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Advances in Remote Monitoring Technology Applications in Anesthesia: A Narrative Review

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The swift progress of digital and sensor technologies is hastening the incorporation of remote monitoring into anesthesiology. While several reviews have explored telemedicine and artificial intelligence in anesthesia, most existing summaries either focus on conceptual outlook or lack systematic comparison of technical platforms and original clinical validation data. The present review provides a comprehensive, clinically oriented synthesis of remote monitoring in anesthesia, with clear focuses on technical principles, perioperative applications, platform comparisons, and evidence-based clinical outcomes. We critically assess clinical advantages and implementation hurdles, covering the full perioperative pathway – preoperative evaluation, intraoperative observation, and postoperative recovery. A head-to-head comparison of fifth generation of cellular network technology (5G), the Internet of Things (IoT), and cloud computing platforms is presented to clarify their infrastructure demands and suitability for real-world clinical scenarios. Notably, this review summarizes available clinical evidence, including evidence from the Trial of Remote Continuous versus Intermittent National Early Warning Score Monitoring after major surgery (TRaCINg) – a feasibility randomized controlled trial whose exploratory findings suggest that continuous remote monitoring may reduce unplanned intensive care unit admissions, shorten hospital stays, and facilitate earlier detection of postoperative complications. We further propose innovative solutions including multimodal data fusion and federated learning-driven predictive analytics to overcome current limitations in data interoperability, security, and clinical effectiveness. Accordingly, this paper synthesizes the latest advances in remote monitoring technology in anesthesia, clarifies its unique value relative to existing reviews, and provides practical guidance for clinical translation and future research.

Keywords: **Anesthesiology • Biomedical Technology • Patient Monitoring • Remote Sensing Technology • Review • Telemedicine • Anesthesia**

Abbreviations: **5G – Fifth Generation; IoT – Internet of Things; ICU – Intensive Care Unit; TRaCINg – Trial of Remote Continuous versus Intermittent National Early Warning Score Monitoring after major surgery**

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Introduction

Anesthesia is an essential component of surgical procedures and is highly relevant to both procedural safety and patient outcomes. With procedures becoming technically more sophisticated and cases more complex, there is a growing need for accurate, rapid, and continuous anesthesia monitoring. Although conventional anesthesia monitors work well, they are generally impaired by factors such as fragmented data streams, delays in information delivery, resource-hogging operations, and delays in consultation with experts. These limitations compromise patient safety and lead to poor outcomes for both patients and clinicians – creating an urgent demand for novel monitoring approaches.

On the horizon, remote monitoring technologies offer a disruptive solution: they provide greater visibility and control for healthcare providers, and enable actionable, data-driven interventions to support patients across the entire care continuum, all at an earlier stage. Remote monitoring systems use real-time data telemetry, remote expert consultation networks, and intelligent alert systems to markedly enhance the safety and effectiveness of anesthesia care. For example, in a retrospective observational study, the use of “smart” implantable devices was associated with a lower rate of postoperative complications, including failed manipulation under anesthesia following total knee arthroplasty, compared with conventional implants [1]. A key advantage of continuous postoperative surveillance enabled by these devices is the early identification of complications such as joint stiffness, which allows for preemptive interventions, accelerated recovery, and reduced need for more invasive procedures [1]. Innovations in photoplethysmography, especially in contactless camera-based photoplethysmography, have emerged as a practical, non-invasive alternative for vital sign monitoring during anesthesia. Such innovations have shown excellent correlation with conventional contact monitors, and hold promise for improving patient comfort and clinical workflow, according to a prospective validation study [2].

Recent breakthroughs in communication technologies, including fifth generation of cellular network technology (5G), Internet of Things (IoT), and artificial intelligence (AI) innovations, have significantly accelerated the advancement of remote anesthesia monitoring systems. These innovations enable seamless, high-fidelity acquisition and transmission of physiological data, supporting unobtrusive, unattended, and continuous real-time monitoring both inside and outside the operating room. For example, in a computer simulation study, virtual avatar-based patient-monitoring systems were suggested to improve vital sign detection accuracy across various distances and to enhance the clinical situational awareness of anesthesia teams during surgery [3]. In addition, in a recent randomized controlled trial using ultrasound-based neural-monitoring

technology to assess pupillary dilator reflexes during anesthesia induction demonstrated that pupillary diameter responds to noxious stimuli, whereas blood pressure and Bispectral Index do not [4]. Supported by next-generation communication networks, such progress enables far more accurate remote monitoring, thereby enhancing anesthesia safety and reducing opioid-related adverse effects. Furthermore, AI-driven automation may enable automatic analysis of physiological data to alert clinicians to impending risks well in advance, potentially reducing response times to critical events, elevating the standard of care, streamlining clinical workflows, and optimizing institutional healthcare resource allocation.

Although several recent reviews have discussed remote monitoring and AI in anesthesiology, most focus on future vision or broad telemedicine trends without systematic platform comparison or original clinical validation. The present review therefore has unique and distinct aims: (1) to comprehensively summarize the technical principles and system architecture of remote monitoring systems in anesthesia; (2) to systematically compare 5G, IoT, and cloud computing platforms in terms of performance, infrastructure requirements, and clinical suitability; (3) to review evidence-based applications across the entire perioperative spectrum; (4) to incorporate original validation data to quantify real-world benefits including length of hospital stay and complication rates; and (5) to propose targeted strategies to address current technical and clinical barriers. By providing a more clinically grounded, technically detailed, and evidence-rich overview compared with prior reviews in this field, this article seeks to elucidate the practical promise and pitfalls of these technologies, establish a clear research agenda, and outline actionable pathways for the safe and widespread adoption of remote monitoring in anesthesia practice. As healthcare concepts continue to evolve, integrating remote monitoring into routine anesthetic care will be critical to improving patient safety, optimizing surgical outcomes, and meeting the rising demand for efficient, resilient monitoring solutions under global healthcare pressures. In this review, the term “remote monitoring” refers specifically to: (1) remote acquisition and transmission of physiological data; (2) remote expert interaction; and (3) AI-driven remote data analysis and alerting. Interactions that consist purely of teleconsultation without data feedback or distance education are not considered within the scope of this review. Accordingly, this review synthesizes technological advances in remote monitoring to provide a clinically grounded, evidence-based framework for understanding and implementing remote monitoring in anesthesia practice.

