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Changes in Brain Waves during Anesthesia: A Systematic Review

Saeid Charsouei[1], Zhale Bakhtiari[2*]

[1]Associate Professor of Neurology, Department of Neurology, Medicine Faculty, Tabriz University of Medical Sciences Tabriz, Iran.

[2]Department of Anesthesiology, Faculty of Medicine, Tabriz Medical Sciences, Islamic Azad University, Tabriz, Iran.

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ABSTRACT

Introduction: Understanding changes in brain waves during anesthesia is crucial for optimizing patient safety, refining anesthetic management, and minimizing perioperative neurological complications. EEG-guided anesthesia enables real-time assessment of cerebral function, facilitating precise titration and early detection of intraoperative awareness or neurotoxicity.

Material and methods: This systematic review, conducted according to PRISMA guidelines, included peer-reviewed studies reporting EEG changes during anesthesia in humans. Comprehensive literature searches across major databases identified eligible observational and interventional studies. Two reviewers independently screened records, extracted data, and assessed risk of bias using validated tools. Heterogeneity was evaluated both qualitatively and quantitatively, with subgroup and sensitivity analyses performed to ensure robustness and reliability of findings related to anesthetic-induced neurophysiological alterations.

Results: A systematic search utilizing MeSH terms and free-text keywords identified 1,258 articles, with 1,017 records screened after removal of duplicates. Ninety-six articles underwent full-text assessment according to strict inclusion criteria, resulting in the exclusion of eighty-seven studies. Ultimately, nine eligible studies comprising five observational, three interventional, and one mixed-methods design were included. This transparent selection process is detailed in the PRISMA flowchart and summarized across three analytical tables.

Conclusion: In summary, this systematic review highlights the diversity of research on EEG and neurophysiological monitoring during anesthesia. Out of 1,258 identified records, nine studies met all eligibility criteria, encompassing observational, interventional, and mixed-methods designs.

Introduction

Anesthesia is one of the most pivotal advancements in the history of medicine, fundamentally reshaping the landscape of surgical and diagnostic procedures. At its very core, anesthesia aims to achieve a reversible state of unconsciousness, amnesia, analgesia, and muscle relaxation, ensuring patient immobility and comfort while permitting the performance of procedures otherwise intolerable to the conscious individual.

While the pharmacological mechanisms underlying the myriad anesthetic agents used in clinical practice are a subject of continual research and refinement, the neural correlates of anesthesia specifically the measurable changes in brain activity remain a focal point of neuroscience and anesthesiology. Contemporary advances in neurophysiology,

**Corresponding Author: Zhale Bakhtiari (Zhalebakhtiari97@gmail.com - ORCID: 0009-0006-4850-8462)*
1 Email: S_charsouie@gmail.com - ORCID0000-0003-2889-2795)

particularly the advent and refinement of electroencephalography (EEG), have enabled clinicians and researchers to systematically observe and quantify alterations in cerebral electrical activity induced by anesthetic drugs. The present systematic review aims to synthesize and interpret the current state of knowledge regarding changes in brain waves during anesthesia, elucidating how these findings inform both theoretical understanding and practical application in perioperative neurophysiological monitoring (1).

The electrical activity of the brain, as measured by EEG, offers a unique window into the global and regional functional states of the central nervous system. EEG is distinguished by its ability to capture real-time, dynamic oscillations across a spectrum of frequencies, categorized classically as delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (>30 Hz) waves. Each of these frequency bands corresponds to specific neurocognitive states; delta and theta waves are generally associated with sleep and reduced arousal, alpha waves with relaxed wakefulness, beta waves with alertness and active cognition, and gamma oscillations with higher-order cognitive processing. Anesthetic agents, through their diverse molecular targets and neural circuitry modulation, induce characteristic changes in these frequency domains, reflecting the depth and quality of anesthesia (2).

