33} Furthermore, activation of excessive N-methyl-D-aspartate receptor (NMDAR) also promotes neuronal death and its stimulation during ischemic stroke, which is the main step in post-stroke damage.³⁴ In addition, the ischemic process triggers an inflammation response by activating brain resident immune cells, microglia, astrocytes, and neurons, as well as recruits leukocytes (macrophages, neutrophils, and T cells) from the bloodstream.^{35,36} This inflammatory response releases cytokines and chemokines, which aggravate tissue damage. Although both pro and anti-inflammatory signals are triggered and considered essential for modulating both wound healing and neuronal cell damage.³⁷ Meanwhile, these inflammatory cytokines can disrupt the integrity of the blood-brain barrier (BBB), allowing harmful substances and immune cells to enter the brain tissue.³⁸ This disruption worsens inflammation and nerve damage and results in vasogenic edema and secondary injury.³⁹ Secondary injuries resulted in impaired function and cognitive outcomes. Meanwhile, the whole mechanism is explained in [Figure 1](#).

Cognitive Outcomes

Cognitive impairments following cerebral infarction are common and can be severe, depending on the size, location, and duration of the ischemic events.⁴⁰ These impairments arise due to the brain's complex connectivity and functional specialization. Cognitive domains include memory, executive function, language, attention, and visuospatial abilities.⁴¹ The nature and degree of cognitive impairment are influenced by the specific brain regions affected and the extent of damage in these areas. The cerebral cortex of the brain is divided into various functional areas, and each location involves a different aspect of cognition. For instance, the frontal lobes, which are the primary center for emotions, personality, and executive decisions and its injury often causes impairments in executive function including, working memory, decision making, and cognitive flexibility.⁴²⁻⁴⁴ Likewise, the parietal lobes is bordered on the ventral and posterior sides by auditory and visual cortex and its anterior portion is occupied by somatosensory cortex.⁴⁵ Parietal lobes play a central role in directing attention to behaviorally relevant environmental issues, which are perceived through audition, vision, touch, smell, and taste.⁴⁵ Its injury can impair spatial awareness, resulting in loss of visual function and attention. In addition, patients may also show signs of hemineglect.⁴⁶ Furthermore, temporal lobes, particularly the medial temporal areas and hippocampus, are essential for retrieving and encoding episodic memories.^{47,48}