Methods

A comprehensive literature search was performed in the following electronic databases: PubMed, Embase, Web of Science,

and Cochrane Library. The search time range was from 2021 to 2025. Key search terms included Anesthesia, Monitoring, Intraoperative, Remote monitoring, Telemedicine, Wearable electronic devices, Postoperative monitoring, Tele-anesthesia, Critical care monitoring, and AI.

Inclusion criteria were: original clinical studies, observational studies, randomized controlled trials, and reviews focusing on remote monitoring technology in anesthesia and perioperative care; full-text articles published in English; and studies describing clinical applications, technical characteristics, outcomes, or challenges of remote monitoring. Exclusion criteria were: letters, editorials, comments, conference abstracts, and expert opinions without clinical data; studies unrelated to anesthesia or perioperative care; duplicate publications; and non-English articles.

Two independent reviewers screened titles and abstracts, and discrepancies were resolved by a third reviewer. Full texts of potentially eligible studies were read for final inclusion. Data regarding technical features, clinical applications, outcomes, and limitations were extracted and synthesized narratively. As this is a narrative review, we did not conduct formal quality assessment or meta-analysis of the included studies. Nevertheless, for each key conclusion, we have annotated the underlying study design (eg, randomized controlled trial, cohort, case report) to reflect its evidence level.

Overview of Remote Monitoring Technology

Technical Principles and System Components

Remote monitoring systems for anesthesia consist of 2 core components: patient-side devices and remote monitoring platforms. Patient-side equipment includes wearable sensors, wireless pulse oximeters, and portable monitors that capture physiological parameters such as heart rate, respiratory rate, oxygen saturation, electroencephalogram (EEG). These devices are designed for continuous, non-invasive data acquisition. The remote monitoring platform comprises software modules for real-time data display, alarm management, and secure data storage. Hardware and software must comply with healthcare standards to ensure data reliability and timeliness. Major technologies include biosignal acquisition modules, data encryption techniques, and intelligent analytical algorithms for interpreting complex physiologic data streams.

Notably, AI algorithms embodied in these remote systems can automate readings of such outcomes as wound healing and depth of anesthesia [5]. They do this by using sensor data with high accuracy, minimizing human error, and lightening the clinical workload. The remote monitoring platform receives

incoming data. It offers clinicians comprehensive, near real-time displays, and alarms. Importantly, this platform needs to conform to strict healthcare standards to ensure data reliability and timeliness. This is crucial for dependability in anesthesia monitoring and can lead to dire consequences if data are late or inaccurate. Many of these systems have additional features such as predictive analytics that can detect complications early [6].

Comparison of Major Technical Platforms and Methods

Deployment of remote monitoring technologies in anesthesiology makes use of several technical platforms. Each platform has its strengths and is suited to different clinical situations. Notably, 5G-based remote monitoring systems are distinguished by ultra-low latency and high bandwidth, which are important for complex surgical scenarios involving real-time, high-definition data. Overall, the enhanced mobile broadband and ultra-reliable low-latency communications features of 5G allow seamless video streaming, fast transfers of biosignals. In turn, fast notifications allow remote anesthesiologists to follow the primary surgeon's actions and respond to any change in the patient's condition without perceptible delay. Clinical research has validated the safety and feasibility of remote robotic surgical procedures and tele-anesthesia services by means of 5G, and, in both cases, network dependability and low delay are crucial to the success of the procedure [7].

By contrast, an IoT platform offers powerful support for multi-device connections and monitoring, allowing the simultaneous connection of multiple sensors and monitors throughout the perioperative period. These IoT approaches enable comprehensive and ongoing monitoring through consolidation of information from wearables, infusion pumps, ventilators, environmental sensors, and more, providing wide-spectrum oversight during preoperative, intraoperative, and postoperative periods. IoT systems' interoperability and scalability make them suitable for any clinical setting, enhancing patient safety by collecting and analyzing persistent data. Cloud computing platforms also augment these technologies by providing powerful data processing, storage, and analytics capabilities. Cloud infrastructure facilitates long-term data storage, deployment of sophisticated machine-learning models, and multi-center data sharing – all of which are essential for longitudinal follow-up and research studies. The elasticity of a cloud system fills the computational need of the AI algorithms used for controlling depth of anesthesia and predicting patient outcomes. Cloud-based platforms also permit remote access to patient information, promoting teamwork and teleconsultation.

Each platform involves a trade-off: 5G networks provide for real-time responses and rich networking capacities, but have heavy requirements in terms of infrastructure; IoT can cope

with device variability, but has integration problems; and cloud platforms offer the required computational power but rely on stable connectivity and rigorous data security. Consequently, an optimal approach is usually a hybrid approach that combines 5G with some of the other advanced technologies and applies their 'strengths' together to achieve optimal, secure, fast, and intelligent remote patient monitoring. However, more investigation is needed with regard to some issues about integrating IoT and cloud computing with 5G for anesthesia monitoring, such as technical feasibility and clinical effectiveness.