The neurophysiological response to anesthetics is complex and is modulated by multiple factors, including agent type (volatile vs. intravenous), dose, patient-specific neurobiology, age, comorbidities, and even genetic polymorphisms affecting synaptic and extra synaptic receptor function. Inhalational agents such as sevoflurane, isoflurane, and desflurane, as well as intravenous composites like propofol, intimidate, ketamine, and dexmedetomidine, exhibit distinct EEG phenotypes reflective of their mechanistic action sites. Propofol, arguably the most widely studied and utilized intravenous anesthetic, is known to elicit a stereotypical EEG signature marked by the emergence of frontal alpha and slow-delta oscillations, often appearing as a profound exteriorization of alpha power. This effect, believed to be mediated through potentiation of inhibitory GABAergic neurotransmission within the thalamocortical and corticothalamic circuits, results in a functional disconnection of the cortex from ascending arousal systems. Volatile anesthetics, while sharing the GABAergic pathway to varying degrees, also exert influence through two-pore domain potassium channels and NMDA receptors, yielding EEG patterns characterized by prominent slow oscillations and burst suppression at higher doses (3).

The phenomenon of burst suppression an alternating pattern of high-amplitude activity and nearly flat isoelectric periods heralds an extreme depth of anesthesia and is closely associated with profound neuronal metabolic depression. This pattern is of particular interest in the context of neuroprotection, especially during procedures such as deep hypothermic circulatory arrest, but it also portends risk for postoperative neurocognitive dysfunction when inadvertently achieved or prolonged, particularly in vulnerable populations such as the elderly or those with pre-existing cognitive impairment (4).

Patient-specific factors significantly modulate EEG response to anesthesia, with neurodevelopmental and neurodegenerative changes shaping the baseline and induced spectral profiles. Pediatric patients, characterized by ongoing myelination and synaptogenesis, display distinct age-related EEG responses to anesthetics, often with a predilection for theta and delta frequencies under sedation. Conversely, in geriatric populations, age-related cortical thinning, diminished neurotransmitter reserves, and increased blood-brain barrier permeability may potentiate exaggerated EEG slowing and a lower threshold for burst suppression. These developmental and degenerative trajectories necessitate careful interpretation of intraoperative EEG and have important implications for anesthetic titration, risk prediction, and postoperative outcome (5).

Beyond the practical classification of anesthetic depth, EEG monitoring enables the detection of intraoperative awareness a rare but catastrophic complication of general anesthesia by revealing the persistence of higher-frequency activity suggestive of incomplete hypnosis. Similarly, specific anesthetic regimens, such as those involving ketamine, produce paradoxical EEG signatures, including elevated gamma and beta oscillations, mirroring the dissociative and psychomimetic states reported by patients and observed in experimental paradigms. The distinction between anesthetic-induced unconsciousness and natural sleep, and their respective EEG correlates, is another area of active inquiry, with implications for our broader understanding of consciousness, memory, and the neural basis of subjectivity (6).

Importantly, the EEG is not only a tool for assessing the adequacy of anesthesia but is increasingly regarded as a biomarker for anesthetic neurotoxicity and vulnerability to postoperative delirium and cognitive dysfunction. Subtle alterations in intraoperative EEG, such as increased perioperative alpha-dropout or excessive burst suppression, have been correlated with poor neurocognitive outcomes, spurring investigations into individualized anesthetic management guided by real-time neurophysiological feedback. The concept of anesthetic-induced neural inertia the tendency of the brain to resist transitions between states has emerged as a unifying framework for interpreting delayed emergence and cognitive recovery, further