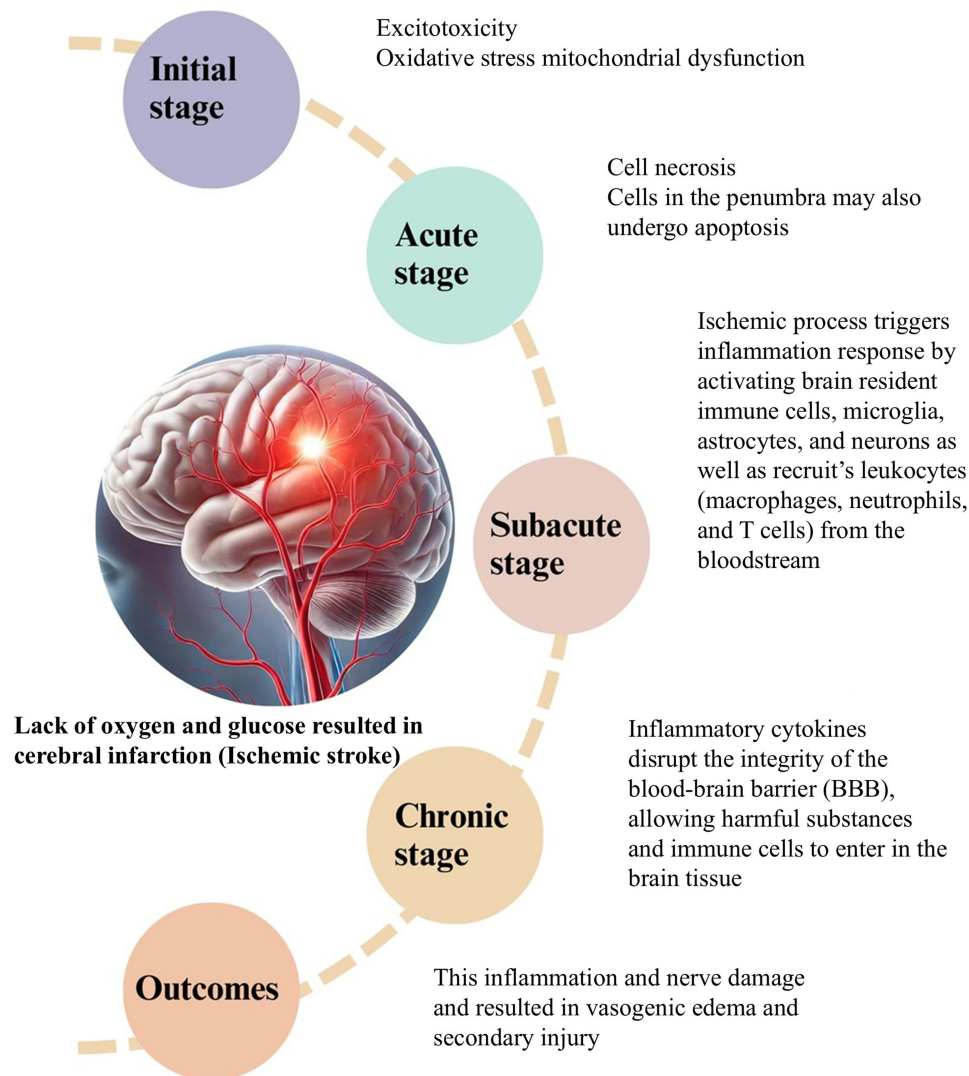


Figure 1 Mechanism of cerebral infarction.

EEG Overview, Its Role in Neurological Assessment, and Pathophysiological Link Between EEG and Stroke

Electroencephalography (EEG) is a non-invasive diagnostic tool used for the measurement of the electric field of the brain by placing electrodes on the scalp, and it measures the voltage potentials or fluctuations resulting from current flow within neurons.¹³ These electrodes are arranged according to a standard system to ensure repeatability and coverage of specific brain regions. Recorded signals are amplified and filtered to remove noise and artefacts before analysis. EEG data is generally observed as waves and classified according to frequency, amplitude, and phase characteristics.⁴⁹ EEG is usually used for the understanding of the neural processes that underlie complex functional domains and higher-order cognitive operations.⁵⁰ Furthermore, EEG also proved to be helpful for the diagnosis of different neurological disorders, including bipolar disorders, depression, and schizophrenia as well as identifying psychiatric biomarkers.⁵¹ EEG analysis has evolved with the advancement of technologies from the qualitative analysis of frequency modulations and amplitude to a comprehensive analysis of the characteristics of the complex spatiotemporal recorded signals.⁵² Moreover, the EEG's ability to monitor the functional status of neural networks makes it a valuable tool in evaluating cerebral infarction (ischemic stroke) patients. As it disrupts neural connections and activity, and the EEG provides insight into the extent and nature of these disruptions.⁵³ It also helps in understanding changes in brain oscillations caused, predicting the outcomes

of recovery, and evaluating treatment methods.^{53,54} Moreover, observable consequences on ECG include spectral slowing, inter-hemispheric asymmetry, network desynchronization, and lower complexity. These disturbances underpin deficits in memory (hippocampo-cortical), executive/attention networks (fronto-parietal), and language (perisylvian), thereby tying EEG features to the outcomes associated with cognitive.⁵⁵

Recent advances in machine learning have greatly enhanced the use of EEG in the diagnosis and rehabilitation of stroke patients. For instance, findings of Giri et al⁵⁶ successfully identified ischemic stroke patients based on EEG using 1D convolutional neural network and batch normalization.⁵⁶ Moreover, another study used a convolutional neural network-gated recurrent unit-harmony search-multivariate optimization to analyze the collected data, resulting in 99.99% prediction accuracy and also demonstrated 11.08% improvement over the results reported in the paper entitled, “Predicting stroke severity with a 3-min recording from Muse portable EEG study”.⁵⁷ Likewise, a study from China also reported excellent results of the proposed ApFu-tree-structures parzen estimator optimized light GBM classifier, which achieved 0.96 precision, 0.96 recall, and 0.96 f1-score.⁵⁸ Collectively, these advances and accurate findings highlight the growing potential of EEG-machine learning integration to improve the detection and diagnosis of stroke, its prognosis, and the monitoring of the rehabilitation process.

EEG Biomarkers/Parameters Commonly Utilized for Stroke Patients

In cerebral infarction (ischemic stroke) research and rehabilitation, specific EEG biomarkers/parameters are used to analyze for the assessment of brain functions, resilience, and connectivity. Key parameters include brainwave pattern, coherence metrics, and power spectral density.