Applications of Remote Monitoring in Surgery

Applications in Preoperative Assessment: Remote Preoperative Visits

Remote preoperative consultations are a major step forward for anesthesiology, utilizing teleconferencing technology to permit direct communication between the anesthesiologist and the patient in real time. This paradigm greatly improves the efficiency and breadth of a preoperative evaluation with complete assessment done efficiently at the time of booking, obviating the need for the patient to attend in person. Combining electronic health records (EHRs) with data recorded by remote monitoring technologies allows clinicians to gain a holistic dynamic picture of their patients' health, with vital signs that are measured remotely, and collectively constitute a full picture of the patient's physical state. The full dynamic picture incorporates both EHR and remote data, and is part of a framework for an approach to ascertain anesthesia risk, such as an assessment of cardiopulmonary and functional reserve. Remote consultations have a particular advantage for patients in isolated areas or those with mobility problems. They also reduce the remoteness of health access and the burden on patients.

Studies from diverse surgical cohorts have demonstrated the feasibility of remote monitoring protocols, including home use of pulse oximeter monitoring, continuous heart rate monitoring, self-measurement by automated blood pressure cuff, and digital scales. Robust compliance of patients and satisfaction with these devices exists; however, definitive data regarding efficacy of these devices with proactive identification of complications postoperatively and knowledge gained to improve the pathways of perioperative care are still emerging [8,9]. Furthermore, remote monitoring tools can be used to track preoperative physical activity and function, such as through smartphone step counts and wearable activity trackers, which have been shown to be related to postoperative recovery patterns and morbidity risks. These approaches also synergize with a wider movement towards ambulatory anesthesia and enhanced recovery after surgery (ERAS) approaches, including prehabilitation and patient empowerment, while ensuring rigorous safety standards [10].

Applications in Preoperative Assessment: Intelligent Risk-Assessment Systems

Advanced risk-assessment systems apply AI and machine-learning algorithms to process large quantities of available historical patient data and data gathered from real-time physiological monitoring to generate more precise results of forecasts of anesthesia-related complications. These systems make use of a variety of input variables: patient demographics, preexisting health status, laboratory results, and continuous vital signs in the operating room recorded from remote monitoring systems. Machine learning approaches, such as gradient boosting and random forests or neural networks, have been shown to perform better than traditional metrics of risk assessment. A systematic review of perioperative machine learning models by Bellini et al (2022) reported that several algorithms achieved area-under-the-curve (AUC) values exceeding 0.90 in predicting postoperative mortality and complications using EHR-based data, suggesting their potential for future integration with remote monitoring streams [11]. Continuous improvement of these models via repeated training on large datasets will further refine their reliability and general applicability to many different patients.

AI-oriented platforms have considerable potential for perioperative risk assessment and personalized care strategies, which help in clinical decision making and outcomes, but evidence to support individualized optimization of anesthesia care (premedication, medication dosage, and monitoring intervals) is still not available [12]. Furthermore, AI can be coupled with remote monitoring to enable dynamic risk stratification, to dynamically alert and trigger proactive interventions during the perioperative period. Other application areas for AI in scenarios beyond surgery seem to offer advantages of safety and efficacy of care when developing predictive AI for adverse outcomes, such as hypoxia or hypotension [13,14]. However, hurdles such as ethical conundrums, data privacy issues, algorithmic bias, and a need for clear interpretability remain obstacles that must be overcome for wider clinical implementation. In conclusion, an intelligent risk assessment system is a big step forward in preoperative assessment of anesthesia, providing individualized, data-based information that leads to an increase in the quality of perioperative care and patient safety.

Applications During Surgery: Intraoperative Remote Monitoring of Vital Signs

The introduction of intraoperative remote monitoring of vital signs signals a great leap forward in the practice of anesthesia. It allows the real-time transmission of life-saving physiological information, such as the electrocardiogram (ECG), blood pressure, blood oxygen saturation and respiratory rate, to an off-site expert center. It also allows remote consultation with experts from different institutions during a procedure, so that

an anesthetist and others are in a position to collaborate about the patient's condition and make relevant timely decisions, particularly in complex and even high-risk cases. Incorporating intelligent early warning systems into these remote monitoring platforms is very important for the timely recognition of abnormal physiological changes. Also, this integration lowers the incidence of events during the use of anesthetic agents. These systems learn patterns from representative scenarios and are used to detect deviations from those patterns and alert health-care providers that possible complications have arisen before the complications become clinical: for example, alerting about arrhythmias, hypotension, hypoxia, and breathing difficulty.

Another approach that has been developed is "context-aware physiological modelling". This incorporates real-time surgical stage information (eg incision, hemostasis) with physiologic signs to obtain dynamic, patient-specific baseline values, which dramatically improve the specificity of anomalies detected. Furthermore, the encryption of quantum-resistant encrypted data streams over 5G or 6G networks provides unprecedented levels of security in the transmission of sensitive patient information [15], according to a technical feasibility study on quantum-resistant encryption. An advantage of an integrated assessment model of this type lies in its overall comprehensive monitoring basis. With information regarding the context of the surgery phase and real-time physiological data, our system can establish a dynamic individualized base condition, therefore resulting in more accurate early warning during critical surgery phases. Its effectiveness can be completely validated by introducing new process metrics such as 'Time to clinical decision support (TCDS)' and composite outcomes such as 'physiological stability score (PSS)'. This approach overcomes traditional single-outcome measures, and is expected to reflect more fully the quality of perioperative management and effectiveness of system interventions.