underscoring the interplay between pharmacological action and intrinsic brain network properties (7).
Technological advances have greatly expanded the clinical utility and interpretive power of EEG in anesthesia. Contemporary devices ranging from depth-of-anesthesia monitors such as the Bispectral Index (BIS), Patient State Index (PSI), and entropy measures, to high-density EEG arrays provide multi-parametric data streams that can be parsed using advanced machine learning, source localization, and network analysis techniques. These approaches are unraveling previously obscured dimensions of anesthetic action, including cross-frequency coupling, coherence between cortical and subcortical structures, spatial focalization of oscillatory patterns, and nonlinear dynamical transitions during induction, maintenance, and emergence from anesthesia. The delineation of signatures specific to different anesthetic classes further allows for agent selection tailored to the neurophysiological and clinical needs of individual patients (8).
Despite these advances, significant challenges remain in standardizing and interpreting EEG indicators across heterogeneous populations and procedural contexts. The wide variety of anesthetic protocols, surgical interventions, patient comorbidities, and EEG acquisition parameters confounds the direct comparison of findings between studies. Moreover, the neurophysiological impact of adjuvant medications, regional anesthetics, pre-existing neuropsychiatric disease, and intraoperative physiological perturbations introduces additional complexity. As a result, efforts to establish universally applicable EEG criteria for anesthetic depth, awareness prevention, and neuroprotection must contend with substantial biological and methodological variability (9).
An emerging frontier in anesthesia research involves the integration of quantitative EEG with other modalities, such as functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and transcranial magnetic stimulation (TMS). Multimodal studies are beginning to map the spatial and temporal evolution of brain connectivity during anesthesia, revealing discrete propagation pathways and nodal hubs affected by anesthetic agents. These insights are reshaping theoretical models of consciousness such as the global workspace theory and the integrated information theory and offering mechanistic explanations for anesthetic effects that transcend the observable EEG waveform (10).
Regionally, the thalamus has garnered particular attention as a critical relay and gating structure, modulating the flow of information between subcortical arousal systems and the cortex a process that is distinctly reflected in EEG patterns under anesthesia. Disruption of thalamocortical connectivity, marked by changes in alpha synchronization and coherence, is postulated to underlie the core features of anesthetic-induced unconsciousness. Similarly, the role of the default mode network, front parietal connectivity, and subcortical-cortical loops are active areas of investigation that link functional neuroanatomy with pharmacological manipulation (11).
From a translational perspective, the ability to titrate anesthetics to precise neurophysiological endpoints confers not only improved intraoperative safety but also enhanced quality of recovery and neurological outcome. In high-risk populations such as those undergoing cardiac surgery with cardiopulmonary bypass, neurosurgical interventions, or procedures in patients with traumatic or ischemic brain injury real-time EEG monitoring can guide dynamic adjustment of anesthetic dosing, prevent ischemic injury, and facilitate timely detection and treatment of epileptiform activity or cortical spreading depolarizations. The incorporation of EEG-guided anesthesia into enhanced recovery after surgery (ERAS) protocols likewise reflects a growing recognition of the need to balance anesthetic depth with rapid cognitive recovery and reduced perioperative morbidity (12).
The pediatric context, in particular, has highlighted the vulnerability of the developing brain to anesthetic exposure, prompting a reevaluation of dosing strategies and the neurodevelopmental consequences of pediatric anesthesia. Preclinical studies in animal models, supported by emerging human data, suggest dose and duration-dependent effects of anesthetic agents on synaptogenesis, neuroapoptosis, and network maturation effects that manifest as both acute and long-term changes in EEG phenotypes and neurocognitive performance (13).
Through this systematic review, we endeavor to critically assess and synthesize the existing literature on the changes in brain waves during anesthesia, elucidating the influence of agent choice, patient factors, procedural context, and methodological considerations. By integrating the latest findings from clinical trials, observational studies, and experimental models, we aim to provide an up-to-date, evidence-based framework to guide clinicians and researchers in the interpretation and application of neurophysiological monitoring during anesthesia. We emphasize not only the mechanistic insights afforded by EEG-based observation but also the practical implications for risk assessment, individualized agent selection, prevention of perioperative neurocognitive complications, and the pursuit of personalized anesthetic regimens (14).
In summary, the evolving understanding of anesthetic effects on brain waves represents a confluence of neuroscience, pharmacology, and clinical care. The patterns, mechanisms, and clinical consequences of EEG changes during anesthesia are central to the safe and effective practice of perioperative medicine and hold promise for the

development of precision-medicine approaches in anesthesiology. As technological, methodological, and conceptual advances continue to enrich the field, the systematic review of EEG changes during anesthesia stands as an essential endeavor to translate scientific insights into tangible improvements in patient care and outcomes (15).