Brainwave Patterns

Brainwave patterns are usually categorized into different patterns based on distinct frequency bands, each frequency band is associated with a specific physiological and cognitive status of the patient. Brainwaves are oscillating electric voltages in the brain which is measured as a few millionths of a volt. Meanwhile, the five main brainwaves recognized widely are listed in Table 1.^{59,60} Cerebral infarction (ischemic stroke) significantly changes these patterns and frequencies, which can provide insights into the extent of the damage that occurred in the brain or its recovery from the damage.

Brainwave Pattern Types

Alpha waves (8–12 Hz) are the dominant oscillations in the brain of human, and are medium frequency oscillations prominent during relaxed, awake states and associated with attention (selection and suppression) and sensory processing⁶¹ as indicated in Figure 2. Patients often exhibit decreased and slower alpha power in the affected hemisphere, which indicates the impaired functioning of the cerebral cortex.⁶² Its restoration over time is a positive prognostic indicator, signifying neural recovery and improved connectivity.

The second important wave is beta, which is a prominent feature of both healthy and pathological sensorimotor processing and is found in the sensory cortex and basal ganglia structures. It is thought to be associated with the sensory processing and motor control.⁶³ Beta waves are high-frequency oscillations (12–35 Hz) associated with active thinking, problem solving, and body movements (Figure 2). Stroke patients have decreased beta power in motor areas, reflecting

Table 1 Different Types of Brainwave Patterns

Frequency Band	Frequency	Brain Status
Alpha	8-12 Hz	Passive attention, very relaxed
Beta	12-35 Hz	Relaxed, active, external attention, anxiety dominant, busy
Gamma	36-90Hz	Concentration, problem solving
Theta	4-8 Hz	Inward focused, deeply relaxed, drowsiness
Delta	0.5–4 Hz	Sleep, dreaming

