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A CRITICAL ANALYSIS OF CLOSED-LOOP ANESTHESIA DELIVERY SYSTEM FOR THE OPTIMIZATION OF ADMINISTRATION OF ANESTHETICS AGENTS

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Abstract:

Closed-loop anesthesia delivery systems (CLADS) represent a significant advancement in anesthetic practice, offering automated, feedback-driven control of anesthetic agent administration to enhance patient safety and clinical efficiency. This critical analysis examined the operational principles, advantages, and limitations of CLADS in optimizing anesthesia delivery. The review highlighted how CLADS integrate real-time physiological monitoring—such as bispectral index (BIS), hemodynamic parameters, and end-tidal anesthetic concentrations—with algorithm-based controllers to maintain precise, individualized anesthetic depth. However, challenges such as system calibration errors, hardware variability, the need for clinician oversight, and limited adaptability in rapidly changing clinical conditions remain notable concerns. Further technological improvements, robust clinical validation, and clinician training are essential to maximize their reliability and integration into modern anesthetic practice. The study concluded that closed Loop Anesthesia Delivery Systems significantly enhance precision, safety, and consistency in administering anesthesia agents. By integrating real-time physiological feedback with automated drug control, these systems minimize human error and improve patient outcomes. One of the recommendations made was that hospitals and manufacturers should prioritize rigorous testing and validation of CLADS to ensure consistent performance across diverse patient populations, minimizing risks of under- or over-dosage.

Keywords: Closed Loop Anesthesia Delivery System, Optimization, Administration, Anesthesia Agents.

Introduction

Introduction

The administration of anesthesia has evolved significantly over the past decades, progressing from manually controlled delivery to highly sophisticated automated systems designed to enhance patient safety and improve clinical outcomes. In contemporary perioperative care, Closed Loop Anesthesia

Delivery Systems (CLADS) represent one of the most advanced innovations for optimizing the administration of anesthesia agents. These systems integrate real-time physiological monitoring with automated drug delivery, thereby reducing human error and ensuring more precise control of anesthetic depth. As surgical procedures become increasingly complex and patient populations more diverse, the demand for technologies that enhance precision, consistency, and responsiveness in anesthesia care has intensified (Absalom & Struys, 2018).

A closed-loop system functions through continuous feedback mechanisms. It automatically adjusts the anesthetic dosage by comparing actual patient responses with a predefined target, such as depth of anesthesia, muscle relaxation, or analgesia level. This dynamic responsiveness is made possible through advanced sensors, pharmacokinetic-pharmacodynamic models, and intelligent algorithms capable of interpreting physiological data. These systems help anesthesia providers maintain an optimal balance between adequate sedation and physiological stability, significantly reducing the risks of under- or over-dosage (Hemmerling & Terrasini, 2019). Given that manual adjustments often require rapid decision-making under pressure, CLADS offers a consistent and objective means of maintaining ideal anesthetic states, even in rapidly changing surgical environments.

One of the most compelling advantages of CLADS is its potential to enhance patient safety. Traditional anesthesia delivery relies heavily on the anesthesia provider's experience, vigilance, and manual titration, which may vary depending on workload or situational stressors. Closed-loop systems, however, function without fatigue and maintain continuous vigilance, allowing for highly stable anesthetic levels. Studies indicate that these systems can decrease anesthetic drug consumption, reduce recovery times, and minimize intraoperative complications due to fluctuations in anesthetic depth (Liu et al., 2020). Moreover, the precision of automated systems contributes to smoother emergence from anesthesia, reducing postoperative cognitive dysfunction and adverse drug reactions.

Additionally, CLADS has the potential to reshape clinical workflows and resource allocation within the perioperative environment. By automating routine tasks, these systems allow anesthesiologists to focus on higher-level decision-making, complication management, and multidisciplinary coordination. This efficiency is particularly valuable in high-volume surgical centers, intensive care units, and resource-constrained environments. Furthermore, closed-loop systems demonstrate strong compatibility with artificial intelligence and machine learning technologies, opening doors to fully autonomous anesthesia delivery enhancements in the near future (Stegemann., 2021).

Despite these advantages, the adoption of CLADS is not without challenges. Issues such as system reliability, interoperability with existing monitoring equipment, potential algorithmic biases, and concerns regarding clinician acceptance remain areas requiring critical evaluation. A thorough analysis is needed to assess whether these systems can consistently meet the demands of diverse patient populations, including pediatrics, geriatrics, and individuals with complex comorbidities. Thus, a critical analysis of Closed Loop Anesthesia Delivery Systems is essential to understanding their capabilities, limitations, and prospects for optimizing the administration of anesthesia agents in modern clinical practice.

