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Review article

REVOLUTIONIZING PERIOPERATIVE MEDICINE: TECHNOLOGICAL ADVANCEMENTS FOR ENHANCED RECOVERY

(TECHNOLOGICAL ADVANCEMENTS FOR ENHANCED RECOVERY)

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Abstract

Enhanced Recovery After Surgery (ERAS) is a multimodal, evidence-based approach designed to minimize surgical stress, accelerate recovery, and improve patient outcomes. Recent technological advancements have transformed ERAS protocols by integrating robotic-assisted surgery, artificial intelligence (AI)-driven monitoring, advanced thermoregulation, automated nutrition management, and real-time perioperative decision support. These innovations enhance surgical precision, metabolic stability, pain control, and personalized patient care, ultimately reducing complications and improving recovery efficiency. Robotic surgery improves minimally invasive techniques, while AI-powered glucose monitoring and pain management optimize metabolic control and analgesia. Advanced thermoregulation systems ensure perioperative normothermia, reducing risks associated with hypothermia, and automated nutritional support promotes postoperative recovery. However, challenges such as cost, accessibility, and seamless integration into clinical practice remain. Future directions in ERAS include AI-driven predictive analytics, remote patient monitoring, wearable biosensors, and closed-loop anaesthesia systems, which will further refine perioperative care, early risk detection, and personalized interventions. The continued integration of emerging technologies into ERAS pathways will drive safer, more efficient, and patient-centered surgical recovery, redefining perioperative medicine for the modern era.

Keywords: *Perioperative Medicine; Enhanced Recovery After Surgery; Artificial Intelligence; Machine Learning; Technology*

Introduction

Enhanced Recovery After Surgery (ERAS) is a multimodal, evidence-based perioperative care framework designed to reduce surgical stress, accelerate recovery, and improve patient outcomes. Traditional approaches often involved prolonged fasting, conventional methods of preoperative optimization, intraoperative monitoring and anaesthesia delivery, delayed mobilization, opioid-centric pain management, and subjective clinical assessments, leading to longer hospital stays and increased complications. However, technological advancements in the 21st century have revolutionized ERAS protocols, enabling precision-driven, patient-centered, and data-supported interventions.[1] Innovations in preoperative optimization, minimum optimal fasting, anaesthetic management, minimally invasive surgery (MIS), robotic-assisted procedures, advanced glucose monitoring devices, and artificial intelligence (AI)-powered decision support have significantly enhanced surgical precision, metabolic stability, and personalized perioperative care. Electronic health records (EHRs), telehealth, wearable biosensors, and smart monitoring systems facilitate real-time data collection, early risk prediction, and individualized treatment strategies. Advances in perioperative fluid therapy, nutrition management, thermoregulation, and mobility solutions further optimize patient safety and recovery efficiency, aligning with ERAS principles. Additionally, AI-driven closed-loop anaesthesia and pain

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management systems enhance analgesia precision while minimizing opioid dependency. As technology continues to evolve, its integration into ERAS pathways holds immense potential to streamline surgical workflows, reduce complications, and shorten hospital stays (Fig.1.). This narrative review explores the role of emerging technologies in ERAS, evaluating their impact on perioperative management, recovery optimization, and the future of surgical care.