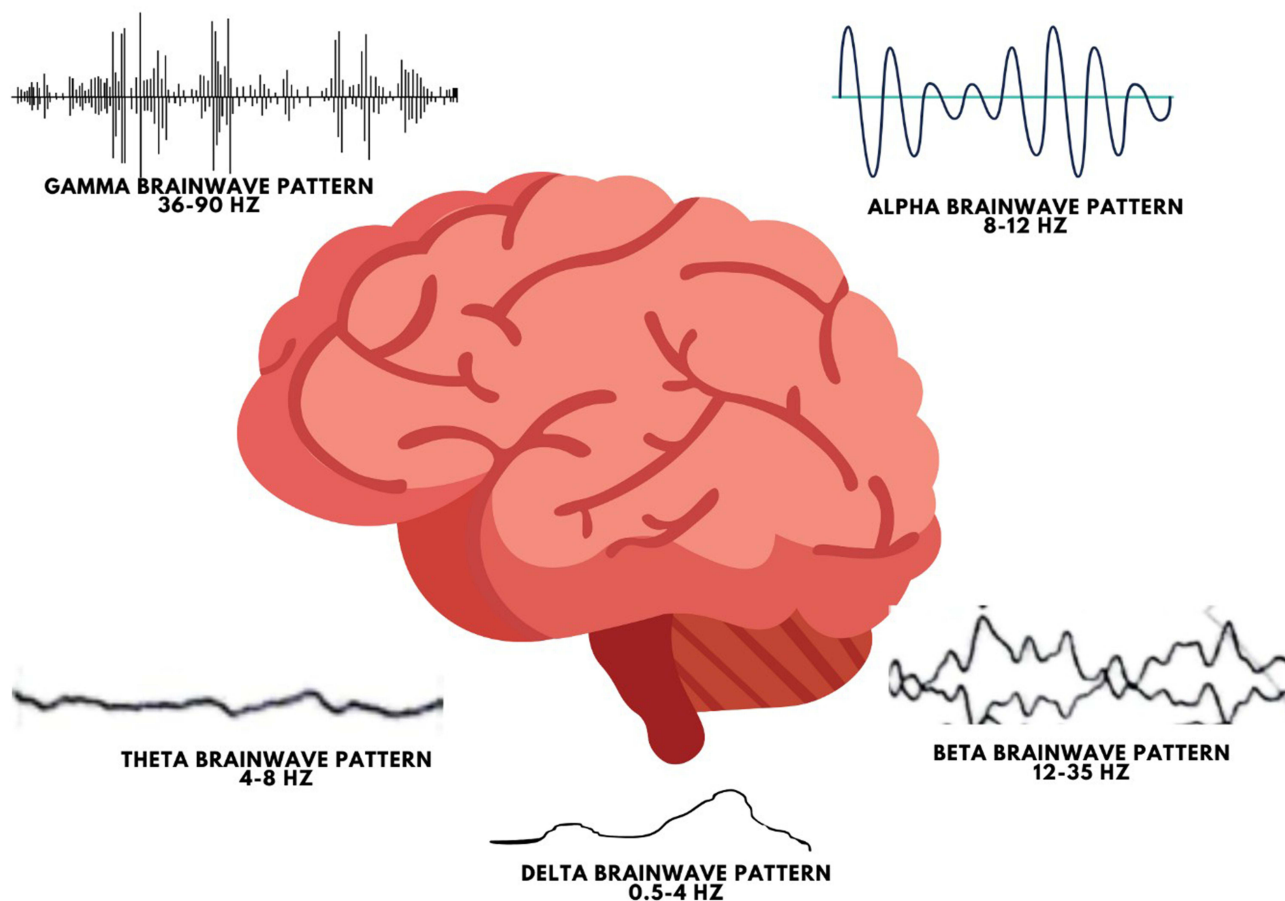


Figure 2 Different brainwave patterns occur in the brain.

impaired planning and motor functions. However, during recovery, increased beta activity is associated with cortical plasticity and motor improvement.⁶⁴

Gamma brainwave is another important high-frequency (36–90 Hz) brainwave (Figure 2), and it generally represents the connections of various neurons together into a network with the aim of storing cognitive and motor parts.⁶⁵ Furthermore, gamma waves likely play a role in neural communication. By reflecting information from the outside world to the brain. These rhythms become evident when the GABA-A system switches from excitation to inhibition. They are mainly found in the hippocampus, dentate gyrus, and CA(1)-CA(3) system and may be related to long-term memory and cognitive performance.⁶⁶

Delta waves are low-frequency (0.5–4 Hz), high-amplitude oscillations that occur during sleep and unconscious states, including anesthesia, slow wave sleep, disorders of consciousness (the vegetative state and coma), and generalized epileptic seizures⁶⁷ as indicated in Figure 2. Patients often show increase in delta activity in the surrounding areas of the infarct, indicating impaired neural function and cerebral activity. Increased delta power is generally associated with poor recovery outcomes.⁶⁸

Furthermore, spectral ratios, such as $(\text{delta} + \text{theta}) / (\text{alpha} + \text{beta})$, higher values predict worse executive outcomes. Likewise, $\text{theta} / \text{alpha}$ ratio and $\text{beta} / \text{theta}$ elevated values are associated with attentional deficits.⁶⁹

Coherence Metrics

EEG coherence metrics measure the functional connectivity between different regions of the brain like the human cortex by analyzing the phase synchronization of oscillations across electrodes. This connection is essential for understanding how cerebral infarction (ischemic stroke) disrupts communication with the neural network.⁷⁰ Recently, coherence has

been used to assess how connected or coherent specific locations in the brain.¹⁸ Moreover, lower intra and inter-hemispheric coupling, particularly in the band of alpha, predicts deficits in working and attention memory. Many studies on the neural basis of language system development have examined EEG coherence.⁷¹ Because language development relies on the coordination of complex neural networks, EEG is a relevant tool to investigate brain functional connections as it is undergoing a crucial growth period.⁷²

Power Spectral Density

Power spectral density represents the energy distribution of the EEG series in the frequency domain, utilized for the evaluation of the brain abnormalities.⁷³ The literature suggests that precise parameterization of the neural power spectrum is essential for proper physiological interpretation of periodic and aperiodic EEG activity.⁷⁴

Association of EEG Biomarkers with Specific Cognitive Outcomes of Stroke (Cerebral Infarction)

These biomarkers provide valuable insights into brain function in cerebral infarction (ischemic stroke) patients. These biomarkers can be used to assess and predict cognitive outcomes after stroke. This is because these indicators reflect the disruption of neural networks and brain function.