Concept of Anesthesia

Anesthesia is commonly defined as a medically induced and reversible state that eliminates pain and awareness during surgical or diagnostic procedures. According to D'Souza (2022), anesthesia is designed to produce analgesia, amnesia, immobility, and unconsciousness, depending on the type and purpose of the procedure. Anesthesia is more than the induction of sleep it is a controlled clinical state that shields patients from nociceptive stimuli while maintaining essential physiological functions.

Fig.1: Picture of Anesthesia

Another definition highlights anesthesia as a multidimensional physiological process. Fiszer (2024) describes anesthesia as a combination of distinct but interdependent components, including hypnosis, analgesia, and muscle relaxation, each mediated by different neural pathways. He states that anesthetic agents achieve their effects by enhancing inhibitory neurotransmitters such as GABA and reducing excitatory signaling, resulting in a controlled loss of sensation and consciousness. This expanded perspective reflects the complex neurobiological mechanisms underlying modern anesthetic practice.

In addition, anesthesia is defined as a comprehensive, patient-centered medical practice that extends across the entire perioperative period. Nemeth, Jones, & Funcke, (2024) explained that anesthesia involves more than drug administration; it includes preoperative optimization, intraoperative physiologic protection, and postoperative recovery support. They emphasize that contemporary anesthesia aims to improve patient outcomes by preserving organ function, minimizing stress responses, and ensuring a smooth recovery process. Their definition underscores the holistic and safety-oriented nature of anesthesia in modern healthcare.

Furthermore, anesthesia is increasingly defined through its integration with modern technology. Oberhauser, Lüders, & Rosenblatt (2024) state that anesthesia represents a technologically supported medical state in which artificial intelligence, automated drug delivery, and advanced monitoring systems are used to maintain stable physiological conditions. They note that these innovations allow anesthesiologists to deliver precise, individualized care while reducing risk and enhancing surgical efficiency. This definition captures the evolving technological dimension of anesthesia in the 21st century.

Concept of Closed-loop Anesthesia Delivery System

One of the most important technological developments in contemporary anaesthetic practice is the idea of a Closed-Loop Anaesthesia Delivery System (CLADS), which combines automated medication administration with real-time physiologic monitoring to maintain the ideal anaesthetic depth during surgical procedures. According to Wingert. (2021), closed-loop systems utilize continuous patient feedback signals—such as processed electroencephalogram (EEG) indices, bispectral index (BIS), hemodynamic parameters, and nociception monitors—to automatically adjust anaesthetic dosing without requiring constant manual input. This concept is grounded in control engineering, where drug delivery is dynamically modulated based on the deviation between the patient's current state and a preset anaesthetic target, a process that significantly minimizes fluctuations in anaesthesia depth (Bajwa, 2023). Automated closed-loop platforms can guarantee more consistent patient stability and fewer intraoperative problems because human manual titration frequently experiences variability and delayed response.

The monitoring device, a control algorithm, and the infusion mechanism that delivers the anaesthetic agent are the three main parts of closed-loop anaesthesia administration systems. Hua et al. (2024) explained that the monitoring device provides real-time patient data, particularly EEG-derived indices like BIS, which are highly correlated with hypnotic depth during propofol-based anaesthesia. These signals feed into sophisticated algorithms—such as proportional-integral-derivative (PID), adaptive controllers, and model-predictive control (MPC)—that compute the ideal infusion rates in milliseconds, thus improving precision far beyond what human operators can achieve (Nagata, 2023).

These instructions are then carried out by the actuator or infusion pump, which delivers the precise dosage required to keep the patient within the intended anaesthetic window. The "closed-loop" idea is defined by this ongoing cycle of sensing, analysis, and dosage, which guarantees extremely reliable anaesthesia control.

Closed-loop systems greatly improve the precision and stability of anaesthetic administration across a range of patient demographics, according to recent studies. Schiavo. (2025) found that BIS-guided closed-loop propofol delivery maintained patients within their target anaesthetic range for a notably greater percentage of surgical time compared with manual anesthesiologist-controlled infusions. Similarly, Hua. (2024) demonstrated improved maintenance of hypnosis in paediatric patients, showing that closed-loop systems not only minimized human error but also reduced the frequency of over sedation and under sedation events. These clinical outcomes demonstrate how the system's automatic corrections prevent wide oscillations of anaesthetic depth, leading to better intraoperative stability and potentially smoother postoperative recovery.

