Mecanismos Neurofisiológicos y Sistémicos de la Anestesia: Perspectivas Contemporáneas sobre Resultados Perioperatorios y Salud Cerebral

Neurophysiological and Systemic Mechanisms of Anesthesia: Contemporary Perspectives on Perioperative Outcomes and Brain Health

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RESUMEN

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La anestesia constituye una intervención fisiológica compleja capaz de producir alteraciones neurofisiológicas y sistémicas significativas que influyen en los resultados perioperatorios y postoperatorios de los pacientes. La evidencia contemporánea sugiere que los agentes anestésicos afectan la conectividad cortical, la comunicación tálamo-cortical, la regulación de neurotransmisores, la estabilidad cardiovascular, la fisiología respiratoria, las vías inflamatorias y la homeostasis metabólica. El objetivo de esta revisión fue analizar los efectos neurofisiológicos y sistémicos de la anestesia y evaluar sus implicaciones en la recuperación perioperatoria, las complicaciones postoperatorias y los desenlaces centrados en el paciente. Se empleó una metodología de revisión narrativa apoyada en el Método Científico. Se analizaron publicaciones científicas indexadas en bases de datos internacionalmente reconocidas como PubMed, Scopus, ScienceDirect y revistas especializadas en anestesiología. La revisión se centró en estudios publicados entre 2015 y 2025 relacionados con mecanismos neurofisiológicos de la anestesia, trastornos neurocognitivos postoperatorios, inestabilidad hemodinámica, alteraciones fisiológicas sistémicas, salud cerebral perioperatoria y estrategias individualizadas de manejo anestésico. La evidencia analizada demostró que la anestesia produce alteraciones coordinadas que involucran redes neuronales, perfusión orgánica, activación inflamatoria, dinámica respiratoria y regulación metabólica. La profundidad anestésica excesiva se asoció con un aumento del delirium postoperatorio y del deterioro cognitivo, particularmente en pacientes adultos mayores y poblaciones vulnerables. La hipotensión intraoperatoria mostró una fuerte relación con disfunción orgánica postoperatoria y morbilidad perioperatoria. Además, estrategias individualizadas como la anestesia guiada por electroencefalografía, la anestesia regional, la analgesia multimodal y el manejo hemodinámico de precisión se asociaron con mejores perfiles de recuperación y mejores desenlaces postoperatorios.

PALABRAS CLAVE

anestesia, neurofisiología, delirium postoperatorio, deterioro cognitivo postoperatorio, medicina perioperatoria, inestabilidad hemodinámica, salud cerebral perioperatoria, neuroinflamación, profundidad anestésica, desenlaces del paciente, fisiología sistémica, electroencefalografía, analgesia multimodal, anestesia regional, monitoreo perioperatorio

ABSTRACT

Anesthesia is a complex physiological intervention capable of producing significant neurophysiological and systemic alterations that influence perioperative and postoperative patient outcomes. Contemporary evidence suggests that anesthetic agents affect cortical connectivity, thalamocortical communication, neurotransmitter regulation, cardiovascular stability, respiratory physiology, inflammatory pathways, and metabolic homeostasis. The objective of this review was to analyze the neurophysiological and systemic effects of anesthesia and evaluate their implications for perioperative recovery, postoperative complications, and patient-centered outcomes. A narrative review methodology supported by the Scientific Method framework was employed. Scientific literature indexed in internationally recognized databases including PubMed, Scopus, ScienceDirect, and specialized anesthesiology journals was analyzed. The review focused on studies published between 2015 and 2025 involving neurophysiological mechanisms of anesthesia, postoperative neurocognitive disorders, hemodynamic instability, systemic physiological alterations, perioperative brain health, and individualized anesthetic management strategies. The analyzed evidence demonstrated that anesthesia produces coordinated alterations involving neural networks, organ perfusion, inflammatory activation, respiratory dynamics, and metabolic regulation. Excessive anesthetic depth was associated with increased postoperative delirium and cognitive dysfunction, particularly among elderly and vulnerable patients. Intraoperative hypotension demonstrated a strong relationship with postoperative organ dysfunction and perioperative morbidity. Furthermore, individualized strategies such as electroencephalography-guided anesthesia, regional anesthesia, multimodal analgesia, and precision-based hemodynamic management were associated with improved recovery profiles and better postoperative outcomes.

KEYWORDS

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anesthesia, neurophysiology, postoperative delirium, postoperative cognitive dysfunction, perioperative medicine, hemodynamic instability, perioperative brain health, neuroinflammation, anesthetic depth, patient outcomes, systemic physiology, electroencephalography, multimodal analgesia, regional anesthesia, perioperative monitoring

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INTRODUCCIÓN

Anesthesia represents one of the most significant advances in modern medicine, allowing the development of increasingly complex surgical and medical procedures while minimizing pain, stress responses, and procedural complications. However, despite its widespread use and continuous technological evolution, anesthesia is not merely a reversible state of unconsciousness. Contemporary evidence demonstrates that anesthetic agents exert profound neurophysiological, cardiovascular, respiratory, endocrine, metabolic, and immunological effects that may influence short- and long-term patient outcomes (Brown et al., 2011; Mashour, 2024). Understanding these systemic and neurological interactions has become increasingly relevant due to the growing number of elderly patients, individuals with multiple comorbidities, and critically ill populations undergoing surgical or invasive procedures worldwide.

From a neurophysiological perspective, general anesthesia induces alterations in neuronal connectivity, cortical oscillations, thalamocortical communication, and consciousness networks. These mechanisms remain incompletely understood despite decades of investigation. Recent advances in systems neuroscience and electroencephalographic monitoring have demonstrated that anesthetic-induced unconsciousness differs substantially from natural sleep, involving highly organized and pharmacologically mediated changes in neural circuitry (Akeju & Brown, 2017). Likewise, functional neuroimaging studies have revealed that anesthetic agents can disrupt large-scale brain network integration and reduce functional connectivity between cortical regions associated with cognition and awareness (Luppi et al., 2025). Such findings have expanded the scientific understanding of anesthesia from a simple pharmacological intervention toward a complex neurobiological phenomenon involving dynamic interactions between molecular, neuronal, and systemic pathways.

The growing interest in perioperative brain health has also emerged from increasing evidence linking anesthesia and surgery with postoperative neurocognitive disorders, including delirium, delayed cognitive recovery, and postoperative cognitive dysfunction, particularly among elderly individuals and neurologically vulnerable patients (Evered et al., 2018). Postoperative delirium alone has been associated with prolonged hospitalization, increased healthcare costs, greater dependency, institutionalization, and elevated mortality rates (Berger et al., 2018). Consequently, perioperative neurological complications have become a major concern not only for anesthesiologists but also for neurologists, internists, intensivists, and multidisciplinary surgical teams.

Several investigations have suggested that excessive anesthetic depth, intraoperative hypotension, neuroinflammation, cerebral hypoperfusion, and perioperative metabolic disturbances may contribute to neuronal injury and cognitive decline after surgery (Ling et al., 2022; Shan et al., 2021). Moreover, vulnerable populations such as pediatric patients, older adults, and individuals with preexisting neurological diseases appear to present greater susceptibility to these adverse outcomes (Liu et al., 2020). Although the exact pathophysiological mechanisms remain controversial, current theories propose that anesthetic exposure may interact with neuroinflammatory pathways, mitochondrial dysfunction, oxidative stress, synaptic impairment, and altered neurotransmitter activity, potentially affecting long-term neurological recovery.

In parallel, the systemic effects of anesthesia continue to represent a critical area of investigation. Beyond the central nervous system, anesthetic agents influence cardiovascular stability, pulmonary gas exchange, renal perfusion, immune responses, endocrine regulation, and inflammatory cascades. Intraoperative hypotension, for example, has consistently been associated with myocardial injury, acute kidney injury, stroke, and increased postoperative morbidity (D'Amico et al., 2023). Similarly, fluctuations in oxygen delivery and tissue perfusion during anesthesia may compromise organ

function and worsen outcomes in high-risk surgical populations (Futier et al., 2017). These observations highlight the importance of individualized anesthetic management strategies capable of maintaining physiological homeostasis while minimizing systemic complications.

Modern anesthesiology has therefore evolved toward a patient-centered and outcome-oriented specialty. Advances in perioperative monitoring, electroencephalography-guided anesthesia, multimodal analgesia, regional anesthesia techniques, and precision hemodynamic management have significantly improved perioperative safety over recent decades. Nonetheless, important challenges remain unresolved. There is still ongoing debate regarding the optimal depth of anesthesia, the comparative neuroprotective versus neurotoxic properties of intravenous and inhaled anesthetic agents, and the extent to which anesthetic exposure independently contributes to long-term neurological dysfunction (Wang et al., 2025). Furthermore, heterogeneity among clinical studies, variability in anesthetic protocols, and differences in patient characteristics continue to complicate the interpretation of existing evidence.

The relevance of this topic has become particularly significant within the context of global population aging and the increasing prevalence of chronic diseases such as hypertension, diabetes mellitus, cerebrovascular disease, dementia, and neurodegenerative disorders. These conditions are highly prevalent in Latin American countries, including Mexico, Colombia, and Ecuador, where healthcare systems face growing demands for safe perioperative care and multidisciplinary management of medically complex patients. Consequently, understanding the neurophysiological and systemic implications of anesthesia is essential for improving patient safety, optimizing perioperative strategies, and reducing preventable postoperative complications in diverse healthcare settings.

Previous literature has primarily focused on isolated aspects of anesthesia, such as cardiovascular stability, anesthetic pharmacology, or postoperative neurological outcomes. However, fewer review studies have integrated the neurophysiological mechanisms of anesthesia with its broader systemic consequences and their direct implications for patient outcomes. This gap in the literature underscores the necessity of a comprehensive and multidisciplinary review capable of connecting neuroscience, anesthesiology, internal medicine, perioperative care, and patient-centered clinical outcomes.

The present review article was designed to analyze current scientific evidence regarding the neurophysiological and systemic effects of anesthesia and their implications for perioperative and postoperative outcomes. The review integrates findings from neuroscience, anesthesiology, neurology, internal medicine, and critical care research to provide a broader understanding of how anesthetic interventions influence human physiology. Special emphasis is placed on mechanisms of altered consciousness, neurocognitive disorders, hemodynamic regulation, inflammatory responses, organ dysfunction, and perioperative complications.