Evidence has been presented that EEG oscillations in the alpha and theta bands specially reflect cognitive and memory performance.⁷⁵ In a prospective study, the prognostic value of EEG was analyzed in 23 post-stroke aphasia patients. Fast Fourier transform EEG power was performed for alpha, theta, and delta frequency waves, and abnormalities outside and within speech areas were associated with the restitution of post-stroke aphasia.⁷⁶ Similarly, in a prospective study, 20 patients with cerebral infarction and 19 healthy controls were exposed to 10-minute EEG resting state examination for the observation of alpha waves for the prediction of motor and cognitive deficit. Alpha waves were found to decrease in patients than controls in the brain regions that are critical for behavioral deficits.⁷⁷ Likewise, in a cohort study, brain atrophy was significantly ($p=0.02$) associated with theta wave with 2.6 odds ratio (OR), intracerebral hemorrhages with delta/theta (2.7 OR, $p=0.005$).⁷⁸ Moreover, a 3-minute resting state EEG was obtained at the bedside in 24 patients with cerebral infarction. Conventional quantitative EEG measurements showed a modest association with a two-phase behavioral impairment in the bivariate model. However, partial least square models for whole brain delta or beta waves were significantly associated with NIH stroke scale ($R^2=0.85$ to 0.90) and the cross-validation models ($R^2=0.72$ to 0.73). A larger volume of infarcts was associated with increased delta power. These findings suggested that EEG collected more important information about cerebral infarction than MRI.⁷⁹ In another prospective study, which included 18 patients with cerebral infarction and compared them with 28 controls. A significant ($p<0.001$) difference was observed in all indices, meanwhile, delta/alpha power ratio showed optimal accuracy with a 3.7 threshold and showed 100% sensitivity and specificity.⁵⁵ Similarly, 15 patients with delayed cerebral ischemia were monitored for any change in the alpha-theta/delta ratio, a 30% decrease that outlasted for 3.7 hours reached 88.9% specificity and 100% sensitivity. This prolonged decrease in alpha-theta/delta ratio can be considered as a reliable biomarker and predictor for delayed cerebral ischemia.⁸⁰ In a retrospective study, 200 patients with a mean age of 60 years were studied, and 121 patients met the criteria of delirium. Delirium was strongly associated with slowing of delta wave (10.3 OR; 95% CI, 5.3–20.1). Overall severity of delirium ($R^2=0.90$) was associated with this slowing.⁸¹ Furthermore, a review article also concluded that the EEG biomarkers can be used for the prediction of post-stroke cognitive impairment.⁸² As in a cross-sectional study, the delta+theta/alpha+beta showed a positive association with NIH stroke scale ($r=0.37$; $p=0.04$). While, a negative association was observed in delta+theta/alpha+beta ($r=-0.65$; $p=0.01$), delta absolute power ($r=-0.39$; $p=0.03$), and alpha-theta/delta ratio ($r=-0.37$; $p=0.04$) with Montreal cognitive assessment.⁸³ Another study utilized EEG biomarkers for the prediction of vascular dementia in post-stroke patients. After the analyses, a high delta frequency wave was observed in patients than in healthy controls, while alpha and beta frequency waves were lower in patients than in healthy controls.⁸⁴ Meanwhile, EEG in the delta phase occurs in sleep with rapid eye movements. However, its origins are thought to be different from the slow wave activity in sleep N3.⁸⁵ Eighty-seven patients were included in a retrospective study for the prediction of cognitive outcomes using EEG attributes, and an observed 97% accuracy. The theta wave was

significantly associated with Montreal Cognitive Assessment scores, and the predictive powers for the right stroke group were $R^2=0.76$, and for the left stroke group, it was 0.65.⁸⁶ Moreover, 105 patients with cerebral infarction were studied and importantly, the central and frontal delta/alpha ratios were found to be related to the severity of brain edema, early deterioration of the nervous system, and poor functional outcomes at 90 days. While the global and frontal delta/alpha ratio, and the delta+theta/alpha+beta ratio were not associated with these outcomes. The predictive outcomes were observed in the frontal delta/alpha ratio, with an AUC of 0.80⁸⁷ (Table 2). These findings are well supported by the findings of a systematic review and meta-analysis, which included 482 participants in 9 studies and observed a higher delta/alpha ratio associated with the modified Rankin scale (mRS) ($r=0.26$, 95% CI, 0.21 to 0.31). While, a higher delta+theta/alpha+beta ratio was correlated with the worst mRS ($r=0.32$, 95% CI, 0.26 to 0.39). Similarly, higher delta/alpha ratio ($r=0.42$, 95% CI, 0.24 to 0.60) and delta+theta/alpha+beta ratio ($r=0.49$, 95% CI, 0.31 to 0.67) were associated with NIH stroke scale.⁸⁸

Overall, across the reviewed studies, most of the studies used resting-state EEG, they differed in the frequency bands analyzed, like alpha, delta, theta, beta and their ratios and their focus on amplitude vs connectivity features, leading to a varied sensitivity in detecting cognitive outcomes. In addition, the differences may also arise in the studies due to characteristics of study populations, study design, EEG metrics, measurement, assessment tools (MoCA, NIH Stroke Scale), and reporting of the outcomes. These altogether explain the heterogeneity of the findings. For instance, larger retrospective studies have linked increased delta/theta activity and elevated delta/alpha ratio to overall edema, neurological severity, poor functional outcomes, and delirium. While, smaller prospective studies targeted very specific domains, like memory or aphasia, demonstrated that alpha and theta oscillations in task-relevant regions predicted domain-specific recovery. Similarly, methodological studies were varied and differed in EEG acquisition time, duration, and analytical approach, yielding variable predictive strength.