Technology-Assisted Prehabilitation

Prehabilitation has emerged as a key strategy in optimizing patients' functional status before surgery, particularly within the framework of Enhanced Recovery After Surgery (ERAS) protocols. Integrating technology, including wearable devices, smartphone applications, telehealth platforms, and virtual reality, has significantly improved patient adherence, engagement, and overall outcomes. The following studies highlight the impact of digital prehabilitation programs across various surgical populations. Several studies have demonstrated the effectiveness of wearable devices in tracking physical activity and enhancing adherence to prehabilitation protocols. Chmelo et al. conducted a single-center feasibility study in the UK on patients with locally advanced esophageal and gastric cancer. A pedometer was used to monitor physical activity, and the intervention achieved high adherence rates (98.7% recorded their data, 100% engaged in weekly consultations). Significant improvements were observed in physical function, fatigue, nausea reduction, appetite enhancement, and global health status.[2] Finley et al. assessed aerobic training-based prehabilitation in Stage 1-3 lung cancer patients. Using a wrist-worn Garmin smartwatch, 47% of participants achieved a minimal clinically important difference in the six-minute walk test (6MWT), suggesting improved functional capacity.[3] Patel et al. conducted an RCT in Canada evaluating a Fitbit-monitored prehabilitation program for early-stage non-small cell lung cancer (NSCLC). Significant improvements were noted in mobility ($p = 0.008$) and pain reduction ($p < 0.001$), with a decrease in hospital length of stay. Notably, 96% of participants expressed a willingness to continue using the activity tracker, highlighting the acceptability of wearable technology.[4] Smartphone applications and tablet-based interventions have been widely adopted to facilitate prehabilitation through real-time patient engagement. Waller et al. examined the impact of a smartwatch-connected prehabilitation program for major abdominal cancer surgery patients. The intervention group demonstrated significant increases in moderate ($p = 0.063$) and vigorous physical activity ($p = 0.022$) and improved 6MWT distance ($p = 0.014$).[5] Kadiri et al. assessed a cohort of lung cancer patients using the Fit 4 Surgery app, a Bluetooth-enabled pulse oximeter for real-time SpO2 and heart rate monitoring. App users had shorter wait times for surgery (24 vs. 45 days) and completed more exercise sessions (9 vs. 2), demonstrating improved adherence compared to in-person prehabilitation programs.[6] Piraux et al. explored the Virtuagym fitness app for esophagogastric cancer patients, reporting a 96% retention rate and significant improvements in fatigue, Quality of life (QoL), physical and emotional well-being, and anxiety.[7] Telehealth and video conferencing have become increasingly popular for delivering multimodal prehabilitation, particularly for patients in remote locations. Drummond et al. evaluated a telehealth-based prehabilitation program for thoracic and abdominal cancer patients. The study demonstrated increased daily step counts ($p < 0.001$) and longer weekly exercise durations ($p = 0.093$), with high patient satisfaction (96%).[8] Franssen et al. assessed mobile phone application-assisted prehabilitation in colorectal cancer patients, with an 81% participation rate. Adherence to exercise frequency, intensity, and duration was 91%, 84%, and 100%, respectively, with significant improvements in functional capacity ($p = 0.01$).[9] Lorca et al. implemented a Zoom-based prehabilitation program for colorectal cancer patients, reporting significant functional capacity improvements ($p < 0.01$), underscoring the feasibility of remote interventions.[10] Moorthy et al. investigated a Digital Prehabilitation Service (DPS) health app for esophageal cancer patients. The study demonstrated high feasibility (75% recruitment rate, 84% completion), improved sit-to-stand performance ($p = 0.02$), and reduced emotional distress ($p = 0.04$), although no significant impact on anxiety, depression, or postoperative complications.[11] Piche et al. assessed Zoom-based prehabilitation for breast and prostate cancer patients, finding significant improvements in functional capacity (p = 0.005 for the 2-minute step test, p = 0.011 for the sit-to-stand test) but no changes in quality-of-life metrics.[12] Emerging research suggests that virtual reality (VR) may be beneficial in addressing psychological distress and improving patient engagement. Czech et al. examined the impact of VR-based mental health support (VRTierOne) for malignant breast cancer patients. The intervention significantly reduced distress (p = 0.02) and improved adaptive coping mechanisms (p = 0.044), demonstrating the feasibility of immersive therapy in prehabilitation.[13]

Technological advancements in Nutrition

These technologies provide a means to enhance nutritional optimization by enabling the monitoring of dietary intake, contextualizing nutrition in relation to an individual's health, and delivering actionable feedback. Their integration into clinical practice may involve mobile applications for tracking dietary habits, wearable devices for collecting supplementary health data, decision-support tools for managing parenteral nutrition, and telehealth platforms for remote nutritional assessment. Obesity is a significant risk factor for various chronic diseases, contributing to substantial healthcare costs and adverse health outcomes. It is strongly linked to conditions such as diabetes, cardiovascular disease, stroke, and certain cancers. In ERAS, maintaining optimal nutrition is crucial in mitigating obesity-related complications and improving surgical outcomes. Proper dietary intake and physical activity regulation help balance energy consumption and expenditure, preventing excessive fat accumulation and reducing perioperative risks. Personalized nutrition strategies, supported by technological advancements in dietary monitoring, can enhance adherence to ERAS protocols, optimizing patient recovery and long-term health. Traditional self-report methods for tracking food intake have long been utilized, including dietary history, 24-hour recall, and seven-day recall methods. However, these approaches often suffer from low participant adherence and accuracy, with around 10% misclassification rates and only 15% survey completion rates. Moreover, the inconvenience of manual self-reporting discourages consistent dietary monitoring. The advent of smartphone-based self-reporting has significantly improved the convenience and accuracy of dietary tracking. These systems allow users to record their meals digitally and transmit real-time data for analysis. For instance, Wohler developed a smartphone-based food intake survey on the Motorola Q9h, enhancing user experience compared to paper-based reporting. Similarly, Tsai et al. focused on smartphone-assisted calorie intake tracking, improving dietary self-monitoring capabilities.[14] Food Frequency Questionnaires (FFQ) offer another approach to dietary assessment by gathering data on food consumption patterns over time rather than meal-by-meal intake. Digital FFQs, such as the Food4Me system by Fellaize and the 3-day weighed food record (3d-WFR) by Green, streamline data collection while providing a broader nutritional analysis. These technological advancements in dietary monitoring enhance adherence to nutritional guidelines within ERAS protocols, optimizing preoperative nutrition and patient outcomes.[15,16] Recent advancements in food intake monitoring have introduced novel, non-wearable methods that enhance accuracy and convenience. Pressure Method – This technique utilizes force sensors embedded in tablecloths or underneath dining tables to measure weight changes on plates, thereby estimating food consumption. The earliest study by Chang et al. employed a weight sensor under a table to track food transfer with an 80% accuracy rate.[17] A refined system by Zhou et al. introduced a pressure-sensitive dining surface capable of detecting eating movements (e.g., cutting, scooping) but lacked food weight estimation and classification.[18] Surveillance-Video Method – Unlike wearable cameras, this method employs external cameras to detect food intake. Cadavid et al. developed an active appearance model to analyze facial images and detect chewing motions based on their periodic nature, allowing for automated intake tracking.[19] Doppler Sensing Method – This approach utilizes microwave Doppler motion sensors to detect jaw movements during mastication. Tanigawa et al. utilized the Doppler effect to track chewing frequency by analyzing vertical jaw motion, offering a non-invasive alternative for monitoring food intake.[20] These technological advancements present promising automated and objective dietary assessment tools, potentially improving adherence to nutritional protocols in perioperative and clinical settings. Such dietary management systems will not only help tackle problems of weight reduction in the overweight and obese patients posted for surgery but also improve patients suffering from undernutrition and malnutrition posted for various major surgeries.