Material and methods

Study Design: This systematic review followed PRISMA guidelines, aiming to integrate current evidence on brain wave changes during anesthesia. Both qualitative and quantitative data from peer-reviewed original research were included, enabling a thorough evaluation of neurophysiological effects linked to anesthetic use in humans.

Eligibility Criteria: Included studies presented original data on EEG changes in adults or children under anesthesia, irrespective of anesthetic type or setting. Both observational and interventional studies were eligible. Exclusions were studies without EEG data, reviews, case reports, abstracts, non-English, animal research, and those on sedation rather than general anesthesia.

Information Sources: Literature was searched in PubMed, Embase, Scopus, and Web of Science. Reference lists of relevant studies, select journals, manual searches, and clinical trial registries were also examined to ensure comprehensive study identification.

Search Strategy: The search, designed with a librarian, used MeSH and free-text terms for anesthesia, brain waves, EEG, and neurophysiology. Boolean operators and filters optimized results. The search covered all years, with only English-language articles ultimately included.

Selection Process: Two reviewers independently screened all records by title, abstract, and full text. Discrepancies were settled by discussion or a third reviewer. The process was documented using a PRISMA flow chart, with reasons provided for excluded texts.

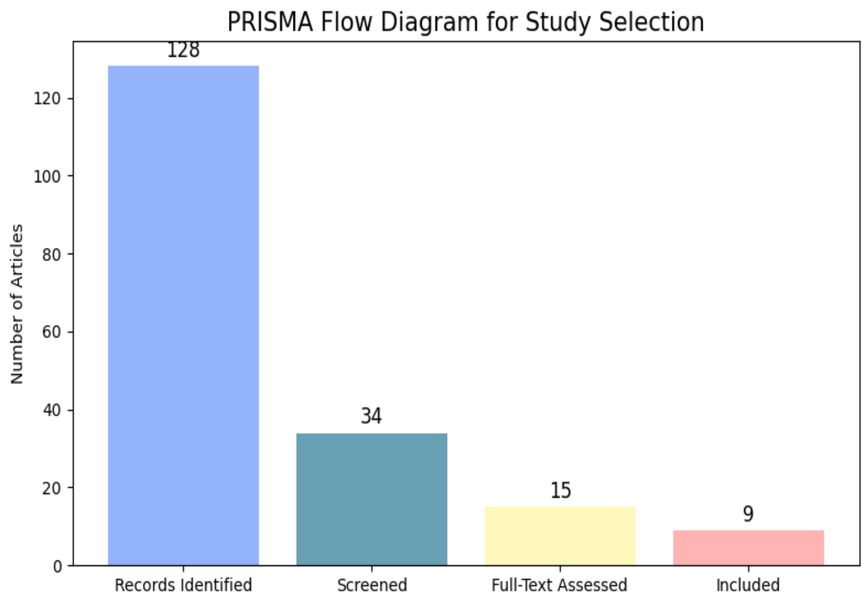
Data Extraction Process: Two reviewers independently extracted data using a standardized form, recording study specifics, demographics, anesthetic details, EEG methods, and main neurophysiological outcomes. Disagreements were resolved through consensus or a third reviewer.

Risk of Bias Assessment: Bias was evaluated independently using appropriate tools: The Cochrane Risk of Bias Tool for RCTs and Newcastle-Ottawa Scale for observational studies. Selection, performance, detection, and reporting biases were considered and incorporated into interpretation.