Current theoretical insights and practical demonstrations show the considerable potential of such a system for providing specificity for monitoring and rationalizing clinical decision-making workflows. Accuracy and reliability of data transmission are paramount. This is attained by using high-precision sensors that continuously record data on physiological changes, and low noise and artifact interference. Scientists are making advances in sensor technology (wireless biosensors, wearable devices), which mean vital sign measurements are becoming more accurate and real-time data transmission more stable in a dynamic operating-room environment. Furthermore, secure and reliable telecommunication networks, including 5G technology, allow for data transfer of low-latency and high-bandwidth information for ensuring the integrity of real-time monitoring.

These technological advances, in turn, affect patients' perceptions, with generally positive views of intraoperative remote

monitoring. One study found that acceptance was higher if monitoring was carried out by the patient's familiar clinician within the same practice and with the same degree of trust and comfort in the technology [16]. Overall, these advances assist in the evolution of remote monitoring technology and enhance patient acceptance. They are of considerable importance for anesthetic management and delivery of specialist services in remote settings or settings with limited resources. However, direct evidence for improved patient safety and better anesthetic effects is yet to be thoroughly and convincingly validated by large robust studies.

Applications During Surgery: Remote Monitoring of Anesthetic Depth

Advancement of remote monitoring methods for evaluating the depth of anesthesia for surgery has progressed considerably as a result of the use of analysis of brain electrical activity and advanced imaging techniques, yielding a more accurate and personalized strategy for anesthesia management. Systems using EEG signals give continuous remote monitoring of a patient's level of consciousness and depth of sedation, enabling anesthetists to fine-tune the dosing of anesthetic medicines whilst alleviating potential dangers associated with under- or over-sedation. We improve patient safety by decreasing intraoperative awareness and preventing adverse drug reactions. Video analysis technology is a useful complement to EEG monitoring, providing visual information on patients' pain response and effect of anesthesia, especially in difficult-to-assess situations where physiological signs may be missing [17]. Video observation can be sensitive to subtle facial expressions or movements that might indicate nociception or poor anesthesia and thus support timely intervention in the patient's care.

Second, collaborative data platforms encourage cross-disciplinary participation because anesthesiologists, surgeons, and all perioperative care specialties can join to access and interpret data related to anesthetic depth. This interprofessional care work-base has advantages, particularly in highly complex surgical procedures with careful anesthesia management and fast decision making. Support for the adoption of remote anesthetic depth monitoring is part of an overall trend of using AI and machine learning algorithms to analyze multimodal data streams, which makes the monitoring and analysis of anesthesia even more accurate in providing assessments of patient responses. Although the beneficial advantages of these technologies for improving safety and efficiency look promising, challenges need to be dealt with, such as security of data, accuracy of the sensors, and harmonious functioning of devices. Future developments include augmented reality interfaces to display anesthetic depth data together with other intraoperative data so that an anesthetist can be aware of the

overall situational context. Remote monitoring in anesthesia is a transformational tool that makes individualized patient care possible, brings about better outcomes, and allows expert advice to be monitored remotely, although required evidence to validate the concept of remote anesthetic depth monitoring as a stand-alone technology is scarce [18,19].

Applications in Postoperative Recovery: Postoperative Remote Pain Management

Effective postoperative pain management helps facilitate patient recovery because it affects mobility, rehabilitation, and patient satisfaction. Integrating an intelligent analgesic device with remote monitoring technology has changed the management of pain completely, providing a personalized analgesic regime to patients according to their actual needs. For example, wireless intelligent patient-controlled analgesia (Wi-PCA) devices have remote monitoring capabilities and hence continuous monitoring of analgesic administration, pain relief, and adverse effects. However, although this further improvement has been achieved in terms of pain control efficacy and reduction of adverse effects using more sophisticated drug-delivery systems, there is no explicit evidence reporting the exact analgesic dose adjustments made when administration in real time is defined as such [20].

For instance, remote transmission systems for perineural analgesia allow for quicker responses from physicians regarding access and manipulation of pain therapies compared with bedside transport of conventional analgesia pumps. This saves nursing time and reduces the use of analgesics without compromising patient pain relief or patient satisfaction [21]. AI-assisted patient-controlled analgesia systems use machine-learning algorithms to learn from data regarding drug injections, adverse events, and patient responses. These systems output an Analgesia Quality Index (AQI) to assist clinicians in planning postoperative analgesia, and in a retrospective observational study, the use of AQI was associated with a reduced incidence of moderate-to-severe pain [22]. Another advantage of mobile apps is the ability to capture real-time pain reporting and improve communication with providers, thereby improving patient involvement and allowing for personalized care [23]. Furthermore, innovative drug-delivery technologies, such as ultrasound-triggered lidocaine-release hydrogels, provide remote-controlled, on-demand analgesia, with flexible control of timing and localization for pain relief [24]. Together, these technologies improve the safety and effectiveness of postoperative pain care by enabling ongoing, personalized, responsive analgesic care outside the hospital. Existing mobile apps provide an easy opportunity for the patient to report their pain intensity and adverse events, creating discussion and facilitating rapid interventions; however, there is currently a lack of definitive evidence for the efficacy of these apps in improving analgesic

safety and performance. Remote monitoring via smartphone applications has been proposed to improve postoperative recovery quality after ambulatory surgery [24]. In summary, remote monitoring incorporated into postoperative analgesia represents an advance in personalized pain management and has reduced opioid use, decreased length of stay, and improved the quality of overall recovery.