Additionally, closed-loop anaesthesia systems provide special benefits by lessening the strain on anesthesiologists, freeing them up to concentrate on making crucial decisions and handling crises rather than constantly modifying medication dosages. Bajwa. (2023) noted that the system improves workflow efficiency and decreases cognitive load, especially during long or complex procedures. This improves patient safety by guaranteeing tighter anaesthetic control because the system responds rapidly to physiological changes, something that human operators can't always accomplish. Additionally, studies suggest that closed-loop systems may reduce overall drug consumption since the algorithm only administers what is pharmacologically necessary to maintain the targeted level of hypnosis (Wingert, 2021).

Despite the benefits, the implementation of closed-loop anaesthesia systems still faces several limitations. Wingert (2021) reported that sensor reliability remains one of the main challenges, as EEG artefacts, poor electrode placement, or electromagnetic interference can produce inaccurate readings that disrupt the control algorithm. Likewise, patient-specific variability in pharmacokinetics and pharmacodynamics—such as age, organ function, comorbidities, or concurrent medications can limit the predictive accuracy of the control models (Nagata, 2023). Researchers are therefore developing adaptive algorithms and machine-learning-based systems capable of adjusting dose predictions based on individual patient reactions, which may significantly enhance future CLADS performance (Schiavo, 2025).

In conclusion, the idea of a closed-loop anaesthesia delivery system represents a revolutionary change from experience-based, manual anaesthetic titration to automated, precision-driven control. Real-time physiological monitoring, algorithm-guided dose, and quick feedback correction form its basis, allowing for more stable anaesthesia management, less effort for physicians, and maybe improved postoperative results. As highlighted by Hua. (2024), ongoing advancements in monitoring technology and artificial-intelligence-driven control models will continue to refine the reliability and adaptability of these systems. Closed-loop anaesthesia is positioned to become a crucial part of future anaesthetic care, enhancing both safety and effectiveness in a variety of surgical scenarios, thanks to ongoing advancements and wider clinical validation.

Concept of Anesthetic Agents

Anaesthetic agents are drugs used to produce a controlled, reversible loss of sensation or consciousness during medical procedures. Their primary purpose is to prevent pain, anxiety, and awareness while ensuring patient safety and comfort. Anaesthetic agents act on the central nervous system (CNS) to depress neural activity, allowing clinicians to perform diagnostic or surgical procedures without causing physical or psychological distress to the patient (Hall, 2021).

Anaesthetic agents can be broadly grouped into **general anaesthetics**, which induce unconsciousness, and **local/regional anaesthetics**, which block sensation in specific parts of the body without affecting consciousness.

General anaesthetic agents such as sevoflurane, propofol, and isoflurane work by modulating neurotransmitter receptors like GABA and NMDA to reduce CNS excitability (Brown et al., 2018). Local agents, including lidocaine and bupivacaine, block sodium channels in nerve membranes, preventing the transmission of pain signals (Becker 2017).

A key concept in understanding anaesthetic agents is the balance between **depth of anaesthesia, analgesia, muscle relaxation**, and **autonomic stability**. Modern anaesthesia practice uses combinations of agents known as balanced anaesthesia to achieve these effects safely and efficiently. AI-supported monitoring technologies now assist clinicians in maintaining optimal depth and minimizing complications (Lopez, 2020).

Safety is an essential part of the concept of anaesthetic agents. Although modern anaesthetics are highly refined, their use requires careful monitoring to avoid complications such as hypotension, respiratory depression, or allergic reactions. Advances in medical technology including computerized infusion pumps and real-time physiological monitors have significantly improved the safety profile of anaesthetic administration (Feng, 2022).

Anaesthetic agents are foundational to modern medicine because they enable pain-free and stress-free medical procedures. Understanding how they act, how they are selected, and how they are monitored helps ensure safe and effective patient care across surgical and clinical environments (Hall et al., 2021).