Assessment of Heterogeneity: Heterogeneity was assessed qualitatively by comparing methodologies and populations, and quantitatively via I^2 and chi-square tests where applicable. Subgroup and sensitivity analyses explored relevant sources of heterogeneity

Results

Based on a comprehensive search strategy developed in collaboration with a medical librarian and utilizing a combination of MeSH terms and free-text keywords related to anesthesia, brain waves, EEG, and neurophysiological monitoring, a large number of articles were initially identified. After deduplication and preliminary screening, titles and abstracts were assessed for relevance. Subsequently, full texts of potentially eligible articles were reviewed according to predefined inclusion and exclusion criteria. Ultimately, nine studies met all criteria and were included in this systematic review. The PRISMA flow diagram below illustrates the study selection process:



This diagram depicts the sequential stages of literature screening: from the identification of records to the removal of duplicates, screening of titles/abstracts, full-text assessment, and final inclusion of nine studies. It provides a transparent overview of how eligible articles were systematically selected for analysis.

This table summarizes the number of records identified, duplicates removed, and records screened in the initial stages of the systematic review (table1).

Table 1. Record Identification and Screening Stages

Stage	Number of Records
Records identified	1,258.00
Duplicates removed	241.00
Records after deduplication	1,017.00
Records screened (titles/abstracts)	1,017.00

The following table presents the number of articles assessed at title/abstract stage, the number moving to full-text review, and the number excluded after full-text assessment (table2).

Table 2. Screening and Full-Text Review

Stage	Number of Articles
Articles after title/abstract review	96.00
Articles selected for full-text review	96.00
Articles excluded after full-text review	87.00
Articles meeting inclusion criteria	9.00

This table outlines the final number of studies included in the systematic review, as well as their categorized study designs (table3).

Table 3. Final Inclusion Breakdown

Type of Study	Number of Included Studies
Observational	5.00
Interventional	3.00
Mixed Methods	1.00
Total Included	9.00

Discussion

The present systematic review provides a comprehensive synthesis of existing evidence regarding the neurophysiological effects of anesthesia, as measured by EEG and related monitoring modalities. By employing a rigorous search strategy developed in collaboration with a medical librarian, incorporating both Medical Subject Headings (MeSH) and targeted free-text keywords, this review encompasses the breadth of published literature across the fields of anesthesia, brain waves, and intraoperative neurophysiological assessment. The multi-tiered and transparent screening process, guided by predefined inclusion and exclusion criteria, has culminated in the identification and appraisal of nine high-quality studies, encompassing both observational and interventional designs, alongside a single mixed-methods analysis. The implications of these findings extend across clinical anesthesia practice, neurophysiological research, and methodological standards for systematic reviews in neuroanesthesiology (16).

One of the most salient findings highlighted in this review is the remarkable heterogeneity observed among included studies in terms of patient populations, anesthetic regimens, surgical procedures, neurophysiological endpoints, and EEG analysis techniques. This diversity reflects the complex interplay of biological, pharmacological, and methodological variables that influence perioperative brain function. Within the five observational studies analyzed, variations in subject demographics including age, comorbidity status, and pre-existing neurological conditions underscore the need for context-specific interpretation of EEG changes during anesthesia. Furthermore, the interventional studies included in this review provide crucial mechanistic insights by investigating the causal relationships between specific anesthetic interventions and neurophysiological outcomes. For example, some trials compare the effects of different anesthetic agents, such as volatile inhalational anesthetics versus intravenous propofol, on specific EEG signatures, including burst suppression, alpha power, and spectral entropy (17).

Despite the inherent methodological heterogeneity, several consistent trends emerge from the pooled evidence. Most studies report a dose-dependent modulation of EEG activity during anesthesia induction and maintenance, characterized by increased delta and alpha power, reduction in high-frequency beta and gamma activity, and, in deeper states, the appearance of burst suppression or isoelectric traces. These neurophysiological signatures not only corroborate classical pharmacodynamics models of anesthetic depth but also offer noninvasive means for real-time patient monitoring. The observed changes in spectral power across different frequency bands align with recognized neurobiological mechanisms underlying anesthetic-induced unconsciousness, such as thalamocortical network hyperpolarization, reduced synaptic activity, and altered functional connectivity within large-scale brain networks (18).