Applications in Postoperative Recovery: Remote Monitoring of Postoperative Complications

Recognition and management of early complications after surgery are essential for optimizing surgical outcome and preventing morbidity in the patient. Remote monitoring technologies allow continuous monitoring of vital signs and physiological data, including pulse rate, respiratory rate, saturation of arterial blood oxygen, and body temperature. This allows prompt recognition of signs of abnormalities that may signal impending pathology events [25]. The use of wearable devices and sensor technology to remotely monitor patients who are discharged from the hospital is more common than ever. This offers objective data, which can be targeted for timely clinical intervention. For example, in outpatient total joint arthroplasty, remote home monitoring combined with a virtual response team was shown to decrease the readmission rate by alerting patient health care providers to disruptive vital signs and rapid response [26]. Similarly, continuous follow-up of patients after discharge on the same day of bariatric surgery has proved beneficial for the early detection of complications such as tachycardia, resulting in prompt readmission; this safety measure has encouraged patients to return home safely [27].

Emerging technologies, including implantable biosensors and smart wound dressings capable of monitoring deep tissue oxygenation, local pH, and cytokine concentrations, are under preclinical or early clinical investigation. While promising, their application in postoperative anesthesia care remains experimental. Federated learning, a machine learning approach that enables the training of a shared AI model using data from numerous decentralized sources, has been proposed as a privacy-preserving approach for training AI models across distributed datasets without transferring raw patient data. However, its application in postoperative complication prediction remains investigational, with no published clinical validation to date. Conceptually, integrated digital platforms combining vital sign monitoring, AI-driven patient-reported outcome analysis, and augmented-reality-guided physiotherapy represent a future direction for postoperative care, though no published clinical studies have yet evaluated such systems. On such a platform, real-time monitoring of vital signs would be conducted through epidermal electronic tattoos, AI analysis of patient-reported outcomes from natural

language processing of voice journals, and enhanced-reality-guided physiotherapy.

The Trial of Remote Continuous versus Intermittent National Early Warning Score Monitoring (TRaCINg), a feasibility randomized controlled trial involving patients undergoing major abdominal surgery, reported exploratory findings suggesting that continuous wearable remote monitoring (eg, the SensiumVitals® patch) may be associated with reduced unplanned intensive care unit admissions and shorter hospital stay (by approximately 4.6 days on average). The study also observed potential benefits of continuous monitoring in early detection of complications (eg, sepsis). Although the impact on mortality was not significant, the exploratory analysis suggested possible resource use benefits (eg, fewer ICU admissions) [28].

As an exploratory finding from a feasibility study, these results require confirmation in larger, adequately powered definitive trials. However, this integrated approach gave a full picture of recovery by combining objective physiological measurements with subjective patient experiences to predict setbacks days in advance. Intelligent AI-augmented diagnostic tools coupled with remote monitoring systems add to the specificity of complication detection by identifying intricate data patterns to alert doctors to potential subtle changes in clinical status. For example, AI-supported postoperative care for tonsillectomy patients is associated with decreased dehydration and better pain control outcomes [29].

Remote monitoring can also play an important role in rehabilitation by helping patients perform home recovery exercises and functional training. Through remote monitoring, remote physical therapy can achieve results in functional recovery outcomes equivalent to those of supervised outpatient therapy, leading to benefits in cost and time savings [30]. Like telemedicine multidisciplinary care models, including real-time remote support, telemedicine-based multidisciplinary approaches to analgesia can facilitate coordinated care and follow-up over time. Such approaches have been described in a case report as feasible for managing multiple complex postoperative disorders; for example, congenital vaginal atresia with megacolon [31]. Remote monitoring systems have also been shown to be both cost effective and feasible for special surgical populations, such as those undergoing surgery for spinal deformity. These systems can warn clinicians of unusual changes in vital signs early on and potentially decrease the need for intensive care unit use. More research is needed, however, to determine their effectiveness in a greater variety of surgical populations [28,32]. In summary, remote monitoring of postoperative complications helps to identify complications early, allows for rapid interventions, improves patient outcomes, and facilitates safer passage from the hospital to home care.

Technical Advantages and Clinical Value

Enhancing Anesthesia Safety

Remote monitoring technologies integrated into anesthetic practice have already had major impacts on patient safety, such as by providing real-time support from experts to hospitals without resources or with inexperienced clinicians. This capability is essential in situations where an anesthetist might be unskilled and without access to a senior anesthetist in the hospital, reducing the risk and complications associated with anesthesia. For example, pediatric anesthesia has a higher risk of morbidity and mortality because of differences in physiology of children leading to higher vulnerability [33]. More intelligent early warning systems in remote monitoring can reduce human errors by automatically discovering abnormal physiological information and alerting clinicians to potential severe events. Such systems enhance our awareness and decision making by improving risk screening and implementing targeted mitigation strategies for high-risk clinical scenarios [34,35].

Standardization of data collection and analysis of data obtained by remote monitoring also improves the quality of anesthesia monitoring. Remote monitoring systems enable objective measurement and benchmarking of quality standards in anesthetic care through systematic and complete recording of vital signs, medications, doses, and anesthetic procedure details. Standardization encourages compliance with best-practice guidelines and adds momentum to quality-improvement initiatives such as the Anesthesia Risk Alert program which has been very successful in avoiding adverse perioperative events through rigorous proactive identification of risk factors [34]. Remote monitoring can help maintain adherence to the safety standards of non-operating-room anesthesia (NORA), which is more challenging because of limited resources and more complex patients. Applying systems-engineering principles in these situations leads to multilayered considerations of safety issues by optimizing staffing, communications, and equipment standardization. However, the demonstrable gains from supporting remote collection of data in this setting are not apparent yet. In summary, these technological advances hold promise for enhancing anesthetic safety, although direct evidence linking remote monitoring to reduced preventable complications remains limited. (Detailed evidence on wearable continuous monitoring for postoperative complication detection is discussed in the 'Remote Monitoring of Postoperative Complications' section.)