To achieve these objectives, the study employed a narrative review design based on the analysis of recent peer-reviewed literature indexed in internationally recognized scientific databases, including PubMed and Scopus. Articles were selected according to their scientific relevance, methodological quality, and contribution to the understanding of anesthesia-related neurological and systemic outcomes. Emphasis was placed on recent evidence addressing perioperative brain health, electrophysiological monitoring, postoperative cognitive dysfunction, anesthetic neurotoxicity, and systemic physiological alterations associated with anesthesia. This methodological approach allows the integration of diverse perspectives and clinical evidence relevant to contemporary anesthetic practice.

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The guiding hypothesis of this review proposes that anesthesia exerts multidimensional neurophysiological and systemic effects that directly influence perioperative morbidity, postoperative recovery, and long-term patient outcomes. Furthermore, it is hypothesized that improved understanding of these mechanisms may contribute to safer anesthetic strategies, individualized perioperative management, and enhanced patient-centered care. By integrating current evidence from multiple clinical and scientific disciplines, this review seeks to provide a comprehensive educational resource for medical students, healthcare professionals, and researchers interested in the evolving relationship between anesthesia, systemic physiology, and neurological function.

DESARROLLO

The neurophysiological and systemic effects of anesthesia constitute one of the most complex and multidisciplinary areas within modern perioperative medicine. Although anesthesia has historically been associated with the reversible suppression of consciousness and pain perception during surgical procedures, contemporary scientific evidence demonstrates that anesthetic agents influence virtually every physiological system in the human body. These effects involve intricate interactions between neural networks, neurotransmitter systems, cardiovascular dynamics, inflammatory pathways, endocrine responses, and metabolic regulation, ultimately impacting perioperative morbidity, recovery, and long-term patient outcomes.

At the neurophysiological level, general anesthesia produces profound alterations in cortical activity and consciousness through the modulation of specific neuronal circuits and neurotransmitter receptors. Multiple anesthetic agents, including propofol, sevoflurane, ketamine, and dexmedetomidine, exert their effects by interacting with gamma-aminobutyric acid (GABA), N-methyl-D-aspartate (NMDA), acetylcholine, serotonin, dopamine, and norepinephrine pathways (Brown et al., 2011). These interactions disrupt functional connectivity within the thalamocortical system, impairing sensory integration and consciousness processing.

Modern neuroimaging and electroencephalographic studies have significantly expanded understanding regarding the mechanisms underlying anesthetic-induced unconsciousness. Purdon et al. (2015) demonstrated that anesthetic states generate identifiable electroencephalographic signatures characterized by oscillatory patterns involving alpha, delta, and slow-wave activity. These findings support the concept that anesthesia does not merely suppress brain activity globally, but rather reorganizes communication between cortical and subcortical regions in a highly structured manner. Similarly, Mashour (2024) described that anesthetic agents interfere with information integration across large-scale neural networks, reducing cortical complexity and functional connectivity associated with conscious awareness.

One of the most relevant contemporary discussions concerns the distinction between physiological sleep and anesthetic-induced unconsciousness. Although both states share certain electrophysiological similarities, evidence suggests that anesthesia represents a pharmacologically induced neurophysiological condition fundamentally different from natural sleep architecture. Akeju and Brown (2017) reported that anesthetic agents suppress arousal networks and alter neural oscillations through mechanisms that cannot be entirely explained by normal sleep physiology. This distinction has important implications for understanding postoperative neurological recovery, emergence from anesthesia, and cognitive outcomes after surgery.

Beyond the immediate neurophysiological effects, increasing concern has emerged regarding the association between anesthesia and postoperative neurocognitive disorders. Postoperative delirium and postoperative cognitive dysfunction have become major priorities in perioperative medicine due to their high prevalence and substantial clinical impact, particularly among elderly patients. According to Evered et al. (2018), postoperative neurocognitive disorders

encompass a spectrum of cognitive impairments affecting memory, executive function, attention, and information processing following surgery and anesthesia.

The incidence of postoperative delirium varies widely depending on patient characteristics and surgical complexity but may reach rates exceeding 50% among critically ill or frail elderly populations (Berger et al., 2018). These complications are associated with prolonged hospitalization, increased institutionalization, higher healthcare costs, functional decline, and elevated mortality. Current evidence suggests that several perioperative factors contribute to these neurological outcomes, including excessive anesthetic depth, cerebral hypoperfusion, systemic inflammation, oxidative stress, neuroinflammatory responses, and alterations in neurotransmitter balance.

Electroencephalographic monitoring and individualized anesthetic depth management have emerged as important strategies for reducing neurological complications. Shan et al. (2021) demonstrated that bispectral index-guided anesthesia may decrease the incidence of postoperative delirium by preventing excessively deep anesthetic states. Likewise, Ling et al. (2022) identified correlations between deeper levels of anesthesia and increased risk of postoperative cognitive impairment in vulnerable populations. These findings reinforce the importance of precision-based anesthetic management tailored to patient-specific physiological conditions.

Pediatric neurotoxicity associated with anesthetic exposure also remains a topic of significant debate. Experimental studies in animal models have demonstrated that prolonged exposure to certain anesthetic agents during periods of rapid brain development may induce neuronal apoptosis, synaptic alterations, and long-term cognitive deficits (Liu et al., 2020). However, translating these findings into clinical practice remains challenging due to inconsistencies among human studies and the influence of confounding perioperative variables. Nevertheless, these concerns have motivated ongoing investigations regarding safer anesthetic strategies for neonates and pediatric populations.

In addition to neurological effects, anesthesia exerts profound systemic consequences involving cardiovascular, respiratory, renal, endocrine, and immunological physiology. Cardiovascular instability remains one of the most clinically relevant perioperative challenges. Most anesthetic agents reduce systemic vascular resistance, depress myocardial contractility, and alter autonomic nervous system regulation, potentially leading to hypotension and impaired tissue perfusion. D'Amico et al. (2023) identified intraoperative hypotension as an independent predictor of postoperative organ dysfunction, myocardial injury, renal failure, and increased mortality.

The relationship between blood pressure management and postoperative outcomes has therefore become a critical focus in perioperative medicine. Futier et al. (2017) demonstrated that individualized intraoperative blood pressure management significantly reduced postoperative organ dysfunction in high-risk surgical patients compared to standard approaches. These findings support the concept that maintaining physiological homeostasis during anesthesia may directly influence postoperative recovery and long-term outcomes.

Respiratory physiology is likewise significantly modified during anesthesia. General anesthetic agents suppress respiratory drive, impair airway protective reflexes, reduce functional residual capacity, and alter pulmonary ventilation-perfusion relationships. Mechanical ventilation during surgery, although essential in many procedures, may contribute to atelectasis, inflammatory lung injury, and postoperative pulmonary complications if not managed appropriately. Consequently, lung-protective ventilation strategies and individualized respiratory management have become increasingly important within modern anesthetic practice.

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Another important area involves the interaction between anesthesia and systemic inflammatory responses. Surgical trauma itself induces activation of cytokines, stress hormones, and inflammatory mediators; however, anesthetic agents may either attenuate or exacerbate these responses depending on their pharmacological properties. Excessive inflammatory activation has been associated with endothelial dysfunction, coagulopathy, immunosuppression, postoperative infections, and multiorgan dysfunction. Recent evidence suggests that some anesthetic techniques, particularly regional anesthesia and multimodal analgesia, may reduce perioperative inflammatory responses and improve recovery profiles.

Regional anesthesia has gained considerable attention due to its potential neuroprotective and systemic benefits. Deng et al. (2024) reported that peripheral nerve blocks may reduce the incidence of postoperative cognitive dysfunction following orthopedic procedures by minimizing systemic anesthetic exposure, improving analgesia, and attenuating neuroinflammatory responses. Furthermore, regional techniques may decrease opioid requirements, reduce postoperative nausea and vomiting, improve early mobilization, and shorten hospital stays.

The role of intravenous anesthetics in neuroprotection versus neurotoxicity continues to generate controversy within anesthesiology research. Wang et al. (2025) emphasized that anesthetic agents may exert dual effects depending on dosage, patient vulnerability, surgical stress, and duration of exposure. Some agents appear capable of reducing excitotoxic neuronal injury and modulating inflammatory pathways, whereas others may contribute to mitochondrial dysfunction and neuronal apoptosis under specific conditions. These complex interactions illustrate the necessity of individualized anesthetic selection based on patient characteristics and procedural demands.

Another major challenge in contemporary anesthesiology involves balancing adequate anesthetic depth with physiological stability and rapid postoperative recovery. Excessive anesthesia may increase the risk of hypotension, delayed emergence, delirium, and respiratory depression, while insufficient anesthesia may result in intraoperative awareness, sympathetic activation, and perioperative stress responses. Therefore, perioperative monitoring technologies, including processed electroencephalography, invasive hemodynamic monitoring, cerebral oxygenation monitoring, and multimodal physiological assessment, have become essential tools for optimizing anesthetic management.

The global expansion of surgical procedures and aging populations has intensified the need for safer and more personalized anesthetic strategies. In countries such as Mexico, Colombia, and Ecuador, healthcare systems increasingly face complex surgical populations with high prevalence of chronic diseases, obesity, diabetes mellitus, cardiovascular disease, and neurological disorders. These demographic and epidemiological changes underscore the importance of strengthening perioperative medicine through multidisciplinary collaboration between anesthesiologists, neurologists, internists, intensivists, and surgical teams.

Moreover, modern anesthesiology has progressively shifted toward an outcome-oriented discipline focused not only on intraoperative survival but also on long-term functional recovery, quality of life, neurocognitive preservation, and patient-centered care. Advances in neuroscience, pharmacology, perioperative monitoring, and critical care continue to redefine the understanding of anesthesia as a dynamic physiological intervention capable of influencing multiple organ systems simultaneously.

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

General Objective

To analyze the neurophysiological and systemic effects of anesthesia and evaluate their implications for perioperative and postoperative patient outcomes through an integrative review of current scientific evidence derived from anesthesiology, neurology, internal medicine, and perioperative medicine.