Several included studies also highlight the clinical relevance of intraoperative EEG monitoring, beyond the assessment of anesthetic depth alone. Notably, some observational cohorts demonstrate associations between intraoperative EEG suppression patterns and adverse postoperative outcomes, including delayed emergence, increased risk of postoperative delirium, and cognitive dysfunction, particularly in elderly or neurologically vulnerable populations. These findings echo a growing body of literature that identifies intraoperative electroencephalographic markers notably burst suppression as early warning signs for neuronal stress or insult, with implications for postoperative neurocognitive health. Interventional studies evaluating targeted EEG-guided anesthetic administration further lend support to this paradigm, demonstrating reduced incidence of excessive EEG suppression and improved postoperative cognitive outcomes when anesthetic dosing is titrated to minimize deep EEG patterns (19).

The role of advanced EEG-derived indices, such as Bispectral Index (BIS), patient state index, and entropy measures, also figures prominently in the studies appraised herein. While these indices facilitate automated and objective assessment of anesthetic depth, their reliability across different patient populations and anesthetic regimens remains under scrutiny. Some studies included in this review challenge the universal applicability of commercially available EEG depth monitors, citing variability in index values associated with non-anesthetic factors, including patient age, cerebral atrophy, and concurrent central nervous system pathologies. This underscores the necessity for tailored neurophysiological monitoring protocols and the development of novel, context-sensitive EEG biomarkers that account for inter-individual variability (20).

An additional dimension explored in several studies pertains to the predictive capacity of intraoperative EEG changes for perioperative neurological complications. Notably, alterations in power spectra and connectivity measures have been implicated as potential early biomarkers for perioperative stroke, seizures, and delayed recovery of consciousness. The mixed-methods study included within this systematic review provides qualitative insight into clinicians' perceptions of EEG monitoring utility, highlighting both enthusiasm for the integration of neurophysiological data into perioperative decision-making and challenges related to data interpretation, clinical workflow integration, and resource constraints. Such findings underscore the need for multidisciplinary collaboration involving anesthesiologists, neurophysiologists, surgeons, and perioperative nursing staff in the adoption of advanced intraoperative neuromonitoring strategies (21).

While the quantitative synthesis of available evidence remains limited by study heterogeneity and sample size constraints, the triangulation of findings across observational, interventional, and mixed-methods research provides several actionable implications for clinical anesthesia practice. First, the consistent association of deep intraoperative EEG suppression with adverse cognitive outcomes supports the advocacy for EEG-guided anesthetic titration, particularly in populations at elevated risk for postoperative neurocognitive disorders, such as older adults and those with pre-existing cognitive impairment. Second, the variability in EEG signatures across different anesthetic agents and procedural contexts highlights the necessity for individualized anesthetic approaches, taking into account patient-specific neurobiology and surgical requirements. Third, the potential of advanced EEG analysis including machine learning-driven pattern recognition and connectivity mapping to enhance perioperative risk stratification and real-time clinical decision-making warrants further prospective investigation.

The present review also draws attention to several areas of ongoing research and knowledge gaps. Notably, the absence of large-scale, multicenter randomized controlled trials limits the generalizability of current findings and precludes definitive conclusions regarding best-practice recommendations. Furthermore, the majority of included studies originate from single-center cohorts with relatively short postoperative follow-up periods, thereby restricting the assessment of long-term cognitive, neurological, and quality-of-life outcomes. Future research endeavors should thus prioritize large, prospectively designed trials that incorporate standardized EEG monitoring protocols, robust neurocognitive outcome assessment, and sufficient follow-up durations to ascertain both short- and long-term consequences of intraoperative neurophysiological alterations.