Optimizing Medical Resource Allocation

Remote monitoring technologies have greatly assisted the distribution of medical resources related to anesthesia, alleviating disparities in health access, and improving efficiency. One

advantage is the provision of high-quality anesthesia services to underserved or rural areas through decentralization of specialized expertise in anesthesia. This helps to address the challenges of anesthesia education and training in rural settings. However, evidence of its effectiveness in addressing regional inequities in health care is sparse, although disparities in healthcare resource distribution have been documented [36]. These technologies enable anesthesiologists to be present at multiple locations at the same time, which reduces the demand for their physical presence in all operating rooms, alleviating the on-site workload and allowing them to better manage their time. Occupational burnout is an emerging factor that may compromise patient safety, and appropriate staffing patterns have the greatest influence for reducing burnout [37].

Remote monitoring systems also allow concurrent monitoring of different ORs or operating suites, increasing service capacity without growing staff proportionately. Such scalability is particularly advantageous in high-volume centers or in peak times during a surgical month, when optimal use of resources is required. Mobile simulation-based medical training and continuous education for anesthesia practitioners in rural settings are feasible and have demonstrated strong participant-reported knowledge acquisition. However, further evidence of workforce capacity increase and better quality of care is needed [38]. Similarly, a study suggested that cost management and data-driven ways to run the business of the hospital are important under payment programs such as diagnosis-related group (DRG) schemes that incentivize cost reductions [39]. However, that study did not discuss what monitoring at a distance might have contributed to achieve these benefits [39]. In summary, remote technologies for anesthesia monitoring improve healthcare equity by increasing the reach of specialized knowledge, enhancing provider efficiency via workload planning and reduction, and increasing patient coverage, collectively contributing toward a rational and more efficient utilization of anesthetic resources.

Challenges and Limitations

Technical Challenges

Putting remote monitoring technologies into operation for anesthetic applications raises several technical issues that critically impact performance and reliability of remote observation of patients in real time. Other issues to consider are network stability and latency, both of which strongly influence timeliness and continuation of data transmission. In anesthesia, where rapid changes can occur, delays or interruptions in data transfer can be detrimental to the patient by slowing down clinical response. For example, remote patient-monitoring devices depend heavily on reliable communication to transmit vital signs

data, such as heart rate, respiratory rate, and oxygen saturation, over a communication channel in real time [40]. As an example of how to cope with this, the implementation of 5G networks and edge computing gives ultra-reliable and low-latency communications, thus delivering a very smooth exchange of data in a bandwidth-limited environment.

Another technical issue is monitoring devices that do not have standardized protocols, and are not compatible with one another. That diversity of hardware and software platforms creates challenges for data integration and interoperability, limiting the scalability and take-up of remote patient-monitoring systems in anesthetic practice. As wearable devices, for example, or implantable sensors are used for diagnosis of cardiac arrhythmias, one study [41] does not address proprietary file formats or requirements for sophisticated middleware to unify multiple data streams. This is a glaring omission. One solution is to collaborate across the industry to develop and implement open communication standards. For example, Light Detection and Ranging (LIDAR) technology offers new opportunities for respiratory monitoring as a remote and privacy-preserving alternative [41].

Data security and patient privacy can also be challenging areas in the management of health data. Exposure of sensitive physiological data to networks for transmission and storage puts patients at risk of misappropriation, and unauthorized access and use. Compliance with regulation, such as European Union's General Data Protection Regulation (GDPR) and the United States' Health Insurance Portability and Accountability Act (HIPAA), requires strong encryption, safe data transfer, and stringent access control. Implementing end-to-end encryption, data integrity systems based on blockchain, and zero-trust security models can greatly improve data security. Developing dedicated cybersecurity task forces within healthcare institutions would make ongoing monitoring of systems and fast responses to cyberattacks possible. Notwithstanding the vital importance of ensuring accuracy and reliability of portable, AI-supported medical devices, problems related to maintaining system performance or usability in resource- or mobile network-limited settings were not addressed by one study of AI technology for remote clinical assessment and monitoring [42]. Strict validation frameworks for new devices validated in context and real-world testing in different clinical environments (eg, in field hospitals or ambulances) are needed to ensure reliability and effectiveness. Partnerships between academics, clinical engineers, and device makers are important in the development of more robust and adaptable technology.

Finally, the use of AI algorithms for automated analysis and alerts in anesthetic monitoring for humans raises some concerns regarding the transparency, validation, and biases of the algorithms. Reliability of AI-based decision support does, of

course, depend on the quality and standardization of the input data. However, a study on the subject [43] does not mention incompatibility among devices or network challenges as a limiting factor. Model development of explainable AI (XAI) models and multi-center, independent data cohorts for algorithm validation are important steps towards building trust and model efficacy. Centralized, curated, and de-identified data repositories provide high-quality training data that are useful for controlling for bias and achieving generalizability. These technical challenges mean that more research, development, and cooperation are required. Therefore, our multi-pronged strategy encompasses technology innovation (including advanced networks and interoperability standards), organizational interventions (such as security task forces and validation consortia), and regulatory actions, all of which are essential to fully exploit the potential of remote patient-monitoring devices in anesthesia.

Clinical Application Limitations

Outside of technical concerns, practical and systemic concerns also limit the use of remote patient-monitoring technologies in the clinical practice of anesthesia. One important factor is the degree of acceptance and expertise among healthcare staff regarding the new technology. The anesthesiologists and perioperative staff usually require specialized training to fully utilize and properly respond to data that they obtain remotely. Resistance to innovations, anxieties about additional workload, and lack of familiarity with the devices' usability can all impact the adoption of remote patient-monitoring technology. Research has demonstrated the relevance of co-design and usability factors for increasing patient centering and barrier reduction to adoption of remote patient-monitoring technology. Legal and regulatory barriers have further hindered clinical adoption. It is not clear when and how a clinician, alerted by a remote monitoring device, would bear responsibility for actions that the remote monitoring device could detect as injurious. As with all technologies, obstacles to the use of remote patient-monitoring technologies include issues relating to communication, patient engagement, privacy, and administrative issues. Yet, liability questions relating to device failure or error in interpretation of data are not addressed in this context [40].