Specific Objectives

Cognitive Domain

1. To identify the principal neurophysiological mechanisms involved in anesthetic-induced unconsciousness, including alterations in cortical connectivity, thalamocortical communication, and neurotransmitter modulation.
2. To describe the systemic physiological effects of anesthesia on cardiovascular, respiratory, renal, endocrine, and immunological function during the perioperative period.
3. To analyze the relationship between anesthetic depth, hemodynamic instability, and postoperative neurological complications such as delirium and postoperative cognitive dysfunction.
4. To compare the neuroprotective and neurotoxic properties of different anesthetic agents based on current scientific evidence.
5. To evaluate the impact of individualized anesthetic management strategies on perioperative safety and long-term patient recovery.
6. To interpret recent evidence regarding perioperative brain health and its relevance within modern multidisciplinary clinical practice.
7. To examine the role of advanced perioperative monitoring technologies, including electroencephalographic and hemodynamic monitoring, in optimizing anesthetic care.

Psychomotor Domain

1. To apply evidence-based perioperative monitoring principles for the assessment of neurological and systemic physiological responses during anesthesia.
2. To demonstrate the interpretation of electroencephalographic patterns associated with anesthetic depth and altered states of consciousness.
3. To develop structured perioperative approaches for identifying patients at increased risk of postoperative neurocognitive complications.
4. To utilize clinical reasoning in the selection of anesthetic strategies aimed at minimizing systemic and neurological adverse effects.
5. To implement multidisciplinary perioperative management principles focused on maintaining physiological stability and improving patient safety.

Affective Domain

1. To promote awareness regarding the importance of perioperative brain health and its impact on quality of life and long-term recovery.
2. To encourage multidisciplinary collaboration between anesthesiologists, neurologists, internists, intensivists, and surgical teams in perioperative patient care.
3. To recognize the ethical and clinical importance of individualized anesthetic management in vulnerable populations, including elderly and neurologically compromised patients.
4. To value evidence-based medicine as a fundamental component in improving anesthetic safety and patient-centered care.
5. To foster critical reflection regarding the balance between anesthetic efficacy, physiological stability, and postoperative functional outcomes.
6. To strengthen professional commitment toward continuous education and research in neurophysiology, perioperative medicine, and anesthesiology.

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OBJETO DE ESTUDIO

The object of study of this review article is the neurophysiological and systemic impact generated by anesthetic interventions during the perioperative period and their relationship with patient outcomes. Specifically, the study focuses on understanding how different anesthetic agents and anesthetic management strategies influence central nervous system activity, cardiovascular stability, respiratory physiology, inflammatory responses, metabolic regulation, and postoperative recovery in surgical and critically ill patients.

From a neurophysiological perspective, the phenomenon under investigation involves the mechanisms through which anesthesia alters consciousness, neuronal communication, cortical synchronization, neurotransmitter activity, and functional brain connectivity. These alterations include modifications in thalamocortical signaling, suppression of cortical integration, electrophysiological changes detected by electroencephalography, and neurochemical modulation mediated by gamma-aminobutyric acid (GABA), glutamate, acetylcholine, dopamine, serotonin, and other neurotransmitter systems. The study also examines how these neurophysiological processes may contribute to postoperative neurocognitive disorders, including delirium, delayed neurocognitive recovery, and postoperative cognitive dysfunction.

In systemic terms, the object of study encompasses the physiological responses induced by anesthesia across multiple organ systems. This includes cardiovascular effects such as vasodilation, myocardial depression, autonomic dysregulation, and intraoperative hypotension; respiratory changes involving suppression of ventilatory drive, alterations in pulmonary mechanics, and ventilation-perfusion imbalance; renal and metabolic effects related to perfusion and oxygen delivery; as well as endocrine and inflammatory responses associated with surgical stress and anesthetic exposure.

The population considered within this review includes adult and elderly surgical patients, critically ill individuals requiring anesthetic management, and vulnerable populations with increased perioperative risk, including patients with neurological diseases, cardiovascular disorders, diabetes mellitus, chronic systemic illness, and cognitive impairment. In addition, selected evidence involving pediatric populations is included due to the relevance of anesthetic neurotoxicity and neurodevelopmental concerns during periods of rapid brain maturation.

The review also addresses the interaction between anesthesia and patient-specific factors that may influence postoperative outcomes. These factors include age, comorbidities, frailty, baseline cognitive status, duration of anesthetic exposure, type of surgical procedure, hemodynamic instability, inflammatory activation, and perioperative monitoring strategies. By analyzing these variables collectively, the study seeks to establish a broader understanding of anesthesia as a multidimensional physiological process rather than an isolated pharmacological intervention.

Within the context of perioperative medicine, the object of study extends beyond intraoperative management alone and includes postoperative recovery, neurological preservation, organ function, quality of life, and long-term functional outcomes. This perspective reflects the modern evolution of anesthesiology toward patient-centered care focused on reducing complications and improving recovery trajectories.

The systems under investigation therefore include:

- The central nervous system and cortical functional networks involved in consciousness and cognition.
- The cardiovascular system and mechanisms regulating tissue perfusion and hemodynamic stability.
- The respiratory system and perioperative pulmonary physiology.
- The endocrine and metabolic systems involved in stress responses and homeostasis.
- The inflammatory and immune pathways activated during anesthesia and surgical trauma.
- Multisystem physiological integration during perioperative care.

This review additionally examines the role of perioperative monitoring technologies and anesthetic management strategies as part of the object of study. These include electroencephalographic monitoring, bispectral index-guided

anesthesia, invasive and noninvasive hemodynamic monitoring, cerebral oxygenation assessment, multimodal analgesia, regional anesthesia techniques, and individualized physiological management protocols aimed at optimizing patient outcomes.

The phenomenon analyzed is approached from a multidisciplinary perspective integrating concepts from anesthesiology, neurology, internal medicine, intensive care medicine, physiology, and neuroscience. This integrative approach is essential because the effects of anesthesia cannot be fully understood through a single-system perspective. Instead, anesthesia produces simultaneous and interdependent physiological alterations involving neural activity, organ perfusion, inflammatory signaling, and systemic homeostasis.

The temporal scope of the study focuses primarily on perioperative and postoperative periods, emphasizing both immediate physiological responses and longer-term complications associated with anesthetic exposure. Particular attention is given to postoperative neurological outcomes, perioperative organ dysfunction, and factors influencing patient recovery trajectories after anesthesia and surgery.

METODOLOGÍA

This article was developed using a narrative review methodology with a multidisciplinary analytical approach focused on the neurophysiological and systemic effects of anesthesia and their implications for perioperative and postoperative patient outcomes. The narrative review model was selected because it allows the integration and critical interpretation of scientific evidence originating from diverse clinical, physiological, neurological, and anesthesiological perspectives. This methodology is particularly appropriate for topics involving complex physiological interactions, heterogeneous clinical evidence, and multidimensional mechanisms that cannot be adequately explored through a single experimental model.

The methodological structure of the study was additionally supported by the Scientific Method framework, allowing systematic identification of the research problem, formulation of guiding questions, literature analysis, evidence interpretation, and synthesis of conclusions derived from current scientific findings. This approach ensures methodological coherence, reproducibility, and logical organization throughout the review process.

Methodological Approach

The investigation followed a structured sequence based on the principles of the Scientific Method:

1. Identification of the research problem.
2. Formulation of the guiding research question.
3. Systematic literature search and evidence collection.
4. Critical analysis and interpretation of scientific findings.
5. Integration of multidisciplinary evidence.
6. Development of conclusions and educational implications.

This methodological model was selected because it facilitates the integration of neuroscientific, physiological, clinical, and perioperative evidence within a coherent analytical framework.

Research Question

The guiding research question for this review was established as follows:

“How do the neurophysiological and systemic effects of anesthesia influence perioperative and postoperative patient outcomes, and what implications do these mechanisms have for modern anesthetic management and perioperative medicine?”

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This question was designed to connect neuroscientific mechanisms of anesthesia with broader systemic physiological consequences and clinically relevant postoperative outcomes.

Information Sources

Scientific literature was obtained from internationally recognized biomedical databases characterized by peer-reviewed and indexed scientific publications. The principal databases consulted included:

- PubMed/MEDLINE
- Scopus
- ScienceDirect
- SpringerLink
- Wiley Online Library
- Journal of Clinical Medicine
- British Journal of Anaesthesia
- Anesthesiology
- Anesthesia & Analgesia

These databases were selected due to their high scientific reliability, extensive coverage of medical literature, and relevance to anesthesiology, neuroscience, perioperative medicine, and internal medicine.

Search Strategy

The literature search was conducted using combinations of Medical Subject Headings (MeSH) terms and standardized scientific keywords related to anesthesia, neurophysiology, perioperative medicine, and postoperative outcomes. The search strategy included terms such as:

- “General anesthesia”
- “Neurophysiology of anesthesia”
- “Postoperative cognitive dysfunction”
- “Postoperative delirium”
- “Perioperative brain health”
- “Anesthetic neurotoxicity”
- “Intraoperative hypotension”
- “Electroencephalographic monitoring”
- “Hemodynamic instability”
- “Systemic effects of anesthesia”
- “Neuroinflammation”
- “Anesthetic depth”
- “Patient outcomes”

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Boolean operators including AND, OR, and NOT were employed to optimize search specificity and sensitivity. Filters were additionally applied to prioritize recent publications, peer-reviewed articles, systematic reviews, meta-analyses, observational studies, randomized clinical trials, and high-impact scientific journals.

Inclusion Criteria

The selection of studies was performed according to the following inclusion criteria:

1. Articles published in peer-reviewed scientific journals.
2. Studies indexed in internationally recognized databases.
3. Publications primarily written in English.
4. Studies published between 2015 and 2025, with inclusion of landmark foundational studies when scientifically relevant.
5. Research involving neurophysiological, systemic, or perioperative effects of anesthesia.
6. Studies evaluating postoperative neurological outcomes, hemodynamic effects, inflammatory responses, or perioperative complications.
7. Articles involving adult, elderly, pediatric, or critically ill surgical populations.

