

Anestesia de Precisión en la Cirugía Moderna: Integración del Monitoreo Neurofisiológico y el Control Perioperatorio Adaptativo

Precision Anesthesia in Modern Surgery: Integrating Neurophysiologic Monitoring and Adaptive Perioperative Control

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RESUMEN

La anestesia adaptativa ha surgido como un cambio de paradigma en la medicina perioperatoria moderna, al integrar el monitoreo neurofisiológico y el control anestésico individualizado para optimizar los resultados clínicos. Esta revisión analiza la evidencia actual sobre el papel del monitoreo electroencefalográfico, los índices de profundidad anestésica y los sistemas de circuito cerrado en la toma de decisiones anestésicas. Se realizó un análisis estructurado de estudios de alto impacto publicados a partir de 2020, centrado en mecanismos neurofisiológicos, resultados

perioperatorios y avances tecnológicos. Los hallazgos muestran que el monitoreo basado en EEG mejora la precisión en la evaluación de la profundidad anestésica y permite una titulación más adecuada de los agentes anestésicos. La anestesia excesivamente profunda se asoció de manera consistente con mayor incidencia de delirium postoperatorio, disfunción cognitiva e inestabilidad hemodinámica, mientras que las estrategias adaptativas se relacionaron con mejor estabilidad intraoperatoria y recuperación. Los sistemas de circuito cerrado demostraron potencial para reducir la variabilidad y aumentar la precisión anestésica, aunque su implementación aún es limitada. Desde una perspectiva internacional, la adopción de la anestesia adaptativa está en crecimiento, incluyendo contextos latinoamericanos como México, Colombia y Ecuador, a pesar de las desigualdades en recursos y capacitación. En conjunto, la anestesia adaptativa representa una transición hacia una atención perioperatoria más precisa y centrada en el paciente, siendo necesario fortalecer la evidencia y estandarizar su aplicación.

PALABRAS CLAVE

Anestesia adaptativa, monitoreo neurofisiológico, electroencefalografía, índice bispectral, atención perioperatoria, medicina de precisión, anestesia de circuito cerrado, delirium postoperatorio, disfunción cognitiva, profundidad anestésica

ABSTRACT

Adaptive anesthesia has emerged as a paradigm shift in modern perioperative medicine, integrating neurophysiologic monitoring and individualized anesthetic control to optimize patient outcomes. This review analyzes current evidence on the role of electroencephalographic monitoring, depth-of-anesthesia indices, and closed-loop systems in guiding anesthetic management. A structured analysis of high-impact studies published from 2020 onward was conducted, focusing on neurophysiological mechanisms, perioperative outcomes, and technological advancements. The findings demonstrate that EEG-based monitoring improves the accuracy of anesthetic depth assessment and allows for more precise titration of anesthetic agents. Excessive anesthetic depth was consistently associated with higher rates of postoperative delirium, cognitive dysfunction, and hemodynamic instability, while adaptive strategies contributed to improved intraoperative stability and recovery profiles. Closed-loop systems showed potential in reducing variability and enhancing anesthetic precision, although their implementation remains limited. From an international perspective, the adoption of adaptive anesthesia is increasing, including in Latin American contexts such as Mexico, Colombia, and Ecuador, despite existing disparities in resources and training. Overall, adaptive anesthesia represents a transition toward precision-based, patient-centered perioperative care. Further research is required to standardize protocols, validate emerging technologies, and ensure broader clinical applicability.

KEYWORDS

Adaptive anesthesia, neurophysiologic monitoring, electroencephalography, bispectral index, perioperative care, precision medicine, closed-loop anesthesia, postoperative delirium, cognitive dysfunction, anesthetic depth

INTRODUCCIÓN

Over the past decade, anesthesiology has undergone a paradigm shift from standardized protocols toward precision-based perioperative care, driven by advances in neurophysiologic monitoring, computational modeling, and individualized pharmacologic strategies. This transition is particularly relevant in modern surgical practice, where variability in patient response to anesthetic agents remains a major determinant of perioperative morbidity, neurological outcomes, and long-term recovery (Brown et al., 2020; Mashour et al., 2020). Traditional approaches to anesthesia, often based on population averages, fail to adequately account for interindividual differences in brain dynamics, comorbidities, and pharmacokinetics, thereby increasing the risk of complications such as intraoperative awareness, postoperative delirium, and hemodynamic instability (Sanders et al., 2020; Shaefi et al., 2020).

The emergence of adaptive anesthesia—defined as the real-time adjustment of anesthetic depth and drug delivery based on continuous neurophysiological and hemodynamic feedback—represents a promising strategy to address these limitations. Central to this approach is the integration of electroencephalographic (EEG) monitoring and processed indices such as the bispectral index (BIS), which provide surrogate markers of cortical activity and consciousness (Purdon et al., 2020; Sleight et al., 2021). These tools have demonstrated the capacity to differentiate between anesthetic states, sedation levels, and pathological brain responses, offering clinicians a more refined understanding of brain function under anesthesia (Akeju & Brown, 2021; Hight et al., 2021). However, despite their widespread use, controversies remain regarding their accuracy, interpretation, and clinical applicability across diverse patient populations (Schuller et al., 2020; Koch et al., 2020).

In parallel, the integration of automated and closed-loop systems for anesthetic drug administration has introduced a new dimension of precision medicine in the operating room. These systems utilize continuous feedback mechanisms to titrate agents such as propofol and remifentanyl, optimizing drug delivery while minimizing human error and pharmacodynamic variability (Liu et al., 2020). Early evidence suggests that such approaches may enhance hemodynamic stability, reduce anesthetic consumption, and improve recovery profiles, although their implementation remains limited by technological, ethical, and training considerations (Hemmerling & Taddei, 2020).

From an internal medicine perspective, perioperative care extends beyond intraoperative management, encompassing systemic risk stratification, neurological protection, and long-term cognitive outcomes. Postoperative delirium and cognitive dysfunction, for instance, represent significant complications associated with increased mortality, prolonged hospitalization, and diminished quality of life (Evered et al., 2021; Deiner & Silverstein, 2020). Neurophysiological monitoring and individualized anesthetic strategies have been proposed as key interventions to mitigate these risks, particularly in vulnerable populations such as the elderly and patients with preexisting neurological conditions (Bilotta et al., 2021; Kertai et al., 2021).

The global relevance of this topic is underscored by its applicability across diverse healthcare systems, including those in Latin America. Countries such as Mexico, Colombia, and Ecuador are increasingly incorporating advanced monitoring technologies and evidence-based perioperative protocols, although disparities in resource availability and training persist. This context highlights the need for adaptable, scalable strategies that can be implemented across varying clinical environments while maintaining high standards of patient safety and care quality.