Clinical Implications of EEG Biomarkers for Post-Stroke Cognitive Care

The clinical impact of EEG biomarkers in the management and improvement of cognitive outcomes is substantial in terms of diagnosis, prognosis, rehabilitation, and long-term care. EEG is a non-invasive, cost-effective, and accessible technique. It enables clinicians to monitor neural activity in the brain and assess the extent of brain abnormalities.

One of the most important roles of EEG biomarkers is the early detection of cognitive impairment. Meanwhile, extracellularly recorded brain oscillations are the most crucial aspects of neurophysiological data that reflect the activity and function of neurons.¹⁹ The signal pattern and strength of brain oscillations may be a reliable biomarker used to detect cognitive impairment and functional recovery.¹⁹ Abnormalities like increased theta wave activity or decreased alpha and beta power are considered as early indicators of cognitive impairment,⁸⁹ and changes in alpha and beta can also be observed in Figure 3 and this figure demonstrates abnormal brain wave activity, which is characterized by high amplitude, irregular, and asynchronous waves in the middle channels. These findings help clinicians to identify high-risk patients developing cognitive impairment after stroke. This leads to early initiation of cognitive rehabilitation programs. Such proactive measures can reverse the progression of cognitive decline. It emphasized the importance of EEG biomarkers in the case of cerebral infarction (stroke) management.

In addition, metrics such as delta/alpha ratio, delta+theta/alpha+beta ratio, and theta/beta ratio also provide robust prediction and show a strong association with cognitive and functional outcomes.^{90,91} These EEG biomarkers further provide clinicians with objective information to stratify patients based on their potential for recovery. This is to ensure that resources are allocated efficiently and prioritize interventions for those most likely to benefit. Furthermore, these biomarkers can also be used to tailor the focus and intensity of rehabilitation programs. Patients with prominent frontal slowing, indicating executive dysfunction, may benefit more from interventions targeting problem-solving and planning skills, and these biomarkers are also helpful in identifying changes in parameters during treatment.⁹² While, patients with later alpha disruption may require treatment that focuses on visual function and spatial attention.⁹³

Another notable importance of EEG biomarkers is their ability to monitor the impact of the treatment strategies. For instance, cognitive pharmacological treatments, rehabilitation programs, and neuromodulatory techniques like transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS) can change the patterns of the brain activity.⁹⁴ Integrating EEG biomarkers into clinical practice also facilitates personalized medicine in post-stroke

Table 2 Role of EEG Biomarkers for the Prediction of Cognitive Outcomes

Study ID	Sample Size	EEG Protocol	EEG Biomarker Features			Cognitive Outcomes		Key Findings
			Amplitude	Frequency (Hz)	Connectivity	Assessment Tool	Domain Assessed	
[76]	23	Resting	Alpha, theta, and delta	Alpha=8-13, beta=13.5-20, Theta=4-7.5	Speech relevant areas	NA	Post-stroke aphasia	EEG successfully indicates local disturbance in the ischemic regions, which reflects failures involving propagation of the alpha band
[77]	39	Resting	Alpha	NA	Functional	The stroke rehabilitation assessment of movement and composite motor score	Cognitive and motor defects	Alpha bands imaginary component of coherence was locally reduced in the regions of brain in stroke patients compared to controls
[78]	154	Resting	Delta and theta	Slowing	NA	Glasgow outcome score	Acute encephalopathy	Theta/delta and theta bands were associated with intracerebral hemorrhages and brain atrophy
[79]	24	Resting	Delta and beta	NA	Functional	NIH stroke scale	Behavioral defects	Higher delta bands are associated with larger infarct volume
[55]	38	Resting	Delta/alpha power ratio, theta and beta	NA	NA	Accuracy, sensitivity and specificity	Acute ischemic stroke	Delta/Alpha power ratio 3.7 demonstrated a higher accuracy
[80]	15	Resting	Alpha-theta/delta	NA	NA	World federation of Neurological Surgeons scale	Delayed cerebral ischemia	Prolonged alpha-theta/delta ratio proved to be a good biomarker for delayed cerebral ischemia
[83]	30		Delta+theta/alpha+beta	NA	Severity	Montreal cognitive assessment, NIH Stroke scale	Stroke severity	Delta absolute power proved to be associated with Montreal cognitive assessment scores, but not with NIH Stroke scale
[84]	19	Resting	Alpha, delta, beta	NA	Coherence	Support vector machine and K-Nearest Neighbour	Cognitive impairment dementia	Support vector machine provided highest accuracy (96%)
[86]	87	Resting	Alpha, beta, gamma, delta, and theta	250	Functional	Montreal cognitive assessment	Cognitive prognosis	Most of the features for cognitive scores were obtained from frontal lobe
[87]	105	Resting	Delta+theta/alpha+beta ratio and alpha-delta ratio	NA	Functional	Modified Rankin scale	Cerebral edema	Delta/alpha ratio was associated with cerebral edema