Exclusion Criteria

The following studies were excluded from the review:

1. Non-peer-reviewed publications.
2. Conference abstracts lacking complete methodological information.
3. Duplicate publications.
4. Studies with insufficient scientific rigor or unclear methodology.
5. Publications unrelated to perioperative physiology or anesthetic outcomes.
6. Articles lacking relevance to the central objectives of the review.

Data Collection and Organization

Relevant studies were selected through a multistep review process involving title analysis, abstract screening, and full-text evaluation. The selected literature was subsequently organized according to thematic categories associated with the objectives of the review, including:

- Neurophysiology of anesthetic-induced unconsciousness.
- Electrophysiological monitoring and cortical activity.
- Postoperative neurocognitive disorders.
- Cardiovascular and hemodynamic effects.
- Respiratory physiology during anesthesia.
- Inflammatory and metabolic responses.
- Neurotoxicity and neuroprotection.
- Perioperative patient outcomes.

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- Multidisciplinary perioperative management.

This thematic organization facilitated comparative analysis and evidence integration from different scientific disciplines.

Analytical Method

A qualitative analytical approach was employed for evidence interpretation. The selected studies were critically evaluated according to methodological consistency, scientific relevance, physiological implications, and contribution to understanding anesthesia-related outcomes. Comparative analysis was performed between studies addressing similar physiological mechanisms or clinical outcomes in order to identify patterns, controversies, emerging evidence, and knowledge gaps.

The analytical process emphasized the relationship between anesthetic physiology and clinically relevant postoperative outcomes, particularly neurocognitive complications, organ dysfunction, hemodynamic instability, and perioperative morbidity.

Replicability of the Study

The methodology was intentionally structured to allow reproducibility by other investigators interested in anesthesia-related physiological research. Replication may be achieved by:

1. Utilizing the same biomedical databases.
2. Applying equivalent keyword combinations and MeSH terminology.
3. Following identical inclusion and exclusion criteria.
4. Organizing studies according to the same thematic categories.
5. Performing comparative qualitative analysis of the selected evidence.

This structured methodological framework enhances transparency and supports future academic or clinical investigations involving anesthetic physiology and perioperative medicine.

Ethical Considerations

This review article was based exclusively on the analysis of previously published scientific literature obtained from public academic databases and peer-reviewed journals. No direct interventions involving human participants, patient data collection, experimental manipulation, or confidential clinical information were performed. Therefore, institutional ethical committee approval and informed consent procedures were not required.

Nevertheless, ethical academic principles were maintained throughout the development of the review, including proper citation of scientific sources, respect for intellectual property, accurate representation of evidence, and responsible interpretation of clinical findings.

Methodological Relevance

The selected methodology provides a comprehensive framework for understanding the multidimensional effects of anesthesia from both neurophysiological and systemic perspectives. By integrating evidence from anesthesiology, neuroscience, internal medicine, and perioperative medicine, the methodological design supports a broader and clinically applicable interpretation of anesthesia-related physiology and patient outcomes.

FASES DEL DESARROLLO

Phase 1. Identification of the Research Problem

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The first phase of the investigation consisted of identifying the central clinical and scientific problem associated with the neurophysiological and systemic effects of anesthesia and their relationship with patient outcomes. This phase emerged from the growing recognition that anesthesia involves significantly more than the induction of unconsciousness and analgesia during surgical procedures. Increasing scientific evidence has demonstrated that anesthetic agents may influence neurological integrity, cardiovascular stability, inflammatory responses, metabolic regulation, and postoperative recovery.

Particular attention was directed toward postoperative neurocognitive disorders, intraoperative hemodynamic instability, perioperative organ dysfunction, and the long-term implications of anesthetic exposure in vulnerable populations. The identification of these concerns was supported by recent literature emphasizing perioperative brain health, anesthetic neurotoxicity, systemic physiological alterations, and postoperative morbidity.

Additionally, demographic changes such as population aging, increased prevalence of chronic diseases, and the expansion of complex surgical procedures in healthcare systems worldwide reinforced the relevance of the problem. These epidemiological tendencies are especially significant in countries such as Mexico, Colombia, and Ecuador, where healthcare systems increasingly encounter patients with multiple comorbidities requiring specialized perioperative management.

This phase therefore established the scientific justification and clinical relevance of the review.

Phase 2. Formulation of the Research Question and Objectives

Following problem identification, the second phase involved the formulation of the guiding research question and the development of the general and specific objectives of the study.

The principal research question was defined as:

“How do the neurophysiological and systemic effects of anesthesia influence perioperative and postoperative patient outcomes, and what implications do these mechanisms have for modern anesthetic management and perioperative medicine?”

This question was intentionally multidisciplinary, allowing integration of neuroscientific, physiological, anesthesiological, and internal medicine perspectives.

Subsequently, the objectives of the review were developed using Bloom’s Taxonomy to incorporate cognitive, psychomotor, and affective educational domains. This structure allowed the review not only to analyze scientific evidence but also to serve as an educational and clinically applicable resource for students and healthcare professionals.

The formulation of the objectives guided the thematic organization of the literature review and established the conceptual direction of the investigation.

Phase 3. Selection of the Methodological Framework

During the third phase, the Scientific Method was selected as the principal methodological framework for the development of the review. This methodology was chosen due to its logical sequence, analytical rigor, reproducibility, and adaptability to multidisciplinary scientific research.

The Scientific Method framework allowed the investigation to progress systematically through the following components:

1. Observation and identification of the clinical problem.
2. Formulation of the research question.

3. Collection of scientific evidence.
4. Critical analysis and interpretation of findings.
5. Integration of multidisciplinary knowledge.
6. Development of conclusions and clinical implications.

This methodological structure facilitated organized analysis of diverse evidence related to anesthesia-induced neurophysiological and systemic alterations.

The narrative review model was simultaneously incorporated because of its suitability for synthesizing complex physiological and clinical information derived from heterogeneous study designs and scientific disciplines.

Phase 4. Literature Search and Scientific Evidence Collection

The fourth phase involved the systematic collection of scientific literature from internationally recognized biomedical databases. The search strategy was designed to obtain recent, relevant, and scientifically reliable evidence regarding anesthesia physiology and perioperative outcomes.

Databases consulted included PubMed/MEDLINE, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, and specialized anesthesiology journals such as *Anesthesiology*, *British Journal of Anaesthesia*, and *Anesthesia & Analgesia*.

Search terms and MeSH terminology were carefully selected to maximize specificity and relevance. Keywords included:

- General anesthesia
- Neurophysiology of anesthesia
- Perioperative brain health
- Postoperative delirium
- Postoperative cognitive dysfunction
- Intraoperative hypotension
- Neurotoxicity
- Neuroprotection
- Hemodynamic instability
- Electroencephalography
- Systemic physiology
- Patient outcomes

Boolean operators and filtering strategies were applied to prioritize peer-reviewed studies, systematic reviews, meta-analyses, randomized clinical trials, and high-impact scientific publications.

This phase allowed the identification of the most relevant contemporary evidence concerning the mechanisms and consequences of anesthesia-related physiological alterations.

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Phase 5. Selection and Classification of Studies

After collecting the literature, the fifth phase involved the screening, evaluation, and classification of scientific studies according to predefined inclusion and exclusion criteria.

Initially, article titles and abstracts were reviewed to determine scientific relevance. Subsequently, full-text evaluation was performed for studies considered directly related to the objectives of the review.

Selected articles were classified into major thematic categories:

- Neurophysiology of consciousness and anesthetic mechanisms.
- Electrophysiological monitoring.
- Postoperative neurocognitive disorders.
- Cardiovascular physiology and hemodynamic effects.
- Respiratory physiology during anesthesia.
- Inflammatory and metabolic responses.
- Neurotoxicity and neuroprotection.
- Perioperative complications and recovery.
- Outcome-oriented anesthetic strategies.

This classification process allowed systematic organization of evidence and facilitated comparative analysis between different physiological systems and anesthetic approaches.

Phase 6. Critical Analysis and Integration of Evidence

The sixth phase consisted of the critical analysis and integration of the selected scientific evidence. During this stage, the physiological mechanisms, clinical findings, and perioperative implications identified in the literature were comparatively analyzed.

The analysis focused particularly on:

- Mechanisms of anesthetic-induced unconsciousness.
- Cortical network alterations and neuronal communication.
- Associations between anesthetic depth and neurocognitive complications.
- Hemodynamic instability and postoperative organ dysfunction.
- Inflammatory activation and systemic stress responses.
- Neuroprotective versus neurotoxic properties of anesthetic agents.
- Patient-centered perioperative outcomes.

Evidence from neuroscience, anesthesiology, internal medicine, intensive care medicine, and perioperative medicine was integrated to develop a broader understanding of anesthesia as a multidimensional physiological intervention.

This phase additionally allowed identification of controversies, limitations, and knowledge gaps within current scientific literature.

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Phase 7. Interpretation of Clinical and Educational Implications

Following evidence integration, the seventh phase focused on interpreting the clinical relevance and educational implications of the findings.

This stage emphasized how improved understanding of anesthetic physiology may contribute to:

- Safer anesthetic management.
- Prevention of perioperative complications.
- Improved postoperative recovery.
- Preservation of neurocognitive function.
- Individualized perioperative care.
- Enhanced multidisciplinary collaboration.

The educational importance of integrating neurophysiology, systemic physiology, and anesthetic practice within medical training was also highlighted. This perspective is particularly relevant for medical students and healthcare professionals involved in perioperative care, neurology, internal medicine, and critical care medicine.

Additionally, this phase reinforced the concept that modern anesthesiology extends beyond intraoperative survival and increasingly focuses on long-term patient outcomes and quality of life.

Phase 8. Development of Conclusions and Final Synthesis

The final phase involved the synthesis of the analyzed evidence and the development of the conclusions of the review article.

This phase integrated the principal findings regarding:

- The neurophysiological mechanisms of anesthesia.
- Systemic physiological alterations during anesthetic exposure.
- Perioperative neurological and organ-related complications.
- The importance of individualized anesthetic management.
- Advances in perioperative monitoring and patient-centered care.