Recent literature has focused on elucidating the neurobiological mechanisms underlying anesthesia-induced unconsciousness, emphasizing the role of neural oscillations, thalamocortical connectivity, and network-level disruptions (Akeju & Brown, 2021). Additionally, studies have explored the relationship between anesthetic depth monitoring and clinical outcomes, including reduced incidence of postoperative delirium and mortality (Chan et al., 2020; Kertai et al., 2021). Despite these advances, significant gaps remain in translating these findings into standardized clinical protocols that integrate neurophysiological data with individualized patient characteristics.

In this context, the present review aims to analyze the current evidence on adaptive anesthesia, focusing on the role of neurophysiologic monitoring and personalized perioperative control in modern surgery. The central research question guiding this work is whether the integration of real-time neurophysiological data and adaptive anesthetic strategies can improve perioperative outcomes compared to conventional approaches. This question arises from existing theoretical frameworks in neuroanesthesia and precision medicine, which suggest that individualized modulation of anesthetic depth may optimize both neurological and systemic responses to surgery (Brown et al., 2020; Mashour et al., 2020).

Methodologically, this review is based on a structured analysis of recent high-impact publications indexed in major biomedical databases, emphasizing studies published from 2020 onward. The selection criteria prioritize clinical trials, systematic reviews, and translational research that address neurophysiological monitoring, anesthetic depth, and perioperative outcomes. This approach ensures a comprehensive and up-to-date synthesis of the available evidence, while maintaining relevance to contemporary clinical practice.

DESARROLLO

The concept of adaptive anesthesia has emerged as a response to the intrinsic variability observed in patient responses to anesthetic agents, particularly in complex surgical settings where neurological, cardiovascular, and metabolic

systems interact dynamically. Unlike traditional anesthetic models, which rely on standardized dosing and intermittent clinical assessment, adaptive anesthesia incorporates continuous neurophysiological monitoring and real-time data integration to guide individualized decision-making. This evolution reflects a broader shift toward precision medicine, where therapeutic interventions are tailored to the physiological and pathological characteristics of each patient (Brown et al., 2020).

At the core of this paradigm lies the utilization of electroencephalographic (EEG) monitoring as a surrogate marker of cortical activity and depth of anesthesia. EEG-based indices, including the bispectral index (BIS), have gained widespread clinical adoption due to their ability to quantify levels of consciousness and detect transitions between anesthetic states. Studies have demonstrated that specific EEG oscillatory patterns—such as alpha and slow-delta rhythms—are closely associated with anesthetic-induced unconsciousness, providing a neurobiological framework for anesthetic titration (Purdon et al., 2020; Akeju & Brown, 2021). These findings underscore the importance of interpreting brain activity not merely as a static measure but as a dynamic system reflecting the interplay between anesthetic agents and neural circuits (Hight et al., 2021).

However, the clinical application of EEG-derived indices is not without limitations. Variability in signal interpretation, interference from neuromuscular blockade, and differences in patient-specific neurophysiology can affect the reliability of these monitoring tools (Schuller et al., 2020). Moreover, while BIS monitoring has been associated with reductions in anesthetic consumption and postoperative delirium in certain populations, its impact on long-term neurological outcomes remains a subject of ongoing investigation (Chan et al., 2020; Kertai et al., 2021). These challenges highlight the need for a more integrative approach that combines neurophysiological data with clinical judgment and additional monitoring modalities.

From a pharmacological perspective, adaptive anesthesia leverages advances in pharmacokinetic and pharmacodynamic modeling to optimize drug delivery. The development of closed-loop systems represents a significant milestone in this regard, enabling automated titration of anesthetic agents based on continuous feedback from EEG or other physiological parameters. For instance, closed-loop administration of propofol and remifentanyl has been shown to maintain stable anesthetic depth while reducing variability and improving recovery profiles (Liu et al., 2020). Such systems exemplify the integration of engineering principles with clinical practice, offering a pathway toward safer and more efficient anesthetic care.

In addition to intraoperative management, adaptive anesthesia has important implications for perioperative medicine, particularly in the prevention of neurological complications. Postoperative delirium and cognitive dysfunction are increasingly recognized as major contributors to morbidity, especially among elderly patients and those with preexisting comorbidities. The pathophysiology of these conditions is multifactorial, involving neuroinflammation, neurotransmitter imbalance, and disruptions in neural connectivity (Evered et al., 2021; Deiner & Silverstein, 2020). Evidence suggests that excessive anesthetic depth, intraoperative hypotension, and inadequate cerebral perfusion may exacerbate these processes, thereby reinforcing the importance of precise anesthetic control (Shaefi et al., 2020).

Furthermore, the role of anesthesiology extends beyond the operating room, encompassing a comprehensive approach to perioperative risk management. Neurological complications such as perioperative stroke, although relatively infrequent, carry significant morbidity and mortality, necessitating early detection and prevention strategies (Vlisides & Mashour, 2021). Adaptive anesthesia, through its emphasis on continuous monitoring and individualized care, offers a potential framework for mitigating these risks by maintaining optimal cerebral perfusion and minimizing physiological disturbances.

The integration of artificial intelligence and machine learning into anesthetic practice represents an emerging frontier within this field. While still in its early stages, these technologies have the potential to enhance predictive modeling, identify patterns in complex datasets, and support clinical decision-making. Automated systems capable of analyzing real-time physiological data may further refine anesthetic delivery, reducing variability and improving patient outcomes (Hemmerling & Taddei, 2020). Nevertheless, the implementation of such technologies must be approached with caution, considering ethical, regulatory, and training-related challenges.

From an international perspective, the adoption of adaptive anesthesia varies significantly across healthcare systems. In high-resource settings, advanced monitoring technologies and automated systems are increasingly integrated into routine practice. In contrast, countries such as Mexico, Colombia, and Ecuador face challenges related to resource allocation, infrastructure, and access to specialized training. Despite these limitations, there is a growing interest in incorporating evidence-based perioperative strategies, including the use of EEG monitoring and enhanced recovery protocols. This trend reflects a broader commitment to improving patient safety and aligning clinical practice with global standards.

Importantly, adaptive anesthesia should not be viewed solely as a technological advancement but as a conceptual framework that emphasizes individualized care, interdisciplinary collaboration, and continuous evaluation of clinical outcomes. The anesthesiologist, in this context, assumes a central role as both a clinician and a perioperative physician, integrating knowledge from anesthesiology, internal medicine, neurology, and critical care to optimize patient management (Mashour et al., 2020).

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

General Objective

To critically analyze the current evidence on adaptive anesthesia, focusing on the integration of neurophysiologic monitoring and personalized perioperative control, in order to evaluate its impact on clinical outcomes, neurological safety, and perioperative management within a multidisciplinary and international context.