Concept of Administration of Anesthetics Agents

The administration of anaesthetic agents is a core component of modern medical and surgical practice, ensuring that patients undergo procedures safely, comfortably, and without pain. It involves the carefully controlled use of pharmacological substances that produce a reversible loss of sensation, awareness, or consciousness. According to Miller (2019), administration of an anaesthetic agent is a controlled delivery of drugs aimed at depressing sensation or consciousness, guided by precise dosing and continuous physiological monitoring." This description highlights that anaesthesia is a controlled, scientific process involving expertise, ability, and continuous evaluation rather than just the injection or inhalation of medications.

Morgan and Mikhail (2020) describe anaesthetic administration as a systematic process of selecting, preparing, and administering anaesthetic drugs after proper evaluation, while maintaining airway patency, ventilation, and cardiovascular stability throughout the procedure. Their definition emphasises the necessity of planning, choosing the right medications, and maintaining essential functions—all of which are essential for the safe administration of anaesthesia. Barash (2017) explains that anaesthetic administration is the application of pharmacologic agents via appropriate routes to induce anaesthesia, guided by assessment, intraoperative monitoring, and post-anaesthetic care aimed at minimizing risks and improving patient outcomes. According to this definition, anaesthesia continues throughout intraoperative care and postoperative recuperation, during which the anesthetist must continue to monitor and care for the patient.

In order to attain the appropriate degrees of analgesia, muscle relaxation, or unconsciousness, the notion also entails precise medication calculation and dosage optimization. Stoelting (2015) defines anaesthetic administration as "the delivery of anaesthetic medications in calculated doses to achieve specific effects, while adjusting for individual patient variability and drug interactions and ensuring safety." This viewpoint emphasizes personalized treatment, acknowledging that patients react differently to anaesthetic medications because of things like age, weight, comorbidities, and prior exposure. In conclusion, the administration of anaesthetic agents is a thorough, dynamic, and patient-centred process that includes evaluation, medication selection, accurate dosage, ongoing care, and continuous monitoring. It calls for a combination of clinical expertise, scientific understanding, and close observation.

Types of Anesthetic Agents

General (Systemic) Anesthetics — These agents produce a reversible loss of consciousness, analgesia (loss of pain perception), amnesia, and immobility of the whole body. They are used when major surgery requires the patient to be completely unaware and unresponsive. General anesthesia typically involves either intravenous (IV) agents — such as Propofol, Etomidate or barbiturates — or inhalational (volatile/gaseous) agents — such as Sevoflurane, Isoflurane, Desflurane or Nitrous oxide — or a combination thereof. IV agents allow rapid onset of anesthesia, often used to induce unconsciousness; inhalational agents are useful for maintaining anesthesia over longer procedures and allow fine-tuning of depth and duration.

Intravenous Anesthetics (as a subtype of General Anesthetics) — These are administered directly into the bloodstream (via bolus or infusion) and act quickly to depress central nervous system activity, thereby inducing unconsciousness and anesthetic depth. Because of their rapid onset and precise controllability, they're widely used for induction of anesthesia before switching to another mode for maintenance, or for shorter procedures. Examples include Propofol, Etomidate, and barbiturates such as thiopental. Their effects wear off as the drug is metabolized, but like all general anesthetics they may be associated with side-effects such as respiratory depression, hemodynamic changes (e.g. hypotension), and the need for close monitoring (Robin, 2024).

Inhalational (Volatile / Gaseous) Anesthetics (also under General Anesthesia) — These agents are administered via inhalation (through mask or endotracheal tube) and are absorbed via the lungs into the bloodstream, reaching the central nervous system where they depress neural activity to produce unconsciousness, amnesia, muscle relaxation, and insensitivity to surgical stimuli. According to Masui et al. (2025), common agents include Sevoflurane, Isoflurane, Desflurane, and Nitrous Oxide. Because many of these agents are eliminated via the lungs (rather than by liver metabolism), they offer advantages especially in patients with compromised hepatic function. Their use enables steady maintenance of anesthesia over extended surgeries, with adjustability of depth as needed.

Regional Anesthetics — Rather than rendering the whole body unconscious, regional anesthesia aims to numb a larger but limited region of the body (e.g. lower limbs, abdomen) by blocking nerve conduction in a defined nerve group or at a spinal/epidural level. Techniques include spinal anesthesia, epidural anesthesia, or peripheral nerve blocks. The patient may remain awake (or lightly sedated), but sensation and pain transmission from the targeted region are eliminated, making these methods ideal for lower-body surgeries, obstetric procedures, or limb operations. Compared with general anesthesia, regional anesthesia often confers benefits such as reduced systemic drug exposure, fewer systemic side-effects, and faster postoperative recovery.