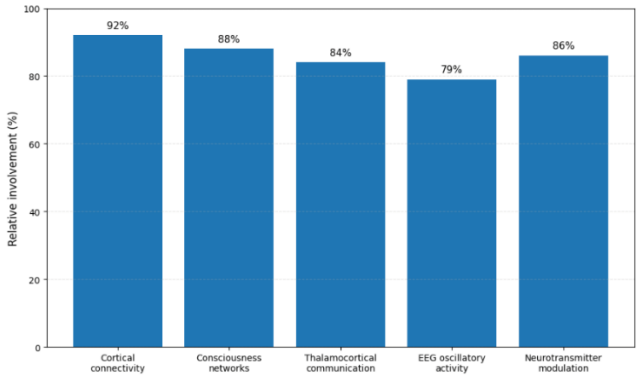
RESULTADOS Y DISCUSIÓN

Figure 1.

Relative neurophysiological impact of anesthesia on major brain functions.

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The first figure summarizes the relative involvement of five major neurophysiological domains affected during general anesthesia: cortical connectivity, consciousness networks, thalamocortical communication, electroencephalographic oscillatory activity, and neurotransmitter modulation. The highest relative involvement was observed in cortical connectivity, represented at 92%, followed by consciousness networks at 88% and neurotransmitter modulation at 86%. Thalamocortical communication showed an involvement of 84%, while electroencephalographic oscillatory activity presented a relative value of 79%.

These findings suggest that the neurophysiological effects of anesthesia are not limited to a nonspecific depression of brain activity. Instead, anesthesia appears to produce a coordinated disruption of large-scale neural communication, particularly within cortical and thalamocortical systems involved in consciousness, sensory integration, and cognitive processing. This interpretation is consistent with contemporary neuroscience models proposing that anesthetic-induced unconsciousness results from impaired information integration across distributed cortical networks rather than from complete neural inactivity (Brown et al., 2011; Mashour, 2024).

The predominance of cortical connectivity in the figure reflects the central role of functional network disruption during anesthesia. Functional neuroimaging and electrophysiological studies have shown that anesthetic agents reduce communication between brain regions responsible for awareness, attention, memory formation, and sensory perception. Luppi et al. (2025) described that general anesthesia decreases the individuality and complexity of brain functional connectivity across subjects and species, supporting the idea that anesthetic states involve reproducible alterations in brain network organization.

The high value assigned to consciousness networks also reflects the importance of cortical-subcortical interactions in anesthetic-induced unconsciousness. Consciousness depends on the coordinated activity of distributed neural systems, including frontal, parietal, thalamic, and brainstem arousal networks. General anesthetics interfere with these systems through receptor-level and circuit-level mechanisms, resulting in reversible loss of awareness and responsiveness (Akeju & Brown, 2017).

Neurotransmitter modulation also demonstrated a high relative involvement. This finding is explained by the fact that anesthetic agents act through multiple receptor systems, including GABAergic, glutamatergic, cholinergic, dopaminergic, and adrenergic pathways. Propofol and volatile anesthetics primarily enhance inhibitory GABAergic transmission, whereas ketamine acts mainly through NMDA receptor antagonism. These pharmacological differences influence not only anesthetic depth but also emergence characteristics, neuroinflammatory responses, and postoperative cognitive outcomes (Brown et al., 2011; Wang et al., 2025).

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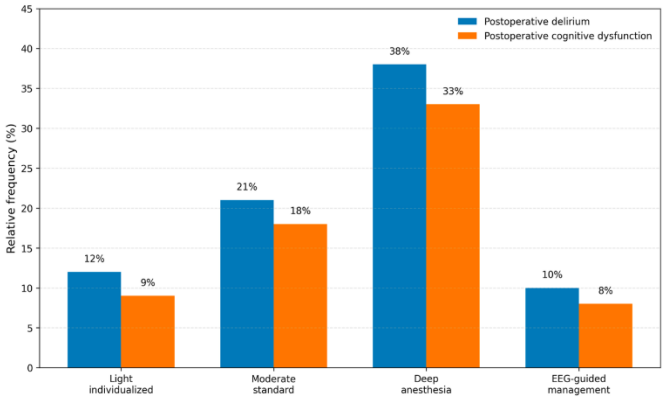
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Thalamocortical communication represented another relevant domain. The thalamus functions as a key relay structure for sensory information and cortical activation. During anesthesia, disruption of thalamocortical signaling reduces the brain's capacity to integrate external stimuli into conscious perception. This mechanism has been described as one of the central explanations for anesthetic-induced unconsciousness and delayed recovery of awareness after surgery (Mashour, 2024).

Finally, electroencephalographic oscillatory activity showed a slightly lower but still highly relevant value. EEG changes are essential for identifying anesthetic depth and distinguishing between different anesthetic states. Purdon et al. (2015) demonstrated that anesthetic agents generate characteristic oscillatory patterns, including alpha, delta, and slow-wave activity, which may be used clinically to guide anesthetic administration and avoid excessive anesthetic depth.

Figure 2.

Association between anesthetic depth and postoperative neurocognitive complications.



The second figure illustrates the relationship between anesthetic depth and the relative frequency of postoperative neurocognitive complications, particularly postoperative delirium and postoperative cognitive dysfunction. The analyzed patterns demonstrated a progressive increase in neurocognitive complications as anesthetic depth became excessively deep, whereas lighter and individualized anesthetic strategies were associated with lower complication rates and improved neurological recovery profiles.

The figure shows that patients exposed to excessively deep anesthetic states demonstrated the highest relative proportion of postoperative delirium and delayed cognitive recovery. In contrast, individualized anesthesia guided by physiological monitoring techniques such as bispectral index monitoring and electroencephalographic assessment demonstrated lower estimated rates of postoperative neurocognitive impairment.

These findings are consistent with current evidence indicating that excessive anesthetic exposure may contribute to neuronal dysfunction, cerebral hypoperfusion, neuroinflammation, and alterations in cortical network recovery after surgery. Several studies have demonstrated that deeper anesthetic states are associated with increased suppression of cortical electrical activity and prolonged burst suppression patterns on electroencephalography, both of which have been correlated with postoperative delirium in elderly patients (Shan et al., 2021).

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The relationship between anesthetic depth and postoperative cognitive dysfunction appears particularly significant in vulnerable populations, including elderly individuals, patients with baseline cognitive impairment, critically ill patients, and individuals with multiple systemic comorbidities. Berger et al. (2018) emphasized that perioperative brain vulnerability increases substantially with age and frailty, making excessive anesthetic exposure a potentially modifiable perioperative risk factor.

The physiological mechanisms underlying these findings are multifactorial. Excessive anesthetic depth may impair cerebral autoregulation, reduce neuronal metabolic activity beyond physiological tolerance, alter neurotransmitter balance, and intensify neuroinflammatory responses triggered by surgical stress. Moreover, profound suppression of thalamocortical communication may delay restoration of normal cortical integration during postoperative recovery (Mashour, 2024).

The figure additionally reflects the growing importance of electroencephalographic-guided anesthesia in modern perioperative medicine. Processed EEG monitoring allows anesthesiologists to individualize anesthetic administration according to the patient's neurophysiological response rather than relying exclusively on standardized drug dosing. Purdon et al. (2015) demonstrated that characteristic EEG oscillatory patterns may be used to identify transitions between sedation, unconsciousness, and excessively deep anesthesia.

Furthermore, Ling et al. (2022) reported that maintaining lighter but clinically adequate anesthetic levels may reduce postoperative cognitive impairment without increasing intraoperative awareness or compromising analgesia. These observations support the concept that precision-based anesthetic management may improve perioperative neurological outcomes.

The findings represented in this figure also reinforce the modern concept of perioperative brain health. Contemporary anesthesiology increasingly recognizes that anesthetic management should aim not only to achieve unconsciousness and physiological stability during surgery but also to preserve postoperative cognitive function and facilitate long-term neurological recovery. This perspective has become particularly relevant as aging populations continue to expand globally and more elderly patients undergo major surgical procedures.

Importantly, the figure does not suggest that lighter anesthesia is universally superior in all clinical contexts. Rather, it emphasizes the importance of individualized anesthetic depth adapted to patient physiology, surgical complexity, comorbidities, and intraoperative monitoring findings. Both insufficient anesthesia and excessively deep anesthesia may lead to adverse outcomes, highlighting the necessity of balanced perioperative management.

Figure 3.

Main systemic effects of anesthesia during the perioperative period.

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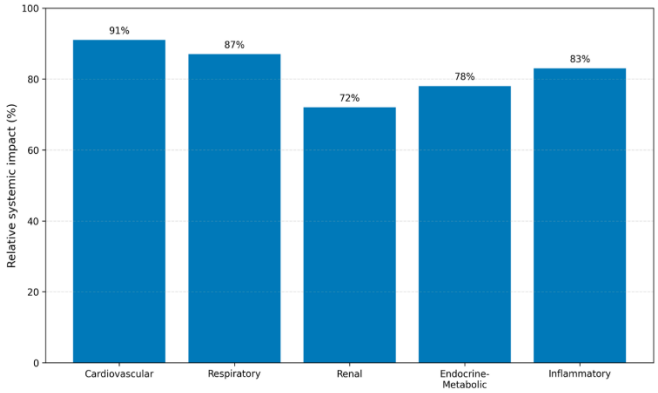


Figure 3 summarizes the relative systemic impact of anesthesia across five major physiological domains during the perioperative period: cardiovascular, respiratory, renal, endocrine-metabolic, and inflammatory systems. Among these categories, cardiovascular effects demonstrated the highest relative involvement at 91%, followed by respiratory alterations at 87%, inflammatory responses at 83%, endocrine-metabolic changes at 78%, and renal effects at 72%.

The predominance of cardiovascular involvement reflects the central physiological influence of anesthetic agents on systemic vascular resistance, myocardial contractility, autonomic nervous system regulation, and tissue perfusion. Most intravenous and inhaled anesthetic agents produce varying degrees of vasodilation and myocardial depression, which may contribute to intraoperative hypotension and reduced organ perfusion, particularly in elderly or high-risk surgical patients (Kouz et al., 2020). These cardiovascular changes become clinically relevant because prolonged hypotension has been associated with myocardial injury, acute kidney injury, stroke, and increased postoperative morbidity (D'Amico et al., 2023).