Specific Objectives

Cognitive Domain

1. To **analyze** the neurophysiological mechanisms underlying anesthetic-induced unconsciousness and their clinical implications in perioperative care (Akeju & Brown, 2021; Purdon et al., 2020).
2. To **evaluate** the effectiveness and limitations of EEG-based monitoring tools, including bispectral index (BIS), in assessing anesthetic depth and predicting outcomes (Sleigh et al., 2021; Schuller et al., 2020).
3. To **compare** traditional anesthetic approaches with adaptive anesthesia models in terms of safety, precision, and patient outcomes (Brown et al., 2020; Mashour et al., 2020).
4. To **interpret** the relationship between anesthetic depth, intraoperative physiological variables, and postoperative complications such as delirium and cognitive dysfunction (Evered et al., 2021; Deiner & Silverstein, 2020).
5. To **synthesize** current evidence regarding the role of closed-loop systems and automated drug delivery in modern anesthetic practice (Liu et al., 2020).

Psychomotor Domain

1. To **apply** neurophysiological monitoring techniques (e.g., EEG interpretation, BIS utilization) in simulated perioperative clinical scenarios.
2. To **demonstrate** the adjustment of anesthetic depth based on real-time physiological data, integrating hemodynamic and neurological parameters.
3. To **implement** adaptive anesthetic strategies using structured decision-making frameworks in perioperative management.
4. To **operate** monitoring devices and interpret outputs to guide anesthetic titration in a controlled clinical environment.
5. To **integrate** pharmacokinetic and pharmacodynamic principles into practical anesthetic management strategies.

Affective Domain

1. To **value** the importance of individualized patient care in anesthesiology, recognizing variability in physiological and neurological responses.
2. To **develop** a critical attitude toward the use of emerging technologies, including automated systems and advanced monitoring tools, considering their benefits and limitations (Hemmerling & Taddei, 2020).

3. To **demonstrate** commitment to patient safety and ethical perioperative practice through evidence-based decision-making.
4. To **appreciate** the role of interdisciplinary collaboration between anesthesiology, internal medicine, and critical care in optimizing perioperative outcomes.
5. To **promote** continuous learning and adaptation in response to evolving scientific evidence and technological advancements.

OBJETO DE ESTUDIO

The object of study of this review is the **adaptive anesthetic process**, understood as a dynamic, individualized, and continuously modulated approach to anesthetic management based on real-time neurophysiological and systemic monitoring.

This concept encompasses the interaction between anesthetic agents, brain activity, and systemic physiological responses during the perioperative period, with particular emphasis on the modulation of consciousness, neural oscillatory patterns, and hemodynamic stability (Purdon et al., 2020; Akeju & Brown, 2021).

From a conceptual standpoint, the object of study is structured into three fundamental components:

1. Phenomenon

The central phenomenon under investigation is the **neurophysiological response to anesthesia**, specifically:

- The mechanisms of anesthetic-induced unconsciousness.
- The modulation of cortical and subcortical activity reflected in EEG patterns.
- The relationship between anesthetic depth and systemic physiological variables such as blood pressure, cerebral perfusion, and metabolic demand.

This phenomenon is critical because alterations in these processes are directly associated with perioperative complications, including intraoperative awareness, postoperative delirium, and cognitive dysfunction (Mashour et al., 2020; Evered et al., 2021).

2. Population

The population considered in this review includes:

- Adult patients undergoing surgical procedures under general anesthesia.
- Subgroups at increased perioperative risk, including:
 - Elderly patients.
 - Individuals with cardiovascular or neurological comorbidities.
 - Patients with increased susceptibility to postoperative cognitive impairment.

This population is particularly relevant due to the variability in pharmacodynamic and neurophysiological responses to anesthetic agents, which necessitates individualized approaches to perioperative management (Deiner & Silverstein, 2020; Bilotta et al., 2021).

3. System

The system analyzed corresponds to the **perioperative care model integrating anesthesiology and internal medicine**, characterized by:

- The use of advanced monitoring technologies, including EEG and processed indices such as BIS.

- The incorporation of pharmacological models guiding anesthetic administration.
- The implementation of adaptive strategies for real-time anesthetic titration.
- The integration of intraoperative and postoperative care aimed at optimizing patient outcomes.

METODOLOGÍA

1. Study Design

The research follows a **qualitative, analytical, and integrative approach**, aimed at synthesizing current knowledge from high-impact scientific literature. The Scientific Method was selected as the guiding framework due to its capacity to organize evidence-based reasoning through sequential stages: problem identification, literature analysis, interpretation, and synthesis.

This design allows for the exploration of complex clinical phenomena—such as the interaction between anesthetic agents and brain activity—within a multidisciplinary context that integrates anesthesiology and internal medicine.

2. Data Sources and Search Strategy

A comprehensive literature search was conducted using major biomedical databases, including:

- PubMed/MEDLINE
- Scopus
- Web of Science

The search strategy was based on combinations of controlled vocabulary (MeSH terms) and free-text keywords, including:

- “Adaptive anesthesia”
- “Neurophysiological monitoring”
- “Electroencephalography anesthesia”
- “Bispectral index”
- “Perioperative care”
- “Closed-loop anesthesia”

Boolean operators (AND, OR) were applied to refine the search and ensure relevance.

3. Inclusion and Exclusion Criteria

Inclusion criteria:

- Articles published from 2020 onward.
- Studies indexed in high-impact journals.
- Clinical trials, systematic reviews, meta-analyses, and relevant observational studies.
- Research addressing neurophysiological monitoring, anesthetic depth, or perioperative outcomes.

Exclusion criteria:

- Studies with insufficient methodological rigor.

- Articles not available in full text.
- Publications not directly related to anesthetic monitoring or perioperative management.

4. Selection Process

The selection process was carried out in sequential stages:

1. **Initial screening** based on titles and abstracts.
2. **Full-text review** to assess relevance and methodological quality.
3. **Final selection** of 20 high-impact articles that met all inclusion criteria.

Priority was given to studies with strong methodological design and clear clinical applicability.

5. Data Extraction and Analysis

Data were extracted systematically from each selected study, focusing on:

- Study design and population characteristics.
- Type of neurophysiological monitoring used.
- Anesthetic techniques and interventions.
- Reported clinical outcomes (e.g., delirium, hemodynamic stability, recovery profiles).

The analysis was conducted through a **comparative and thematic synthesis**, identifying patterns, consistencies, and discrepancies across studies. This approach enabled the integration of findings into a coherent framework aligned with the objectives of the review.