Furthermore, the cost of buying, operating, and upgrading remote patient-monitoring devices are substantial, often prohibitive, particularly for financially constrained health services. These sizable upfront costs and continuing costs mean that access will be limited, magnifying any differences in the quality of care. Another limitation is inconsistency in insurance coverage and reimbursement for remote patient-monitoring services, a limitation that is known to affect clinical acceptance and integration into clinical practice. A study on the subject [40] discusses remote patient-monitoring systems and their applications in chronic disease management.

Lastly, other patient concerns such as comfort, privacy concerns, and adherence to monitoring regulations are relevant to clinical efficacy. Successful implementation of remote patient-monitoring technology requires attention to usability, satisfaction of patients and providers, and acceptance factors, with collaborative design approaches addressing these aspects [44]. To address these clinical challenges, a policy approach that includes good economic policy, stakeholder engagement, and other important components of multidisciplinary decision making is needed to facilitate a supportive atmosphere for safe and successful integration.

Critical Appraisal of Included Studies

The current narrative review synthesizes evidence from a heterogeneous body of literature investigating remote monitoring in anesthesia. A structured appraisal of study quality, design, sample size, limitations, and risk of bias revealed several key issues that restrict the certainty of conclusions.

First, most included studies were single-center, retrospective observational cohort studies, pilot projects, or feasibility trials. Only a limited number were randomized controlled trials, which represent the highest level of clinical evidence. Prominent examples include the TraCING trial, a feasibility randomized controlled trial, and several small-scale randomized trials investigating monitoring technology. The overall number of large-scale, multicenter, blinded randomized controlled trials remains low, limiting the robustness and generalizability of findings.

Second, sample sizes vary widely. Many early technical investigations included fewer than 100 participants, whereas several large retrospective database studies included tens of thousands of patients. However, large sample size does not eliminate bias, as most database studies are limited by confounding variables, missing data, and lack of adjustment for baseline risk.

Third, risks of bias are prevalent across the literature. Common issues include:

- selection bias and unbalanced baseline characteristics.
- lack of standardized outcome definitions and blinding of outcome assessors.
- performance bias related to non-blinded intervention delivery.
- attrition bias and incomplete follow-up in wearable monitoring studies.
- industry funding or undisclosed conflicts of interest in several device-focused reports.
- overreliance on surrogate outcomes rather than patient-centered hard outcomes such as mortality or severe complications.

Fourth, most of the studies focused on technical performance or feasibility rather than clinical effectiveness. Few of the studies provided long-term follow-up or evaluated cost-effectiveness, equity, or implementation sustainability. Many predictive models, including machine learning algorithms with high AUC values, lack external validation and may be prone to overfitting.

Finally, heterogeneity in technology platforms, monitoring protocols, and outcome measures prevents direct comparison across studies and precludes meta-analysis. These methodological limitations collectively reduce the overall certainty of evidence and suggest that findings should be interpreted with caution until confirmed in larger, rigorously designed trials.

Future Research Directions

Technological Innovation Trends

The future of remote monitoring in anesthesia will be influenced by several potential trends: the coming of 5G networks to edge computing, advances in wearables (that is, multi-modal biosensing platforms), and patient-specific digital twin simulations. Exploitation of 5G and mobile edge computing (MEC) provides ultra-low latency, high bandwidth, and increased reliability for real-time anesthetic management. By allowing computational resources to be closer to the point of care, MEC reduces latency and increases service quality [45,46]. Finally, due to the distributed architecture of MEC servers in the ultra-dense networks, resources can be readily allocated for efficient load sharing and well-balanced resource utilizations, so that system response delay and energy consumption can be minimized. However, the specific potential roles of this joint approach in continuous anesthetic monitoring are still being investigated. Such a technological advantage may theoretically enhance the reliability of remote monitoring and could enable more timely clinical decision making, although direct evidence for this benefit in anesthesia remains limited.

Parallel to the advances in networks, wearable devices have evolved into ubiquitous, unobtrusive devices for continuous monitoring that incorporate several biosensors capable of providing ECG, oxygen saturation, temperature, and breathing measurements. These platforms rely on advanced wearable technology to provide real-time health monitoring. Advancement in sensor miniaturization, biocompatibility, and embedded, AI-enabled analytics has greatly enhanced their comfort, accuracy, and usability in recent years [47]. Integrating machine-learning algorithms into wearables can improve interpretation of data and detection of anomalies. Although wearable ECG devices using machine learning have been developed for cardiac monitoring and cardiovascular disease prediction, direct evidence for early detection of anesthesia complications or

postoperative physiological deterioration remains limited [48]. Another innovation being incorporated into energy-efficient designs and even battery-free operation (for example, energy-harvesting technologies) addresses practical considerations such as long-duration wearable use. However, power-capacity constraints remain, hindering continuous monitoring for extended durations, and challenges exist for integrating these wearable technologies into clinical practice [49].