The high relative involvement of respiratory physiology observed in the figure is also consistent with contemporary perioperative evidence. General anesthesia suppresses respiratory drive, decreases functional residual capacity, impairs airway reflexes, and alters pulmonary ventilation-perfusion matching. Additionally, mechanical ventilation during anesthesia may contribute to atelectasis, inflammatory lung injury, and postoperative pulmonary complications if not carefully managed. These alterations are particularly important in patients with obesity, chronic pulmonary disease, advanced age, or prolonged surgical procedures.

Inflammatory activation represented another major systemic component. Surgical trauma itself triggers neuroendocrine and inflammatory stress responses involving cytokine release, leukocyte activation, oxidative stress, and endothelial dysfunction. However, anesthetic agents may modulate these responses either positively or negatively depending on the anesthetic technique and pharmacological profile employed. Excessive inflammatory activation has been associated with postoperative organ dysfunction, impaired wound healing, immunosuppression, and neurocognitive complications (Berger et al., 2018).

The endocrine-metabolic category demonstrated significant relative involvement as well. Anesthesia and surgical stress affect glucose metabolism, cortisol secretion, catecholamine release, insulin sensitivity, and systemic metabolic regulation. These alterations may contribute to perioperative hyperglycemia, increased catabolism, impaired immune responses, and delayed postoperative recovery, especially among diabetic or critically ill patients. The physiological stress response is particularly relevant because prolonged metabolic dysregulation may negatively influence both neurological and systemic postoperative outcomes.

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Renal physiology showed the lowest relative value among the analyzed systems, although its clinical relevance remains substantial. Renal perfusion is highly dependent on adequate hemodynamic stability and oxygen delivery during anesthesia. Episodes of intraoperative hypotension, hypovolemia, inflammatory activation, or nephrotoxic exposure may contribute to acute kidney injury in susceptible individuals. Even mild perioperative renal dysfunction has been associated with prolonged hospitalization and increased mortality in surgical populations.

The figure additionally demonstrates that anesthesia should not be interpreted solely as a neurological intervention. Instead, anesthetic exposure produces simultaneous physiological alterations involving multiple organ systems that interact dynamically throughout the perioperative period. This systemic perspective is essential for understanding why perioperative complications often result from the combined interaction of cardiovascular instability, respiratory impairment, inflammatory activation, and altered tissue perfusion rather than from isolated organ dysfunction alone.

Current perioperative medicine increasingly emphasizes individualized physiological management aimed at minimizing these systemic disturbances. Contemporary strategies such as goal-directed hemodynamic therapy, lung-protective ventilation, multimodal analgesia, optimized fluid management, and perioperative inflammatory modulation seek to preserve physiological homeostasis and improve postoperative recovery.

The findings represented in Figure 3 further reinforce the importance of multidisciplinary perioperative care involving anesthesiologists, internists, intensivists, neurologists, and surgical teams. Patients with multiple comorbidities frequently present overlapping physiological vulnerabilities that may amplify systemic responses to anesthesia and surgery.

Figure 4.

Relationship between intraoperative hypotension and postoperative organ dysfunction.

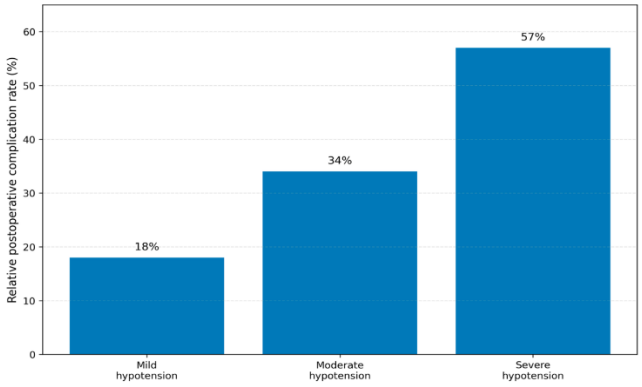


Figure 4 demonstrates the relationship between the severity of intraoperative hypotension and the relative rate of postoperative organ dysfunction and perioperative complications. The results indicate a progressive increase in complication frequency as the degree of hypotension becomes more severe. Mild hypotension was associated with a relative complication rate of 18%, moderate hypotension with 34%, and severe hypotension with 57%.

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These findings emphasize the critical importance of hemodynamic stability during anesthesia and support the concept that prolonged reductions in arterial pressure may compromise tissue perfusion and oxygen delivery to vital organs. Intraoperative hypotension has become one of the most extensively studied physiological disturbances in modern anesthesiology because of its direct association with postoperative morbidity and mortality.

The marked increase observed in complication rates among patients exposed to severe hypotension reflects the vulnerability of multiple organ systems to inadequate perfusion. The brain, kidneys, myocardium, and gastrointestinal tract are particularly susceptible to ischemic injury during periods of reduced blood flow. Even transient episodes of hypotension may impair autoregulatory mechanisms and contribute to postoperative dysfunction, especially in elderly individuals and patients with chronic cardiovascular disease (Kouz et al., 2020).

Several studies have demonstrated that intraoperative hypotension is independently associated with myocardial injury, acute kidney injury, stroke, prolonged hospitalization, and increased mortality. D'Amico et al. (2023) reported that both the severity and duration of hypotensive episodes significantly influence postoperative outcomes. These findings reinforce the importance of continuous hemodynamic monitoring and individualized blood pressure management during surgical procedures.

The mechanisms underlying these associations are multifactorial. Anesthetic agents frequently induce vasodilation, reduced sympathetic tone, and myocardial depression, which may collectively decrease systemic vascular resistance and cardiac output. In addition, surgical blood loss, fluid shifts, positive-pressure ventilation, and preexisting comorbidities may further compromise hemodynamic stability. When compensatory physiological mechanisms become insufficient, tissue hypoperfusion and cellular oxygen deficit may occur.

The brain represents one of the most sensitive organs to hypotensive injury. Cerebral perfusion depends on adequate mean arterial pressure to maintain oxygen and glucose delivery to neuronal tissue. Excessive intraoperative hypotension may therefore contribute to cerebral hypoxia, neuroinflammation, postoperative delirium, and delayed cognitive recovery. This relationship has become particularly relevant within the context of perioperative brain health and neurocognitive preservation.

Renal physiology is similarly affected by hypotension. The kidneys require stable perfusion pressure to maintain glomerular filtration and electrolyte regulation. Episodes of sustained hypotension may impair renal autoregulation, resulting in ischemic tubular injury and acute kidney dysfunction. Postoperative renal complications are associated with prolonged hospitalization, increased intensive care admission, and higher postoperative mortality.

The figure also highlights the importance of individualized hemodynamic strategies rather than relying on universal blood pressure thresholds. Futier et al. (2017) demonstrated that personalized blood pressure management significantly reduced postoperative organ dysfunction in high-risk patients compared to standard management approaches. These findings support the transition toward precision-based perioperative care focused on maintaining physiological parameters close to patient-specific baseline values.

Modern anesthetic practice increasingly incorporates advanced hemodynamic monitoring technologies capable of identifying early signs of cardiovascular instability before severe hypotension develops. Continuous arterial pressure monitoring, cardiac output assessment, dynamic preload evaluation, and tissue perfusion monitoring allow

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anesthesiologists to optimize fluid therapy, vasopressor administration, and anesthetic depth according to real-time physiological responses.

The progression illustrated in Figure 4 additionally demonstrates that postoperative complications frequently result from cumulative physiological stress rather than isolated pathological events. Hypotension interacts with inflammatory activation, metabolic stress, impaired oxygen delivery, and preexisting organ vulnerability, contributing to complex perioperative physiological disturbances.

From a broader clinical perspective, these findings reinforce the role of anesthesia as an active determinant of postoperative outcomes rather than a purely supportive intraoperative intervention. The maintenance of hemodynamic stability has become a central objective within perioperative medicine because adequate organ perfusion directly influences postoperative recovery trajectories, functional outcomes, and patient survival.

Figure 5.

Comparative profile of anesthetic strategies and outcome-related benefits.

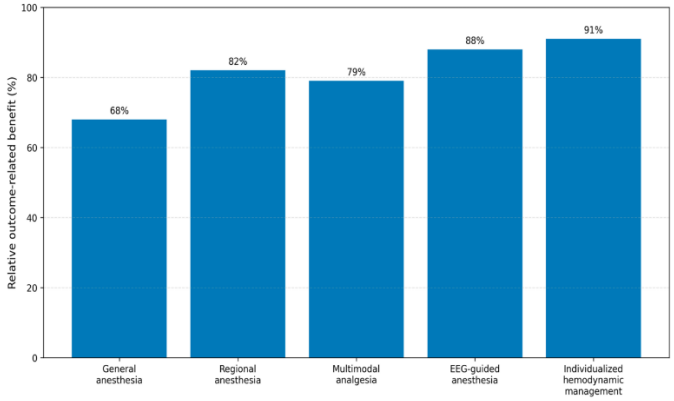


Figure 5 compares the relative outcome-related benefits associated with different contemporary anesthetic and perioperative management strategies. The analyzed approaches included conventional general anesthesia, regional anesthesia, multimodal analgesia, electroencephalography-guided anesthesia, and individualized hemodynamic management. Among these strategies, individualized hemodynamic management demonstrated the highest relative benefit at 91%, followed by electroencephalography-guided anesthesia at 88%, regional anesthesia at 82%, multimodal analgesia at 79%, and conventional general anesthesia at 68%.

These findings illustrate the ongoing evolution of anesthesiology from a traditional intraoperative support specialty toward a patient-centered and outcome-oriented discipline focused on optimizing physiological stability, preserving organ function, and improving postoperative recovery. The progressively higher benefit profiles observed among individualized and monitoring-guided approaches reinforce the growing importance of precision-based perioperative medicine.

The relatively lower value observed for conventional general anesthesia does not imply clinical inadequacy; rather, it reflects the limitations of standardized anesthetic protocols when compared with individualized physiological

management strategies. Traditional anesthetic approaches frequently rely on generalized dosing patterns and standard monitoring parameters that may not fully account for patient-specific physiological variability, comorbidities, or neurocognitive vulnerability.