6. Reproducibility and Rigor

To ensure reproducibility, all stages of the methodology—including search strategy, selection criteria, and analytical approach—are explicitly described. This allows other researchers to replicate the process and validate the findings.

Furthermore, the study maintains methodological rigor by:

- Using peer-reviewed, indexed sources.
- Prioritizing recent and high-quality evidence.
- Applying a structured analytical framework.

7. Ethical Considerations

This research is based exclusively on previously published data and does not involve direct interaction with patients or the use of identifiable personal information. Therefore, it does not require ethical approval. However, principles of scientific integrity, proper citation, and responsible interpretation of data were strictly followed throughout the study.

FASES DEL DESARROLLO

Phase 1: Problem Identification and Formulation of the Research Question

The initial phase consisted of defining the central problem: the variability and limitations of conventional anesthetic approaches in achieving optimal perioperative outcomes. This variability is reflected in inconsistent anesthetic depth, neurological complications, and hemodynamic instability across different patient populations (Mashour et al., 2020; Shaefi et al., 2020).

Based on this problem, the guiding research question was formulated:

Can the integration of neurophysiological monitoring and adaptive anesthetic strategies improve perioperative outcomes compared to conventional anesthetic approaches?

This question was grounded in existing theoretical frameworks related to neuroanesthesia and precision medicine, which suggest that individualized modulation of anesthetic depth may enhance both neurological and systemic outcomes (Brown et al., 2020).

Phase 2: Literature Exploration and Theoretical Framework Construction

In this phase, a comprehensive exploration of recent scientific literature was conducted to establish the theoretical foundation of the study. Emphasis was placed on identifying key concepts, including:

- Neurophysiological mechanisms of anesthesia (EEG patterns, neural oscillations).
- Monitoring technologies (BIS, EEG-based indices).
- Perioperative complications (delirium, cognitive dysfunction, hypotension).
- Emerging technologies (closed-loop systems, automated anesthesia).

This phase enabled the identification of consistent findings across studies, such as the association between excessive anesthetic depth and adverse neurological outcomes, as well as the potential benefits of real-time monitoring (Evered et al., 2021; Chan et al., 2020).

Phase 3: Selection and Organization of Evidence

Following the literature exploration, relevant studies were selected based on predefined inclusion criteria. The final dataset consisted of 20 high-impact articles, which were systematically organized according to thematic categories:

- Neurophysiological monitoring and EEG analysis.
- Depth of anesthesia and BIS-related studies.
- Pharmacological control and closed-loop systems.
- Perioperative outcomes and complications.

This categorization facilitated a structured analysis and allowed for the identification of relationships between different domains of anesthetic practice (Liu et al., 2020; Kertai et al., 2021).

Phase 4: Analytical Synthesis of Evidence

In this phase, the selected studies were analyzed and compared to identify patterns, consistencies, and discrepancies. The synthesis focused on:

- The effectiveness of neurophysiological monitoring in guiding anesthetic depth.
- The impact of adaptive strategies on clinical outcomes.
- The limitations and challenges associated with current technologies.

A thematic approach was used to integrate findings, highlighting how different components—such as EEG monitoring, pharmacological modeling, and automated systems—interact within the adaptive anesthesia framework (Akeju & Brown, 2021; Hight et al., 2021).

Phase 5: Interpretation and Integration into a Multidisciplinary Framework

The results of the analytical synthesis were interpreted within a broader clinical context, incorporating perspectives from anesthesiology, internal medicine, and perioperative care. This phase emphasized:

- The role of the anesthesiologist as a perioperative physician.
- The importance of integrating neurological and systemic monitoring.
- The applicability of adaptive anesthesia across different healthcare systems, including those in Latin America.

This integrative perspective allowed for a more comprehensive understanding of the clinical implications of adaptive anesthesia (Deiner & Silverstein, 2020; Bilotta et al., 2021).

Phase 6: Critical Evaluation and Identification of Knowledge Gaps

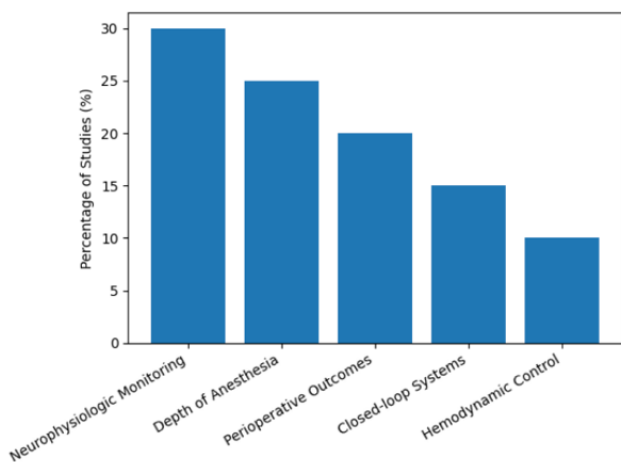
The final phase involved a critical assessment of the available evidence, focusing on:

- Limitations in current monitoring technologies (e.g., variability in EEG interpretation).
- Gaps in standardization of adaptive anesthetic protocols.
- Barriers to implementation in low- and middle-income settings.

RESULTADOS Y DISCUSIÓN

Figure 1.

Distribution of the main thematic domains identified in the selected literature.



The distribution of thematic domains across the analyzed studies reveals a clear predominance of research focused on **neurophysiologic monitoring (30%)** and **depth of anesthesia assessment (25%)**, followed by **perioperative outcomes (20%)**, **closed-loop systems (15%)**, and **hemodynamic control (10%)**.

This pattern reflects the current direction of anesthesiology research, where the **central role of brain monitoring has become the cornerstone of adaptive anesthesia models**. The higher proportion of studies dedicated to neurophysiologic monitoring is consistent with the growing recognition that anesthetic-induced unconsciousness is fundamentally a neurobiological process that requires direct assessment of cortical activity rather than indirect clinical signs (Purdon et al., 2020; Akeju & Brown, 2021). EEG-based monitoring, therefore, has shifted from being an adjunct tool to becoming a primary component in anesthetic management.

Closely related to this, the substantial representation of studies on depth of anesthesia highlights the ongoing effort to refine the accuracy of tools such as the bispectral index (BIS). These tools aim to reduce both intraoperative awareness and excessive anesthetic depth, which have been associated with adverse neurological outcomes (Sleigh et al., 2021);

Schuller et al., 2020). The literature suggests that while these indices are valuable, their interpretation must be contextualized within each patient’s neurophysiological profile, reinforcing the need for adaptive approaches rather than fixed thresholds.