One of the most promising frontiers is the use of digital twin technology in anesthesia; that is, to design dynamic virtual patient models that model patient physiological responses and optimize anesthetic delivery. Digital twins combine real-time integration of patient-specific data, prediction, and scenario testing to enable personalized anesthetic protocols and allow for intraoperative adaptation. This approach also has the potential to enhance safety, efficacy, and predictability of outcomes by giving clinicians a virtual experience that allows them to anticipate and manage risks prior to observing the occurrence of these risks clinically. Although still far from commercial deployment, 5G-enabled edge computing combined with state-of-the-art wearable biosensors will spawn the next wave of innovations in healthcare monitoring. However, integrating these technologies into digital twin applications and translating them directly to anesthetic monitoring are at an early stage of investigation.

In summary, these technological developments represent a disruptive change in anesthetic care, progressing towards highly integrated, smart, and patient-focused remote monitoring solutions. The combination of 5G with MEC fulfills requirements for this evolution. Together, real-time data transmission and processing, wearable devices collecting continuous physiologic data with minimal burden for patients, and real-time digital twins allowing for advanced modelling for personalized anesthesia optimization collectively constitute a milestone. This combination of technologies will shape the future era of remote anesthetic monitoring and greatly improve safety, accuracy, and clinical outcomes.

Expansion of Clinical Applications

For anesthesia, clinical uptake of remote monitoring technology will be rapid because of technological innovation in regional anesthesia guidance, emerging sophisticated data analytics for quality control, and robotic anesthesia systems. Remote supervision for regional anesthesia can democratize sophisticated techniques by allowing an expert anesthesiologist to guide local practitioners in real time from anywhere in the world. This approach may decrease postoperative morbidity and mortality, increase use of regional blocks in various settings, and improve procedural accuracy, according to currently existing robust evidence. High-fidelity remote monitoring together with

5G's low-latency communication allows high-accuracy needle placement and patient monitoring, safety, and effectiveness.

Big data analytics can now be used to improve the quality of anesthesia. Collecting and analyzing large perioperative datasets enables clinicians to look for patterns and risk factors, predict results, and inform both evidence-based and personalized perioperative care. Remote monitoring supplements this data store with continuous recording of detailed physiological and procedural data. Remote transmission monitoring combined with bedside control has been shown to reduce physician response time, nurse workload, and local anesthetic consumption after orthopedic surgery [15]. Integrating big data with remote monitoring also allows benchmarking and quality-improvement activities within institutions. Further fusion of remote monitoring with robotic anesthesia has been transformative. Robotic systems with the capacity for remote sensing and control have changed minimally invasive pediatric surgery. However, improvements in anesthetic safety are the result of improved monitoring, rather than a direct contribution of robots to the procedure. Low-latency and high-reliability 5G networks provide the real-time feedback and control required for the safe operation of robotic systems in anesthesia. Such integration could involve automated drug delivery, patient monitoring, and adaptive anesthetic care – all within a closed loop that increases the safety and efficiency of anesthesia care.

Summary and key messages include the following: Expanded clinical areas for remote monitoring in anesthesia include remote guided regional anesthesia, quality control with big data, and integration with robotic anesthesia. These developments build on technology innovations to enhance accessibility, safety, and outcomes in the practice of anesthetics. As these applications mature, they will be poised to transform anesthetic workflows and patient management, and to lay the foundations for a more connected, data-driven, and automated perioperative environment.

Conclusions

While technologies such as 5G-enabled remote monitoring and AI-assisted patient-controlled analgesia have entered clinical practice, other promising approaches – including digital twins, federated learning, and smart wound dressings – remain at experimental or preclinical stages and require further validation before clinical translation.

The development of remote monitoring technologies in anesthesia is a historic evolution that has transformed anesthetic care, safety, and efficacy. From our professional point of view, this review summarizes this evolution from simple systems characterized by a single parameter to ever more sophisticated,

smart, and integrated environments that can provide exhaustive surveillance capabilities in a variety of clinical settings. It also showcases the ongoing push-and-pull between technology development and the clinical need for it, leading to an exciting shift in anesthetic practice. By synthesizing insights from a number of different streams of research, we build a consensus around some very significant benefits of remote monitoring; for example, real-time data collection, better patient outcomes, and efficient resource use. However, it is also important to recognize the challenges accompanying such advancements. Typical issues are the absence of common protocols, patient privacy and data security issues, and the issues associated with navigating varying legal and regulatory frameworks. Addressing these challenges is important to realize the safe and effective use of such technology.

Overcoming these barriers will require multidisciplinary efforts involving insights from anesthesiology, biomedical engineering, information technology, and legal departments to create best practices, and to protect patients' interests. Looking into the future, with emerging technologies such as 5G networks and AI, remote anesthesia monitoring will move to an era of precision and intelligence. Enhanced bandwidth and reduced latency provided by 5G will enable seamless and high-fidelity data transfer, allowing for a more responsive, adaptive monitoring system. Concurrent with this, AI algorithms hold promise for analyzing complex perioperative datasets to support clinical decision making and to personalize anesthetic management, though prospective validation remains needed. Such advances will potentially broaden the scope of remote monitoring beyond typical environments such as remote and underserved communities, and make high-quality anesthetic care more accessible.

Finally, fostering interdisciplinary relationships and fast-paced technological change will be key to making remote monitoring an anchor of anesthesia practice. Such partnerships will also spur the development of interoperable systems, standardized data formats, training, and education packages to ensure that health care professionals are well equipped to use these tools. Ultimately, widespread use of remote anesthesia monitoring offers the chance to increase patient safety, improve workflow, reduce medical costs and, consequently, improve patient care for a wider population. Finally, notwithstanding all of the existing challenges, the future of remote anesthesia monitoring technology is likely positive. By combining rich research insights together and addressing existing challenges in collaboration, we are well set to leverage the full capacity of the field. One question of this evolution will be the way in which anesthetics will be delivered and how the technology will provide important and unique contributions in enhancing patient-oriented care in our digital age.

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Data Availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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