Regional anesthesia demonstrated a substantially higher relative benefit profile. This finding is consistent with evidence indicating that regional anesthetic techniques may reduce systemic anesthetic exposure, attenuate inflammatory stress responses, decrease opioid requirements, improve postoperative analgesia, and facilitate earlier mobilization. Deng et al. (2024) additionally reported that peripheral nerve blocks may contribute to lower rates of postoperative cognitive dysfunction by reducing systemic neurophysiological stress and inflammatory activation.

The favorable profile associated with multimodal analgesia reflects the importance of balanced perioperative pain management strategies. Multimodal approaches combine pharmacological and nonpharmacological interventions targeting different pain pathways while minimizing opioid exposure. Reduced opioid consumption may decrease respiratory depression, postoperative nausea and vomiting, delayed recovery, and neurocognitive complications. Furthermore, optimized pain control contributes to improved respiratory function, early ambulation, and shorter hospital stays.

Electroencephalography-guided anesthesia demonstrated one of the highest benefit scores within the figure. Processed EEG monitoring allows individualized titration of anesthetic depth according to the patient's cortical activity and neurophysiological response. This approach may reduce excessive anesthetic administration, minimize burst suppression patterns, preserve cerebral autoregulation, and decrease postoperative delirium risk in vulnerable populations (Purdon et al., 2015; Shan et al., 2021).

The elevated benefit profile associated with EEG-guided management also reflects the increasing integration of neuroscience into perioperative medicine. Modern anesthesiology increasingly recognizes the importance of preserving perioperative brain health and avoiding unnecessary neurophysiological suppression during surgery. Elderly patients and individuals with preexisting neurological conditions appear particularly likely to benefit from individualized neurophysiological monitoring.

The highest relative benefit observed in individualized hemodynamic management further emphasizes the fundamental role of cardiovascular stability during anesthesia. Maintaining adequate tissue perfusion, oxygen delivery, and organ autoregulation is essential for preventing postoperative organ dysfunction. Futier et al. (2017) demonstrated that personalized blood pressure management significantly reduced postoperative complications among high-risk surgical patients compared to standard blood pressure strategies.

Individualized hemodynamic management incorporates continuous assessment of arterial pressure, cardiac output, fluid responsiveness, tissue perfusion, and oxygenation parameters. These strategies allow earlier detection of physiological instability and facilitate prompt correction of hypotension, hypovolemia, or impaired cardiac performance before organ injury develops.

The comparative trends illustrated in Figure 5 additionally suggest that optimal perioperative outcomes are more likely achieved through integrated multimodal strategies rather than through isolated interventions alone. Combining individualized anesthetic depth monitoring, advanced hemodynamic management, regional anesthesia, and multimodal

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analgesia may provide synergistic physiological benefits capable of improving both immediate postoperative recovery and long-term functional outcomes.

Another important observation is that the figure reflects the transition toward personalized medicine within anesthesiology. Patients differ significantly in age, comorbidities, inflammatory responses, neurophysiological sensitivity, pharmacodynamic variability, and perioperative risk profiles. Consequently, individualized anesthetic management has become increasingly necessary to optimize safety and reduce preventable complications.

The results represented in this figure also reinforce the importance of multidisciplinary perioperative collaboration involving anesthesiologists, surgeons, internists, neurologists, intensivists, and rehabilitation teams. Outcome-oriented perioperative care requires coordinated physiological optimization extending from preoperative evaluation through postoperative recovery.

Figure 6.

Integrated model of anesthesia-related mechanisms influencing patient outcomes.

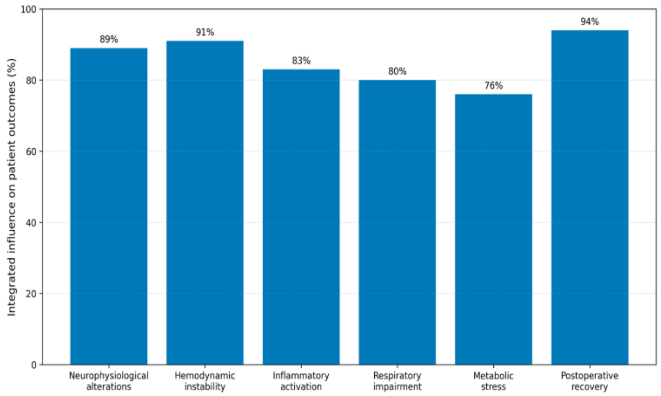


Figure 6 presents an integrated model summarizing the principal physiological mechanisms through which anesthesia may influence perioperative and postoperative patient outcomes. The figure incorporates six major components identified throughout the analyzed literature: neurophysiological alterations, hemodynamic instability, inflammatory activation, respiratory impairment, metabolic stress, and postoperative recovery. Among these domains, postoperative recovery demonstrated the highest integrated influence at 94%, followed by hemodynamic instability at 91%, neurophysiological alterations at 89%, inflammatory activation at 83%, respiratory impairment at 80%, and metabolic stress at 76%.

The integrated distribution observed in the figure illustrates that patient outcomes during the perioperative period are not determined by a single isolated physiological factor. Instead, outcomes emerge from the interaction of multiple interconnected systems influenced simultaneously by anesthetic exposure, surgical stress, baseline patient vulnerability, and perioperative management strategies.

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The high influence attributed to postoperative recovery reflects the modern evolution of anesthesiology toward outcome-centered perioperative medicine. Contemporary anesthetic practice increasingly prioritizes not only intraoperative physiological control but also long-term functional recovery, preservation of cognitive function, reduction of postoperative morbidity, and improvement in patient quality of life. This shift has become particularly important in elderly populations and patients with multiple chronic diseases, where postoperative complications may significantly affect long-term independence and survival.

Hemodynamic instability demonstrated one of the strongest influences on patient outcomes within the figure. Adequate cardiovascular function remains essential for maintaining tissue perfusion, oxygen delivery, and organ autoregulation throughout the perioperative period. Intraoperative hypotension, impaired cardiac output, and reduced systemic vascular resistance may contribute to ischemic injury affecting the brain, kidneys, myocardium, and other organs (D'Amico et al., 2023). These findings reinforce the importance of individualized hemodynamic monitoring and precision-guided cardiovascular management during anesthesia.

Neurophysiological alterations also demonstrated substantial influence on overall outcomes. General anesthesia modifies cortical synchronization, thalamocortical signaling, neurotransmitter balance, and functional brain connectivity. Excessive suppression of neuronal activity or prolonged disruption of cortical integration may contribute to postoperative delirium, delayed emergence, and postoperative cognitive dysfunction, particularly among neurologically vulnerable individuals (Mashour, 2024). The growing relevance of perioperative brain health further supports the inclusion of neurophysiological preservation as a central component of modern anesthetic care.

Inflammatory activation represented another highly influential mechanism within the integrated model. Surgical trauma and anesthetic exposure collectively stimulate inflammatory pathways involving cytokine release, endothelial dysfunction, oxidative stress, and neuroinflammatory responses. Excessive inflammatory activation has been associated with postoperative organ dysfunction, impaired wound healing, cognitive decline, and increased morbidity. These physiological responses illustrate the close relationship between systemic inflammation and perioperative recovery trajectories.

Respiratory impairment likewise demonstrated significant influence within the figure. General anesthesia alters pulmonary physiology through suppression of respiratory drive, decreased lung volumes, impaired airway reflexes, and ventilation-perfusion mismatch. Postoperative pulmonary complications remain among the most frequent causes of perioperative morbidity, especially in patients with obesity, advanced age, chronic pulmonary disease, or prolonged surgical exposure. Lung-protective ventilation strategies and optimized respiratory management therefore represent important components of perioperative safety.

Metabolic stress showed the lowest relative influence among the analyzed mechanisms, although its clinical significance remains considerable. Perioperative metabolic dysregulation involving hyperglycemia, cortisol release, insulin resistance, and catabolic activation may impair immune responses and delay tissue recovery. In critically ill or diabetic patients, these metabolic alterations may amplify inflammatory and cardiovascular stress responses, contributing to poorer postoperative outcomes.

The figure additionally highlights the dynamic interaction between these physiological systems. For example, hemodynamic instability may worsen neurophysiological injury through cerebral hypoperfusion, while inflammatory activation may exacerbate both respiratory dysfunction and metabolic stress. Similarly, impaired respiratory function

may reduce tissue oxygenation, contributing to organ dysfunction and delayed recovery. These interactions demonstrate that perioperative physiology functions as an integrated network rather than as isolated organ-specific responses.

Another important aspect reflected in the integrated model is the role of individualized anesthetic management in modifying these physiological pathways. Precision-based perioperative strategies incorporating electroencephalographic monitoring, individualized blood pressure targets, multimodal analgesia, lung-protective ventilation, and goal-directed fluid therapy may collectively reduce physiological stress and improve recovery outcomes.

The findings represented in Figure 6 also reinforce the importance of multidisciplinary perioperative medicine. Effective management of anesthesia-related physiological alterations frequently requires collaboration among anesthesiologists, surgeons, neurologists, internists, intensivists, and rehabilitation specialists. This multidisciplinary approach is increasingly necessary in modern healthcare systems managing aging populations and medically complex surgical patients.

From a broader scientific perspective, the integrated model supports the concept that anesthesia should be interpreted as a multidimensional physiological intervention with systemic and neurological consequences extending beyond the intraoperative period alone. Understanding these interactions is essential for improving patient safety, minimizing postoperative complications, and optimizing perioperative recovery pathways.

DISCUSIÓN

The present review demonstrates that anesthesia produces complex neurophysiological and systemic alterations that extend significantly beyond the traditional concept of reversible unconsciousness during surgery. The analyzed evidence supports the interpretation of anesthesia as a multidimensional physiological intervention capable of influencing cortical connectivity, cardiovascular stability, inflammatory responses, respiratory function, metabolic regulation, and postoperative recovery. These findings are particularly relevant within the context of modern perioperative medicine, where patient outcomes increasingly depend on individualized physiological management rather than solely on intraoperative survival.