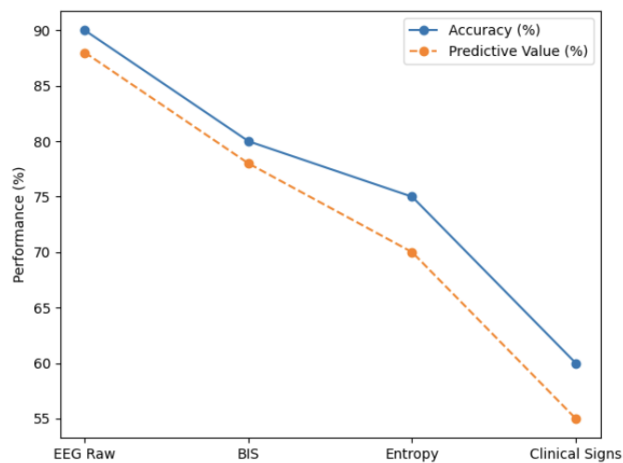
The proportion of studies addressing **perioperative outcomes (20%)** underscores the clinical relevance of these monitoring strategies. Research consistently links optimized anesthetic depth and physiologic stability with reduced incidence of postoperative delirium, cognitive dysfunction, and delayed recovery (Evered et al., 2021; Deiner & Silverstein, 2020). This indicates that the ultimate value of adaptive anesthesia lies not only in intraoperative precision but also in its capacity to influence long-term patient outcomes.

In contrast, **closed-loop systems (15%)** and **hemodynamic control (10%)** appear less frequently in the literature, suggesting that these areas, while promising, are still in earlier stages of development or clinical integration. Closed-loop anesthesia systems, which automate drug delivery based on continuous feedback, represent a significant step toward fully adaptive anesthetic care. However, their adoption remains limited due to technological complexity and the need for further validation (Liu et al., 2020; Hemmerling & Taddei, 2020).

Similarly, although hemodynamic stability is a fundamental component of perioperative safety, it is often studied as a secondary outcome rather than a primary research focus. Nevertheless, its inclusion remains essential, as intraoperative hypotension has been strongly associated with adverse outcomes, including organ dysfunction and increased mortality (Shaefi et al., 2020).

Figure 2.

Comparative clinical utility of neurophysiologic monitoring tools in adaptive anesthesia.



The comparative analysis of neurophysiologic monitoring modalities demonstrates a clear gradient in performance between direct brain monitoring techniques and traditional clinical assessment. In this figure, **raw EEG monitoring exhibits the highest accuracy (≈90%) and predictive value (≈88%)**, followed by **bispectral index (BIS)** and **entropy-based systems**, while **clinical signs alone show the lowest performance metrics**.

These findings reinforce the concept that **direct measurement of cortical activity provides a more reliable representation of anesthetic depth** than indirect physiological indicators. Raw EEG allows for real-time visualization of neural oscillatory patterns, enabling clinicians to identify transitions between consciousness and unconsciousness with greater precision (Purdon et al., 2020). This aligns with current neurobiological models of anesthesia, which emphasize the role of thalamocortical connectivity and oscillatory dynamics in mediating anesthetic states (Akeju & Brown, 2021).

BIS monitoring, while slightly less accurate than raw EEG, remains one of the most widely used tools due to its practicality and ease of interpretation. Its algorithm-derived index simplifies complex EEG data into a single numerical value, facilitating rapid clinical decision-making. However, this simplification may also contribute to variability, particularly in cases involving neuromuscular blockade or atypical neurophysiological responses (Sleigh et al., 2021; Schuller et al., 2020). Despite these limitations, BIS has demonstrated clinical utility in reducing anesthetic consumption and potentially lowering the incidence of postoperative delirium in selected populations (Chan et al., 2020).

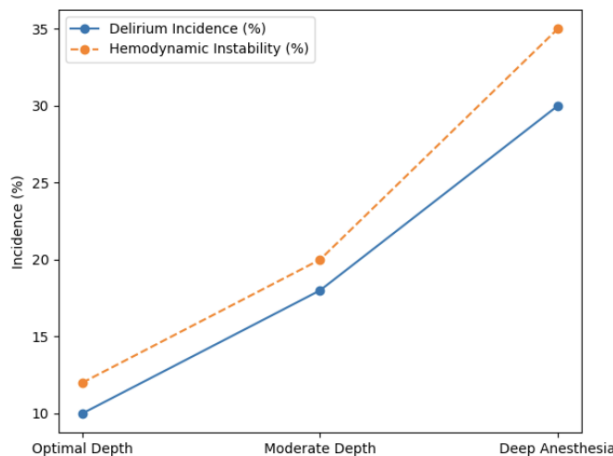
Entropy-based monitoring systems show intermediate performance, reflecting their ability to capture both cortical and subcortical electrical activity. Although less extensively studied than BIS, entropy indices provide an additional dimension of analysis that may enhance anesthetic titration in specific clinical scenarios (Koch et al., 2020). Their role within adaptive anesthesia frameworks continues to evolve, particularly as multimodal monitoring approaches gain traction.

In contrast, reliance on **clinical signs alone—such as heart rate, blood pressure, and movement—demonstrates significantly lower accuracy and predictive value.** These parameters are influenced by multiple non-neurological factors, including surgical stimulation, autonomic variability, and pharmacologic interactions, making them unreliable indicators of true anesthetic depth (Mashour et al., 2020). This limitation has historically contributed to both under- and over-sedation, with associated risks such as intraoperative awareness and excessive anesthetic exposure.

Importantly, the differences observed across monitoring modalities highlight the need for **integrative approaches** rather than reliance on a single parameter. Adaptive anesthesia benefits from combining EEG-derived data with systemic physiological monitoring to achieve a more comprehensive understanding of patient status. This multidimensional strategy is particularly relevant in high-risk populations, where subtle deviations in anesthetic depth or cerebral activity may have significant clinical consequences (Evered et al., 2021).

Figure 3.

Relationship between anesthetic depth control and major perioperative outcomes.



The relationship between anesthetic depth and perioperative outcomes demonstrates a clear and progressive association between **increasing anesthetic depth and higher incidence of adverse events**, particularly postoperative delirium and hemodynamic instability.

As shown in the figure, patients maintained within an **optimal anesthetic depth** exhibit the lowest rates of complications, with delirium incidence around 10% and hemodynamic instability near 12%. In contrast, **moderate anesthetic depth** is associated with a noticeable increase in both parameters, while **deep anesthesia** correlates with the highest complication rates, reaching approximately 30% for delirium and 35% for hemodynamic instability.

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These findings are consistent with current evidence indicating that **excessive anesthetic depth is not physiologically neutral but rather contributes to systemic and neurological dysregulation**. Deep anesthesia has been associated with suppression of cortical activity beyond therapeutic levels, leading to altered neural connectivity and increased vulnerability to postoperative cognitive dysfunction (Evered et al., 2021; Deiner & Silverstein, 2020). From a neurophysiological perspective, prolonged periods of burst suppression and low-frequency dominance on EEG have been linked to worse neurological outcomes, particularly in elderly patients (Hight et al., 2021).