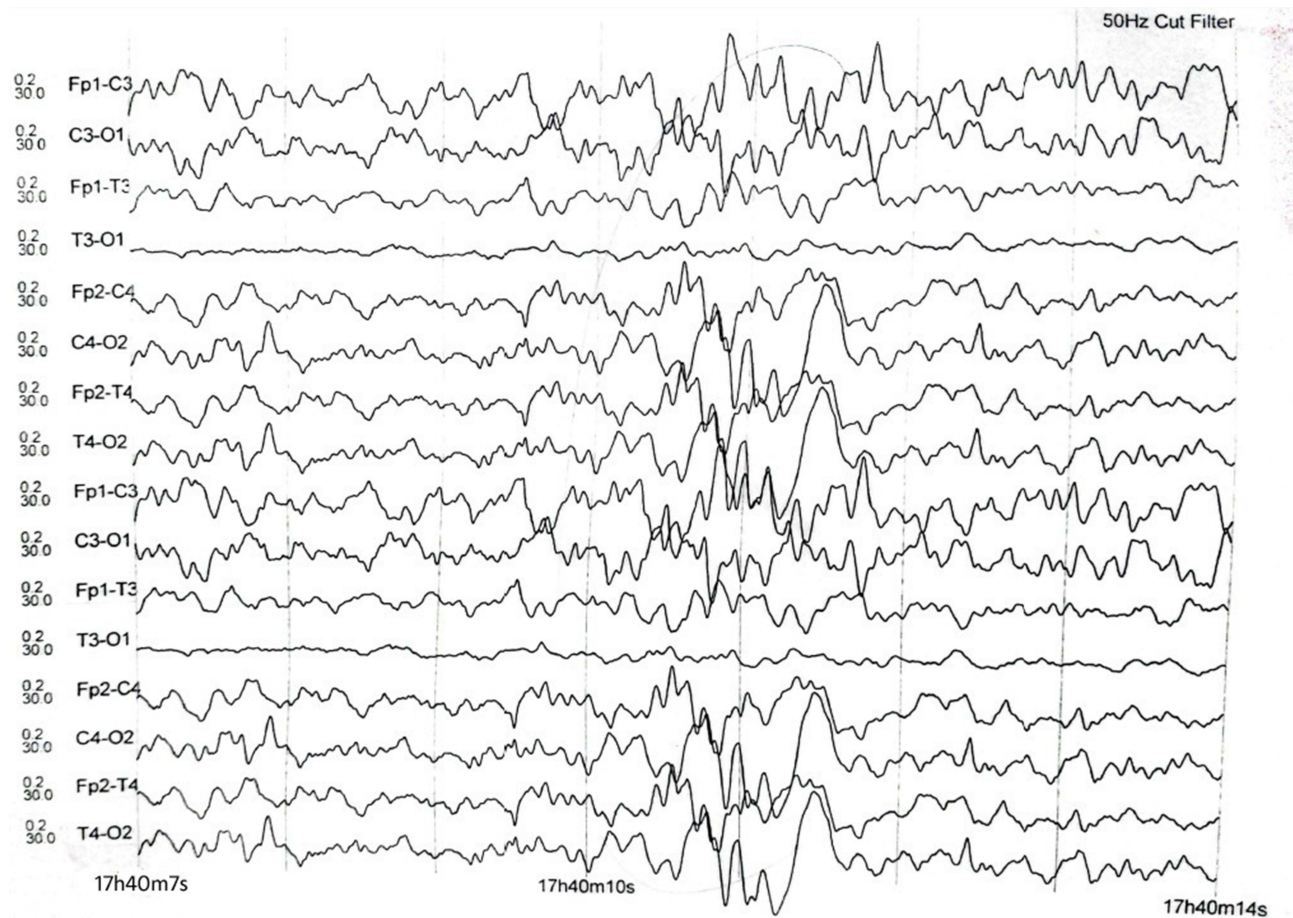


Figure 3 Abnormal EEG of a 2-year male patient (This EEG was performed on 10–20 standard placements with sedated patient. The posterior dominant rhythm showed alpha activity. Beta activity was observed in the anterior head region).