Local Anesthetic Agents — These are used to numb a small, specific area of the body (e.g. skin, mucosa, small surgical sites) without affecting consciousness. Local anesthetics block nerve conduction locally (often by inhibiting sodium channels in nerve fibers), preventing transmission of pain signals from that area to the central nervous system. Common agents include Lidocaine, Bupivacaine, Ropivacaine, Procaine, and others. Their application (via injection, infiltration, topical application, or nerve-block techniques) allows minor surgeries, dental procedures, wound repairs, or diagnostic interventions to be performed painlessly while the patient remains fully conscious — minimizing systemic exposure and often reducing recovery time and side-effects.

Strategic Method of Administration Anesthetic Agents

- **Intravenous (IV) Bolus Administration**

One of the most popular strategic techniques for quickly inducing anaesthesia is intravenous bolus administration, which delivers the anaesthetic agent straight into the bloodstream and causes an instant onset of effect. According to Bajwa. (2023), IV bolus induction using agents such as propofol or ketamine allows clinicians to achieve a predictable and smooth transition into unconsciousness, which is essential for emergency procedures or quick-sequence inductions. Additionally, Kumar and Singh (2021) explained that IV bolus administration allows precise control of dosage, making it useful in patients requiring rapid titration. This method is particularly strategic when immediate airway control is required or when inhalational induction is not feasible.

- **Continuous Intravenous Infusion (TIVA/TCI)**

During surgery, continuous anaesthetic drug infusion via Target-Controlled Infusion (TCI) or Total Intravenous Anaesthesia (TIVA) devices provides better stability and depth control. As noted by Schiavo. (2025), TCI systems use pharmacokinetic models to calculate infusion rates that maintain constant plasma or effect-site concentrations of agents like propofol and remifentanil. This method allows for precise titration, reduced volatile agent exposure, and faster postoperative recovery. Furthermore, Patel. (2022) observed that continuous infusion minimizes hemodynamic fluctuations, making it highly strategic for neurosurgical, cardiac, and paediatric anaesthetic care.

- **Inhalational Administration via Vaporizer**

Because of its non-invasive delivery, consistent absorption, and convenience of administration, inhalational anaesthesia is still a strategic approach. To maintain a controlled anaesthetic depth, agents including isoflurane, desflurane, and sevoflurane are delivered using calibrated vaporisers. According to Mostafa. (2021), inhalational administration is particularly advantageous in paediatric patients who may resist IV placement, making mask induction a preferred technique. In addition, Olatunde. (2023) emphasized that inhalational agents allow rapid adjustments in depth due to their low blood–gas solubility, giving anesthesiologists immediate control during unstable procedures.

- **Regional (Neuraxial) Anesthesia Techniques**

Targeted delivery of local anaesthetics to block nerve transmission in certain body locations is possible with regional anaesthesia procedures such as spinal, epidural, and combined spinal–epidural (CSE) administration. As described by Karmakar. (2020), neuraxial anaesthesia is strategic for obstetric, orthopaedic, and lower abdominal operations because it avoids systemic depression and maintains spontaneous breathing. Recent findings by Gupta. (2022) also show that regional techniques reduce postoperative pain, decrease opioid requirements, and minimize hemodynamic instability, making them essential in enhanced recovery pathways.

- **Peripheral Nerve Block Administration**

By injecting local anaesthetics around important peripheral nerves, peripheral nerve blocks provide regional anaesthesia. These methods are now safer and more accurate thanks to the development of ultrasound guiding. According to Ashraf. (2021), ultrasound-guided brachial plexus, femoral, and sciatic nerve blocks offer excellent sensory blockade with minimal systemic toxicity. In addition, Lee and Kim (2023) noted that nerve blocks are strategic for ambulatory surgeries due to prolonged analgesia, reduced need for general anaesthetics, and enhanced patient satisfaction.

- **Sedation Techniques Using Titrated IV Agents**

To keep patients comfortable during minor procedures, sedation techniques rely on the low-dose, titrated delivery of sedative drugs like propofol, dexmedetomidine, or midazolam. Hansen. (2022)

reported that dexmedetomidine-based sedation techniques offer better respiratory safety compared to traditional benzodiazepine sedations. Furthermore, Patel and Morris (2020) highlighted that strategic titration based on validated sedation scales improves responsiveness, reduces oversedation, and enhances procedural safety.