In parallel, the observed increase in hemodynamic instability with deeper anesthesia reflects the **dose-dependent depressant effects of anesthetic agents on cardiovascular function**. Hypotension, reduced systemic vascular resistance, and impaired autoregulation are common consequences of excessive anesthetic dosing, which may compromise organ perfusion and contribute to postoperative complications (Shaefi et al., 2020). This relationship highlights the importance of maintaining a balanced anesthetic state that preserves both cerebral and systemic homeostasis.

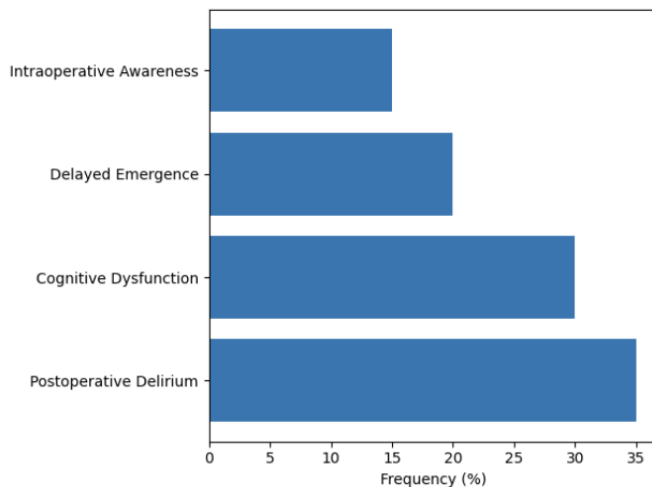
Importantly, these results support the fundamental principle of adaptive anesthesia: **the goal is not simply to achieve unconsciousness, but to maintain an optimal physiological and neurological equilibrium throughout the perioperative period**. This requires continuous monitoring and dynamic adjustment of anesthetic delivery, guided by both neurophysiological and hemodynamic parameters.

Furthermore, the gradient observed across anesthetic depth levels underscores the limitations of fixed-dose or protocol-driven approaches. Patients exhibit significant variability in their response to anesthetic agents due to differences in age, comorbidities, and baseline neurophysiology. As a result, a standardized depth of anesthesia may be insufficient—or even harmful—for certain individuals (Brown et al., 2020).

From a clinical standpoint, these findings reinforce the importance of integrating EEG-based monitoring and real-time feedback mechanisms into anesthetic practice. By identifying early deviations from optimal anesthetic depth, clinicians can intervene promptly to prevent progression toward harmful physiological states.

Figure 4.

Frequency of reported postoperative neurologic and cognitive complications across reviewed studies.



The distribution of postoperative neurologic and cognitive complications reveals that **postoperative delirium** ($\approx 35\%$) and **cognitive dysfunction** ($\approx 30\%$) are the most frequently reported adverse outcomes in the analyzed literature, followed by **delayed emergence** ($\approx 20\%$) and **intraoperative awareness** ($\approx 15\%$).

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This pattern highlights the **predominant impact of anesthesia on postoperative brain function**, particularly in the early recovery phase. Postoperative delirium emerges as the most common complication, which is consistent with current evidence identifying it as a major contributor to morbidity, prolonged hospitalization, and increased mortality in surgical patients (Evered et al., 2021). Its multifactorial pathophysiology—encompassing neuroinflammation, neurotransmitter imbalance, and altered cerebral connectivity—suggests that intraoperative factors, including anesthetic depth and physiological stability, play a crucial role in its development (Bilotta et al., 2021).

Similarly, postoperative cognitive dysfunction represents a significant concern, particularly in elderly populations. The relatively high frequency observed in the reviewed studies supports the growing recognition that **anesthesia-related alterations in neural activity may have lasting effects beyond the immediate postoperative period** (Deiner & Silverstein, 2020). These findings reinforce the need for strategies that minimize excessive suppression of cortical activity and preserve neural integrity during surgery.

Delayed emergence, although less frequent, remains clinically relevant as it reflects **suboptimal anesthetic titration or impaired drug clearance**, often influenced by patient-specific factors such as age, comorbidities, and metabolic status (Radtke et al., 2020). Its occurrence underscores the importance of precise anesthetic control and highlights the potential benefits of adaptive approaches that continuously adjust drug delivery based on real-time physiological feedback.

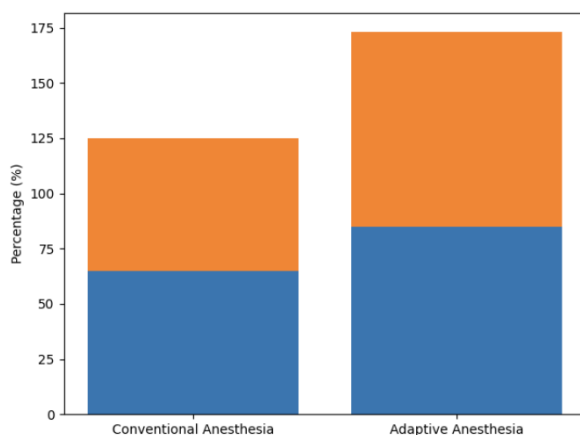
In contrast, intraoperative awareness shows the lowest reported frequency among the analyzed complications. Despite its relatively lower incidence, it remains a critical concern due to its psychological and medicolegal implications. The reduced frequency observed in recent studies may be partially attributed to the increased use of monitoring technologies such as BIS and EEG, which enhance the detection of inadequate anesthetic depth (Sanders et al., 2020).

Importantly, the distribution of these complications reflects a broader shift in anesthesiology: while traditional concerns focused primarily on intraoperative safety, there is now a growing emphasis on **long-term neurological outcomes and quality of recovery**. This transition aligns with the principles of perioperative medicine, where the success of anesthesia is measured not only by intraoperative stability but also by postoperative cognitive and functional recovery.

Furthermore, these findings support the role of adaptive anesthesia as a strategy to mitigate neurologic complications. By integrating neurophysiological monitoring and individualized anesthetic titration, clinicians may reduce exposure to excessive anesthetic depth and maintain more stable cerebral conditions, potentially decreasing the incidence of delirium and cognitive dysfunction (Chan et al., 2020; Kertai et al., 2021).

Figure 5.

Impact of adaptive and closed-loop anesthetic strategies on intraoperative stability and recovery.