cognitive care. Each patient is unique with differences in brain injury location and severity, which can affect cognitive outcomes. EEG biomarkers can also allow customization of care plans based on individual brain activity patterns.

Challenges and Limitations

The role of EEG biomarkers in predicting cognitive outcomes faces several challenges and limitations. One important issue is the diversity of EEG acquisition protocols and analysis techniques. Variability in electrode settings, signal processing algorithm, and the definition of cognitive outcomes can lead to inconsistent results. Moreover, EEG signals are sensitive to noise, foreign objects and pre-processing variability, such as filters, artifact rejection, epoch length, and re-referencing, which can markedly influence the features. This makes it difficult to discern clinically relevant biomarkers without advanced pre-processing methods. In addition, mixing acute and chronic EEG weakens signals, and recovery trajectories are non-linear. Moreover, ERP neuropsychology and tasks may also unfairly penalize patients with aphasia, conflating language and cognition. The lack of large multicenter studies also limits the statistical power of universally validating biomarkers, in addition to integrating EEG findings with neuroimaging methods and other clinical parameters. Not much has been explored yet, which is an obstacle to a holistic prognosis. Ethical concerns regarding the cost and accessibility of EEG in resource-limited settings also prevent its routine use. Resolving these limitations is important to improve the predictive utility of EEG biomarkers in cerebral infarction (ischemic stroke) patients.

Recommendations

It provides a non-invasive and cost-effective method for early identification of patients at risk of cognitive decline. Integrating EEG measures to improve prognosis, such as power spectral density, functional connectivity and the potential associated with the event into post-stroke assessments. Standardization of EEG protocols and reporting standards (specify time post-stroke, pre-processing pipeline, and artefact criteria) is important to ensure reproducibility and comparability of these protocols. Longer-term studies are required to assess the temporal evolution of EEG changes and their relationship to recovery or deterioration of cognition. Integrating EEG biomarkers with neuroimaging and clinical assessment can provide a multimodal approach. This will improve and enhance the accuracy of predictions. Integrating machine learning algorithms or artificial intelligence to analyze large-scale EEG data may increase efficiency in identifying complex patterns that predict cognitive outcomes.

Future Directions

A large-scale, long-term studies are required to examine the predictive utility of specific EEG parameters in various patient populations and with various factors. Exploring the integration of EEG biomarkers, which can improve prediction models for cognitive recovery. Exploring temporal changes in EEG patterns and their relationship with rehabilitation outcomes, can provide insights into the dynamics of neuroplasticity, facilitating real-time clinical applications. Future research should focus on the development of standardized EEG protocols and machine learning algorithms. Studies evaluating the cost-effectiveness and accessibility of EEG in routine post-stroke care could support its wider use in clinical practice. Machine learning approaches should be used for prognosis and combining EEG features, like spectral, connectivity, and complexity. External validation studies should also be focused on testing in different hospitals, at various times, and with other devices. Multimodal fusion studies should also be considered, and combine EEG with perfusion, lesion network mapping, and blood biomarkers for developing more comprehensive risk models.

Conclusions

This literature review highlights the potential of EEG biomarkers in predicting cognitive outcomes in cerebral infarction (ischemic stroke) patients and correlates with cognitive domains. It is a non-invasive and cost-effective method for early assessment and intervention planning. Important biomarkers included brainwave patterns (alpha, beta, theta, gamma, delta), power spectral changes, and coherence patterns. It has shown a strong association with post-stroke cognitive impairment, including memory, attention, and executive function disturbances. The findings highlight the utility of EEG in monitoring recovery trajectories and customizing rehabilitation strategies. However, our study also highlights the lack of standardized protocols in terms of specifying the time post-stroke, pre-processing pipeline, and artefact criteria used. Therefore, future multicenter research is required for validation and development of standardized protocols. Furthermore, integrating EEG with advanced imaging and machine learning may further improve prediction accuracy and increase its role in precision stroke care.

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