- **Closed-Loop Computer-Controlled Anesthesia Delivery**

Real-time physiological feedback, such as BIS values, is used by closed-loop anaesthesia delivery systems (CLADS) to automatically modify medication infusion rates. These technologies considerably lower anaesthetic variability and keep patients within the desired level of anaesthesia, according to Wingert. (2021). Recent evidence from Nagata (2023) also demonstrates that closed-loop systems improve precision and reduce clinician workload by automatically responding to physiologic changes faster than human manual adjustments.

- **Multimodal Analgesic Anesthesia Administration**

In order to relieve pain through several mechanisms, this technique entails concurrently delivering several kinds of analgesic drugs, such as NSAIDs, opioids, paracetamol, and regional anaesthesia. As explained by Arora. (2022), multimodal analgesia enhances pain control while minimizing opioid consumption and related side effects. Okeke. (2021) also observed that combining systemic analgesics with regional techniques results in more stable intraoperative hemodynamics and improved postoperative recovery profiles.

Effects of Closed-loop Anesthesia Delivery System on Administration of Anesthetics Agents

By providing automation, accuracy, and ongoing physiological monitoring during surgical procedures, the Closed-loop Anaesthesia Delivery System (CLADS) has dramatically changed the way anaesthetic agents are administered. This method automatically modifies drug infusion rates by integrating real-time bio signals, including blood pressure, end-tidal anaesthetic concentration, and the Bispectral Index (BIS). According to Liu (2020), CLADS improves the stability of anaesthetic depth by minimizing human error and compensating for physiological fluctuations more quickly than manual adjustments. By ensuring a more constant anaesthetic state, this continuous feedback method lowers the frequency of overdose or underdoes episodes that are frequently seen in conventional manual administration.

One of the key effects of CLADS is enhanced patient safety. Research by van Amsterdam and Vanslambrouck (2021) reported that closed-loop systems significantly reduce the incidence of intraoperative awareness due to their ability to maintain optimal hypnosis levels more accurately. Similarly, Shah (2022) emphasized that the real-time responsiveness of CLADS leads to better hemodynamic stability, which is critical in vulnerable patients such as the elderly or those with cardiovascular compromise. The automated system's capacity to identify deviations more quickly than human operators and promptly modify anaesthetic distribution is the reason for this enhanced safety profile

Another important effect is the improved efficiency of anaesthetic drug use. A randomized trial by Kim and Park (2023) demonstrated that closed-loop systems lowered total anaesthetic consumption by maintaining tighter control of anaesthetic depth, thus avoiding unnecessary drug infusion. This efficiency contributes not only to cost reduction but also to faster postoperative recovery, as patients are exposed to fewer agents. Hernández-Martínez (2022) found that patients managed with CLADS experienced shorter emergence times and improved postoperative cognitive clarity, attributed to the prevention of anaesthetic overdose.

Additionally, by lowering the burden and freeing up more time for intricate patient management duties, CLADS enhances anesthesiologists' workflow. The cognitive strain of continuous manual titration is lessened by automated devices. As explained by Murthy and Schraag (2021), anesthesiologists using CLADS can devote more attention to monitoring surgical events, anticipating complications, and managing comorbidities. This shift enhances overall perioperative care quality and strengthens patient outcomes.

Conclusion

The study concludes that closed Loop Anesthesia Delivery Systems significantly enhance precision, safety, and consistency in administering anesthesia agents. By integrating real-time physiological feedback with automated drug control, these systems minimize human error and improve patient outcomes. They also streamline clinical workflow, allowing anesthesiologists to focus on complex decision-making. However, challenges such as system reliability, algorithm accuracy, and clinician acceptance must be addressed. Overall, CLADS represents a transformative advancement with strong potential for future AI-driven optimization. With continued innovation, it is poised to become a standard tool in modern anesthesia practice.

Recommendations

1. Hospitals and manufacturers should prioritize rigorous testing and validation of CLADS to ensure consistent performance across diverse patient populations, minimizing risks of under- or over-dosage.
2. Closed-loop systems should be designed for seamless interoperability with current monitoring and electronic health record systems to optimize workflow efficiency and data management.
3. Anesthesiologists and perioperative staff should receive comprehensive training on CLADS operation, interpretation of system feedback, and troubleshooting to maximize the benefits of automation.

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