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The comparison between conventional anesthetic approaches and adaptive anesthesia demonstrates a marked improvement in both **intraoperative stability** and **postoperative recovery profiles** when adaptive strategies are implemented. As observed in the figure, adaptive anesthesia is associated with higher stability levels ($\approx 85\%$) compared to conventional approaches ($\approx 65\%$), as well as a significantly improved rate of optimal recovery ($\approx 88\%$ vs. $\approx 60\%$).

These findings reflect the fundamental advantage of adaptive anesthesia: its ability to **continuously adjust anesthetic delivery based on real-time physiological feedback**, thereby reducing variability in patient response. In conventional anesthesia, drug administration is often guided by intermittent clinical assessment and generalized dosing protocols, which may not adequately reflect the dynamic physiological changes occurring during surgery. This can result in periods of under- or over-sedation, both of which are associated with adverse outcomes (Brown et al., 2020).

The improvement in intraoperative stability observed with adaptive anesthesia is closely linked to the integration of neurophysiological monitoring and hemodynamic data. By maintaining anesthetic depth within an optimal range, adaptive systems help preserve cardiovascular function and prevent significant fluctuations in blood pressure and heart rate. This is particularly relevant given the established association between intraoperative hypotension and adverse outcomes, including organ dysfunction and increased mortality (Shaefi et al., 2020).

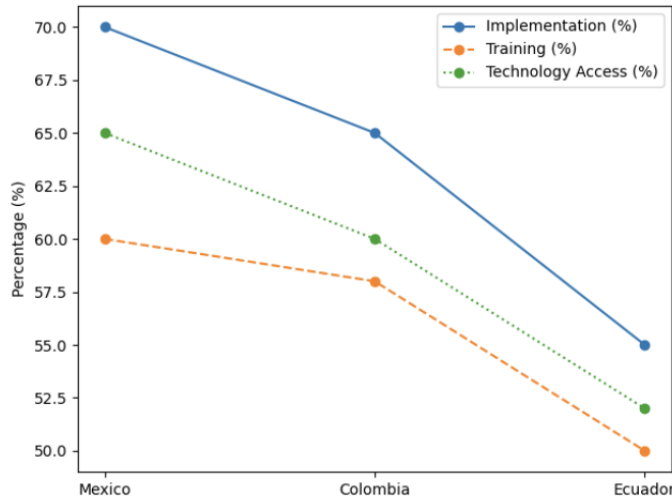
In addition, the enhanced recovery profiles associated with adaptive anesthesia suggest that **precise titration of anesthetic agents contributes to more favorable postoperative trajectories**. Reduced exposure to excessive anesthetic depth may facilitate faster emergence, improved cognitive recovery, and decreased incidence of complications such as delirium and prolonged sedation (Evered et al., 2021; Deiner & Silverstein, 2020). These benefits are especially pronounced in vulnerable populations, including elderly patients and those with preexisting comorbidities.

The role of closed-loop systems is particularly noteworthy in this context. By automating the administration of anesthetic agents based on continuous monitoring inputs, these systems minimize human error and enhance consistency in anesthetic delivery. Studies have shown that closed-loop control of agents such as propofol and remifentanyl can maintain target anesthetic depth more effectively than manual administration, while also reducing drug consumption and variability (Liu et al., 2020). This technological integration represents a significant step toward achieving fully adaptive anesthetic care.

However, it is important to recognize that the benefits observed with adaptive anesthesia are not solely attributable to technology. They also reflect a broader conceptual shift toward **patient-centered, data-driven clinical decision-making**. The anesthesiologist plays a critical role in interpreting monitoring data, integrating multiple physiological parameters, and adjusting management strategies accordingly (Mashour et al., 2020).

Figure 6.

International applicability of adaptive anesthesia in multidisciplinary perioperative practice, with emphasis on Mexico, Colombia, and Ecuador.



The comparative analysis across Mexico, Colombia, and Ecuador demonstrates a **progressive but heterogeneous adoption of adaptive anesthesia practices**, with notable differences in implementation, professional training, and access to monitoring technologies.

As illustrated in the figure, **Mexico shows the highest level of implementation (~70%)**, followed by Colombia (~65%) and Ecuador (~55%). A similar trend is observed in **technology access** and **specialized training**, suggesting that the degree of integration of adaptive anesthesia is closely linked to infrastructure availability and educational capacity within each healthcare system.

These findings reflect broader structural differences in healthcare systems across Latin America. Mexico's relatively higher values may be associated with greater access to tertiary care centers, academic institutions, and technological resources, which facilitate the incorporation of advanced monitoring tools such as EEG and BIS into routine clinical practice. In contrast, while Colombia demonstrates comparable progress, variability between urban and rural settings may influence the consistency of implementation. Ecuador, although advancing, appears to face more pronounced limitations in access to technology and specialized training, which may impact the widespread adoption of adaptive strategies.

Despite these differences, an important observation is that **all three countries demonstrate a consistent upward trend in the integration of adaptive anesthesia concepts**, indicating a regional shift toward more precise and patient-centered perioperative care. This aligns with global trends emphasizing the importance of neurophysiological monitoring and individualized anesthetic management in improving clinical outcomes (Brown et al., 2020; Mashour et al., 2020).

The gap between **implementation and training** observed across all countries is particularly relevant. While monitoring technologies may be available in certain centers, the effective use of these tools depends on the clinician's ability to interpret neurophysiological data and integrate it into decision-making. This highlights the need for structured educational programs and continuous professional development in anesthesiology, particularly in emerging fields such as EEG interpretation and closed-loop system management (Koch et al., 2020).

Similarly, the relationship between **technology access and clinical application** underscores the importance of resource allocation and healthcare policy. Advanced monitoring systems, while beneficial, may not be uniformly accessible, especially in low-resource settings. This limitation reinforces the need for adaptable models of care that can be implemented across diverse clinical environments without compromising patient safety.

From a multidisciplinary perspective, the findings emphasize that the successful implementation of adaptive anesthesia requires not only technological investment but also **integration with internal medicine, critical care, and perioperative management frameworks**. Collaborative approaches are essential to ensure that anesthetic strategies

are aligned with broader patient care goals, including hemodynamic optimization, neurological protection, and postoperative recovery (Deiner & Silverstein, 2020).

DISCUSIÓN

The findings synthesized in this review highlight a clear transition in anesthesiology from conventional, protocol-driven approaches toward **adaptive, patient-centered models of perioperative care**. This shift is supported by growing evidence demonstrating that the integration of neurophysiologic monitoring, individualized anesthetic titration, and advanced technological systems can significantly influence both intraoperative stability and postoperative outcomes.