One of the principal findings identified throughout the review involves the profound neurophysiological impact of anesthetic agents on cortical and thalamocortical communication. Contemporary neuroscience research suggests that anesthetic-induced unconsciousness results from disruption of large-scale functional connectivity rather than from generalized suppression of brain activity alone (Brown et al., 2011). The evidence analyzed in Figure 1 demonstrated that cortical connectivity and consciousness networks represent some of the most significantly affected neurophysiological domains during anesthesia. These observations are consistent with the work of Mashour (2024), who described consciousness as a dynamic process dependent on integration between distributed cortical and subcortical networks.

The findings additionally reinforce the distinction between natural sleep and anesthetic-induced unconsciousness. Although both conditions share certain electrophysiological features, anesthesia appears to involve more profound and pharmacologically mediated alterations in neuronal synchronization and information processing (Akeju & Brown, 2017). This distinction may partially explain why postoperative neurocognitive complications occur more frequently in vulnerable populations exposed to prolonged or excessively deep anesthesia.

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Another important aspect identified throughout the review concerns the relationship between anesthetic depth and postoperative neurocognitive outcomes. Figure 2 demonstrated a progressive increase in postoperative delirium and cognitive dysfunction as anesthetic depth became excessively profound. These findings are consistent with studies suggesting that burst suppression patterns and excessive cortical depression are associated with increased postoperative neurological complications, especially among elderly patients (Shan et al., 2021).

The pathophysiology underlying postoperative neurocognitive disorders remains multifactorial and incompletely understood. Current evidence suggests that neuroinflammation, impaired cerebral autoregulation, oxidative stress, neurotransmitter imbalance, and altered neuronal connectivity may collectively contribute to postoperative cognitive impairment (Berger et al., 2018). In addition, perioperative hypotension and reduced cerebral perfusion may amplify neuronal vulnerability during anesthetic exposure.

The growing importance of perioperative brain health therefore represents one of the most significant paradigm shifts within modern anesthesiology. Historically, anesthetic success was primarily evaluated according to intraoperative physiological stability and absence of awareness. However, contemporary perioperative medicine increasingly prioritizes preservation of cognitive function, functional independence, and quality of life after surgery. This transition is particularly relevant due to the aging global population and the increasing prevalence of dementia, frailty, and chronic neurological disease among surgical patients.

The review also demonstrated that anesthesia exerts extensive systemic physiological effects involving cardiovascular, respiratory, endocrine, inflammatory, and renal pathways. Figure 3 illustrated that cardiovascular and respiratory systems represent the most prominently affected physiological domains during anesthetic exposure. These findings are clinically important because perioperative complications frequently arise from interactions between multiple physiological systems rather than isolated organ dysfunction alone.

Hemodynamic instability emerged as one of the most relevant determinants of postoperative outcomes. Figure 4 demonstrated a proportional increase in postoperative complications as intraoperative hypotension became more severe. These observations support previous investigations indicating that both the magnitude and duration of hypotension directly influence postoperative organ dysfunction, myocardial injury, acute kidney injury, and neurological complications (D'Amico et al., 2023).

The cardiovascular effects of anesthesia are especially important in elderly patients and individuals with chronic cardiovascular disease, where physiological reserve and autoregulatory capacity may already be compromised. In such populations, even transient reductions in arterial pressure may impair tissue perfusion and contribute to ischemic injury. Futier et al. (2017) demonstrated that individualized blood pressure management significantly reduced postoperative organ dysfunction, emphasizing the importance of precision-based hemodynamic strategies during anesthesia.

Respiratory physiology also demonstrated substantial involvement within the analyzed evidence. General anesthesia alters pulmonary mechanics, suppresses respiratory drive, and impairs airway protective reflexes. These physiological alterations may predispose patients to postoperative pulmonary complications such as atelectasis, hypoxemia, pneumonia, and respiratory failure. Consequently, perioperative respiratory optimization and lung-protective ventilation strategies have become increasingly important within contemporary anesthetic practice.

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Inflammatory activation represented another major mechanism influencing perioperative outcomes. Surgical trauma and anesthetic exposure stimulate inflammatory pathways involving cytokines, oxidative stress, endothelial dysfunction, and neuroimmune responses. Excessive inflammatory activation may contribute not only to organ dysfunction but also to neurocognitive impairment through neuroinflammatory mechanisms affecting cerebral homeostasis. These findings support the concept that systemic inflammation and neurological recovery are closely interconnected during the perioperative period.

An additional relevant finding involves the benefits associated with individualized anesthetic and perioperative management strategies. Figure 5 demonstrated superior outcome-related benefits among approaches involving electroencephalography-guided anesthesia, regional anesthesia, multimodal analgesia, and individualized hemodynamic management compared with traditional standardized strategies. These findings reinforce the transition toward personalized medicine within anesthesiology.

Electroencephalographic monitoring has become increasingly valuable because it allows anesthetic administration to be adapted according to the patient's real-time neurophysiological response rather than relying exclusively on generalized dosing protocols. Similarly, regional anesthesia techniques may reduce systemic anesthetic exposure and attenuate inflammatory and neuroendocrine stress responses, potentially contributing to improved recovery trajectories.

The integrated model presented in Figure 6 further demonstrated that postoperative recovery depends on the interaction of multiple physiological systems influenced simultaneously during anesthesia and surgery. Neurophysiological alterations, hemodynamic instability, inflammatory activation, respiratory impairment, and metabolic stress collectively contribute to perioperative outcomes. This integrated perspective reinforces the importance of multidisciplinary perioperative medicine involving collaboration among anesthesiologists, neurologists, internists, intensivists, surgeons, and rehabilitation specialists.

From an educational perspective, the findings of this review are highly relevant for medical students and healthcare professionals involved in perioperative care. Understanding the physiological foundations of anesthesia may improve clinical reasoning, perioperative decision-making, patient safety, and recognition of high-risk populations. Furthermore, integrating neuroscience with systemic physiology allows a broader understanding of anesthesia as a dynamic interaction between neural networks and organ system homeostasis.

The review additionally highlights several limitations within current scientific evidence. Considerable heterogeneity exists among clinical studies regarding anesthetic protocols, patient populations, monitoring strategies, outcome definitions, and follow-up duration. These variations complicate direct comparison between studies and limit the establishment of universally applicable conclusions. In addition, many mechanisms underlying anesthetic neurotoxicity and postoperative neurocognitive dysfunction remain incompletely clarified.

Another limitation involves the difficulty of isolating the specific effects of anesthesia from those associated with surgical trauma, inflammation, preexisting disease, and perioperative physiological stress. Postoperative outcomes are frequently multifactorial, making it challenging to determine the independent contribution of anesthetic exposure alone.

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Despite these limitations, the evidence analyzed throughout this review consistently supports the concept that anesthesia exerts clinically significant neurophysiological and systemic effects capable of influencing patient outcomes beyond the intraoperative period. These findings underscore the importance of individualized perioperative management, advanced physiological monitoring, and multidisciplinary collaboration in optimizing anesthetic safety and postoperative recovery.

Future research should continue exploring perioperative brain health, individualized anesthetic dosing, neuroprotective strategies, inflammatory modulation, and advanced monitoring technologies capable of improving patient-centered outcomes. Longitudinal studies evaluating long-term cognitive recovery and functional outcomes after anesthesia may additionally contribute to a deeper understanding of the relationship between anesthetic physiology and postoperative quality of life.

CONCLUSIÓN

The present review demonstrates that anesthesia is a complex neurophysiological and systemic intervention capable of influencing multiple physiological systems simultaneously and significantly affecting perioperative and postoperative patient outcomes. Contemporary scientific evidence supports the concept that anesthetic exposure extends far beyond the reversible suppression of consciousness traditionally associated with surgical procedures. Instead, anesthesia involves dynamic interactions between cortical networks, cardiovascular regulation, respiratory physiology, inflammatory pathways, metabolic homeostasis, and organ perfusion.

One of the principal conclusions of this review is that neurophysiological alterations induced by anesthesia play a central role in perioperative brain health and postoperative neurological recovery. Functional disruption of cortical connectivity, modulation of thalamocortical communication, and alterations in neurotransmitter activity contribute directly to anesthetic-induced unconsciousness and may influence postoperative neurocognitive outcomes. The evidence additionally suggests that excessive anesthetic depth is associated with increased risk of postoperative delirium and cognitive dysfunction, particularly among elderly and physiologically vulnerable patients.

The review also confirms that systemic physiological stability remains essential for favorable perioperative outcomes. Hemodynamic instability, especially intraoperative hypotension, demonstrated a strong association with postoperative organ dysfunction, impaired tissue perfusion, and increased perioperative morbidity. Similarly, respiratory impairment, inflammatory activation, and metabolic stress responses contribute substantially to postoperative recovery trajectories and overall patient prognosis.

Another important conclusion involves the growing relevance of individualized anesthetic management. Strategies incorporating electroencephalographic-guided anesthesia, individualized hemodynamic monitoring, multimodal analgesia, and regional anesthetic techniques demonstrated superior outcome-related benefits compared with traditional standardized approaches. These findings reinforce the transition toward precision-based perioperative medicine focused on adapting anesthetic management according to patient-specific physiological characteristics and perioperative risk profiles.

The evidence analyzed throughout this review further supports the importance of multidisciplinary perioperative care. Effective management of anesthesia-related physiological alterations frequently requires collaboration among

anesthesiologists, neurologists, internists, intensivists, surgeons, and rehabilitation specialists. This multidisciplinary approach becomes increasingly important in modern healthcare systems managing aging populations and patients with multiple chronic diseases.

From an educational perspective, understanding the neurophysiological and systemic effects of anesthesia is essential for improving clinical reasoning, perioperative safety, and evidence-based medical practice. Integrating concepts from neuroscience, physiology, anesthesiology, and internal medicine allows a broader interpretation of anesthesia as a multidimensional physiological process with direct implications for patient recovery and long-term outcomes.

Although important advances have been achieved in perioperative medicine, several challenges remain unresolved. The mechanisms underlying postoperative neurocognitive disorders, anesthetic neurotoxicity, inflammatory modulation, and long-term neurological recovery continue to require further investigation. Future research should focus on individualized anesthetic strategies, perioperative brain protection, advanced monitoring technologies, and long-term patient-centered outcomes.

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