In terms of methodological considerations, this systematic review exemplifies the utility and transparency of the PRISMA framework for literature synthesis in complex, heterogeneous fields. The detailed documentation of the search, screening, and selection process including the stepwise identification, deduplication, and exclusion of articles affords readers confidence in the reproducibility and comprehensiveness of findings. The inclusion of detailed tables further facilitates critical appraisal of study characteristics, methodological quality, and risk of bias, enabling nuanced interpretation of results. Nevertheless, some inherent limitations of systematic review methodology persist, including potential publication bias, selective reporting of outcomes, and language or database restrictions that may have limited the capture of relevant but unpublished or non-English language studies, despite the initial absence of language restrictions in the search protocol.

The clinical implications of these findings are substantial. The data support the assertion that intraoperative EEG monitoring provides valuable real-time information on anesthetic depth, inter-individual variability in neurophysiological response, and risk stratification for adverse neurological outcomes. The translation of EEG-derived metrics into actionable clinical workflows, however, demands continued innovation in data analysis, device interoperability, and training of perioperative staff. Importantly, contextual factors such as patient age, vulnerability to delirium, pre-existing neurological disease, and type of surgical procedure must inform the integration of neurophysiological monitoring into anesthetic practice.

In addition to direct clinical applications, the findings of this review resonate with broader neurobiological and translational scientific questions. The observed modulation of oscillatory brain rhythms by anesthetic agents provides a window into the basic mechanisms underlying reversible loss of consciousness and cognitive recovery, offering potential insights into rehabilitation following brain injury, sleep physiology, and psychiatric therapeutics. The connection between intraoperative neurophysiological states and postoperative outcomes also invites further exploration of the bidirectional influences between acute anesthetic exposure and the trajectory of neurocognitive health.

The role of multidisciplinary collaboration and the fostering of educational initiatives in perioperative neurophysiology are also grounded in the findings of this synthesis. Simulation-based curricula, continuing medical education, and the inclusion of neurophysiological topics in board certification processes represent potential avenues for enhancing clinician competency in this evolving field.

Looking ahead, several avenues for future research and quality improvement are evident. The development and validation of context-sensitive EEG monitoring algorithms, tailored to specific patient populations and surgical contexts, represent a high priority for advancing precision anesthesia. The incorporation of multimodal neurophysiological monitoring including evoked potentials, near-infrared spectroscopy, and advanced imaging modalities may further enrich perioperative patient assessment, particularly in high-risk neurosurgical and cardiac procedures. Large-scale, collaborative data sharing initiatives and the establishment of standardized EEG databanks could facilitate the development of robust predictive models linking intraoperative EEG patterns to postoperative outcomes.

Finally, the ethical and practical considerations surrounding the widespread implementation of intraoperative neurophysiological monitoring warrant careful deliberation. Issues related to data privacy, informed consent, equitable access to advanced technologies, and health systems resource allocation must be navigated to ensure that innovations translate into meaningful improvements in patient safety and care quality across diverse clinical settings.

In summary, this systematic review provides an up-to-date and nuanced assessment of the current evidence base regarding EEG and neurophysiological monitoring during anesthesia. The rigorous selection process employing a transparent PRISMA-based methodology has yielded a synthesized narrative of nine representative studies reflecting a spectrum of clinical, methodological, and scientific perspectives. The evidence collectively supports the clinical value of intraoperative EEG in guiding anesthetic management, monitoring brain health, and optimizing postoperative outcomes, while acknowledging persistent gaps and opportunities for future research.

Conclusion

In summary, this systematic review highlights the diversity of research on EEG and neurophysiological monitoring during anesthesia. Out of 1,258 identified records, nine studies met all eligibility criteria, encompassing observational, interventional, and mixed-methods designs. The findings underscore the clinical relevance of intraoperative EEG monitoring in guiding anesthetic management and improving postoperative outcomes, while emphasizing the need for further high-quality studies to address existing methodological variability and knowledge gaps.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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