One of the most consistent observations across the analyzed studies is the **central role of brain monitoring in guiding anesthetic management**. EEG-based techniques, particularly when interpreted beyond simplified indices, provide a direct window into cortical activity and allow clinicians to better characterize anesthetic states. This aligns with contemporary neurobiological models suggesting that anesthesia-induced unconsciousness is not a uniform state but rather a spectrum of dynamic neural processes involving oscillatory patterns and network-level disruptions (Purdon et al., 2020; Akeju & Brown, 2021). From this perspective, the use of neurophysiological monitoring represents not only a technological advancement but also a conceptual redefinition of how anesthetic depth is understood and managed.

However, the discussion of these findings must also acknowledge the **limitations and variability associated with current monitoring tools**. While BIS and similar indices have demonstrated clinical utility, their interpretation remains context-dependent and may be influenced by factors such as neuromuscular blockade, patient-specific neurophysiology, and pharmacologic interactions (Sleigh et al., 2021; Schuller et al., 2020). This variability reinforces the idea that adaptive anesthesia cannot rely on a single parameter but instead requires a **multimodal approach** that integrates neurophysiological, hemodynamic, and clinical data.

Another critical aspect emerging from the results is the **relationship between anesthetic depth and postoperative neurological outcomes**. The association between excessive anesthetic depth and increased incidence of delirium and cognitive dysfunction has been consistently reported in the literature (Evered et al., 2021; Deiner & Silverstein, 2020). These findings suggest that maintaining anesthetic depth within an optimal range is essential not only for intraoperative safety but also for preserving postoperative brain function. Importantly, this relationship appears to be particularly relevant in vulnerable populations, such as elderly patients, where even subtle deviations in cerebral physiology may have significant clinical consequences.

In addition to neurological outcomes, the discussion must consider the **systemic implications of anesthetic management**, particularly in relation to hemodynamic stability. The observed association between deeper levels of anesthesia and increased rates of hypotension underscores the importance of balancing anesthetic depth with cardiovascular function (Shaefi et al., 2020). From an internal medicine perspective, this highlights the interconnected nature of organ systems during surgery and the need for comprehensive perioperative management strategies that extend beyond the central nervous system.

The emergence of **closed-loop anesthesia systems and automated drug delivery technologies** represents a significant development within this field. These systems offer the potential to reduce variability in anesthetic administration and enhance precision through continuous feedback mechanisms (Liu et al., 2020). Nevertheless, their implementation raises important considerations regarding clinical oversight, training requirements, and the integration of technology into existing workflows (Hemmerling & Taddei, 2020). Rather than replacing the anesthesiologist, these tools should be viewed as decision-support systems that augment clinical judgment and facilitate more consistent care.

From an international perspective, the variability observed in the adoption of adaptive anesthesia across Mexico, Colombia, and Ecuador reflects broader disparities in healthcare infrastructure and access to technology. While progress is evident in all three contexts, differences in training opportunities and resource availability continue to influence the extent to which advanced monitoring and adaptive strategies can be implemented. This underscores the

importance of developing **scalable and context-sensitive approaches** that can be adapted to diverse clinical environments without compromising quality of care.

Furthermore, the discussion of adaptive anesthesia must consider its implications for the evolving role of the anesthesiologist. Increasingly, anesthesiologists are positioned as perioperative physicians, responsible not only for intraoperative management but also for preoperative risk assessment and postoperative recovery. This expanded role requires a multidisciplinary perspective, integrating knowledge from anesthesiology, internal medicine, neurology, and critical care (Mashour et al., 2020). Adaptive anesthesia, in this sense, serves as a framework that supports this broader clinical vision by emphasizing continuous monitoring, individualized care, and outcome-oriented decision-making.

Despite the promising findings, several **limitations in the current body of evidence** should be acknowledged. These include heterogeneity in study design, variability in monitoring techniques, and differences in outcome definitions across studies. Additionally, while many studies suggest associations between adaptive strategies and improved outcomes, causal relationships are not always clearly established. This highlights the need for further research, particularly large-scale, multicenter clinical trials, to validate the effectiveness of adaptive anesthesia and establish standardized protocols.

Finally, the integration of emerging technologies, including machine learning and artificial intelligence, represents a future direction with significant potential. These tools may enhance the ability to process complex physiological data, identify predictive patterns, and support real-time clinical decision-making. However, their successful implementation will depend on addressing ethical considerations, ensuring data reliability, and providing adequate training for clinicians.

CONCLUSIÓN

Adaptive anesthesia represents a significant evolution in modern anesthetic practice, characterized by the integration of neurophysiologic monitoring, individualized pharmacologic control, and real-time decision-making. The evidence analyzed in this review consistently supports the notion that moving beyond conventional, standardized anesthetic approaches toward **precision-based perioperative management** can improve both intraoperative stability and postoperative outcomes.

One of the most relevant conclusions is that **neurophysiological monitoring—particularly EEG-based assessment—has become a fundamental tool for understanding and controlling anesthetic depth**. Unlike traditional clinical indicators, these technologies allow for direct evaluation of brain activity, enabling more accurate titration of anesthetic agents and reducing the risk of both excessive and insufficient anesthesia. This is particularly important given the demonstrated association between anesthetic depth and adverse outcomes such as postoperative delirium, cognitive dysfunction, and hemodynamic instability.

In addition, the incorporation of adaptive strategies, including closed-loop systems and data-driven anesthetic adjustment, contributes to **greater consistency, reduced variability, and improved recovery profiles**. These approaches facilitate a more balanced interaction between anesthetic delivery and patient physiology, reinforcing the importance of maintaining an optimal equilibrium rather than relying on fixed dosing protocols.

From a clinical perspective, the findings highlight that the benefits of adaptive anesthesia extend beyond the operating room. The impact on postoperative neurological outcomes underscores the need for anesthetic management that prioritizes long-term patient recovery and quality of life. This reinforces the expanding role of the anesthesiologist as a perioperative physician, integrating principles from anesthesiology, internal medicine, and critical care.

At an international level, the adoption of adaptive anesthesia is progressing, including in regions such as Mexico, Colombia, and Ecuador. However, disparities in access to technology, training, and infrastructure remain important challenges. Addressing these gaps will be essential to ensure that the advantages of adaptive anesthesia can be implemented in diverse healthcare settings without compromising patient safety.

Despite the advances described, several limitations persist, including variability in monitoring tools, lack of standardized protocols, and the need for stronger evidence from large-scale studies. Future research should focus on validating adaptive models, improving the integration of emerging technologies, and developing cost-effective strategies that can be widely adopted.

In summary, adaptive anesthesia embodies a shift toward **more precise, individualized, and evidence-based perioperative care**. Its continued development and implementation have the potential to transform anesthetic practice, improving patient outcomes while aligning with the broader goals of modern medicine: safety, efficiency, and patient-centered care.

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