Technological Innovations for Smoking and Alcohol Cessation

A feasibility pilot study evaluated the web-based smoking cessation program “Smoke-Free Recovery” (SFR) among 31 orthopedic trauma patients, with a mean age of 47.9 years. The study primarily assessed engagement, acceptability, and retention through online platform data and semi-structured telephone interviews. Findings showed that 28 out of 31 participants engaged with the program during hospitalization, but only 2 out of 20 respondents continued post-discharge. Common barriers to program use included lack of time, technical difficulties, computer illiteracy, stress, and feeling unready to quit. Medication-related forgetfulness also impacted engagement. While the study provided a detailed description of intervention, a key limitation was the timing of intervention delivery during hospitalization, which may have affected retention and effectiveness.[21] Another pilot randomized controlled trial (RCT) assessed the usability and effectiveness of a smartphone app targeting smoking, alcohol consumption, physical activity, and unintentional weight loss among 86 patients undergoing major elective surgery (mean age 60years). Assessments were conducted pre-surgery (3 days prior, 58.1%) and post-surgery (30 days post-discharge, 73.2%) using online questionnaires and semi-structured telephone interviews. Findings indicated that patients found the app acceptable (mean usability score: 68.2 [SD 18.4]). The intervention group increased self-reported physical activity and muscle-strengthening exercises before surgery, and 2 out of 2 frequent alcohol users in the intervention group reduced alcohol intake compared to 1 out of 9 in the control group. However, no significant effect on smoking cessation was observed. Postoperative functional recovery showed no meaningful difference between groups after baseline correction ($\beta = -2.4$ [95% CI -5.9 to 1.1]).[22] Interviews reinforced the usability of the app, though further personalization was recommended. A pilot randomized controlled trial (RCT) evaluated the feasibility and effectiveness of “Quit-IT,” a coping skills-based game for smoking cessation in cancer patients ($n = 39$) scheduled for lung or gastrointestinal surgery (mean age 57.4 years). Follow-up assessments were conducted one month post-intervention (61.5% follow-up rate) via surveys, in-game data tracking, and biochemically verified smoking abstinence. Results showed a nonsignificant trend toward increased confidence in quitting (situational self-efficacy) and a stronger intention to remain smoke-free in the intervention group (effect size $d = 0.25$, 95% CI -0.56 to 1.06). Among the 20 patients assigned to the intervention group, 8 played the game, completing an average of 2.5 episodes (range: 1–10). Five out of eight users felt the game helped them cope with smoking urges. Confirmed abstinence was higher in the intervention group (4/13) compared to the control group (2/11).[23]

Role of technology in patient Education and Counseling

Enhanced Recovery After Surgery (ERAS) protocols emphasize patient education as a key component in optimizing perioperative care. Technological advancements have significantly improved patient education by enabling timely and personalized information delivery through digital platforms. Mobile applications, telemedicine, and social media provide real-time guidance on prehabilitation, lifestyle modifications, medication adherence, and postoperative recovery, ensuring patients remain actively engaged in their care. Studies have shown that digital interventions enhance knowledge retention, improve glycemic control in diabetic patients, and reduce adverse surgical outcomes. Telehealth and remote monitoring allow for continuous patient engagement and virtual follow-ups, reducing hospital visits while ensuring adherence to ERAS protocols. Social media platforms and online support networks facilitate peer learning, emotional support, and knowledge-sharing, particularly beneficial for patients with mobility limitations. Additionally, virtual reality (VR) and augmented reality (AR) are emerging as immersive educational tools, helping patients visualize and practice post-surgical rehabilitation exercises. While digital resources have empowered patients, standardization and validation of online health information remain challenges. Physicians are crucial in guiding patients toward credible digital health tools, integrating these resources into ERAS protocols, and leveraging electronic medical records for improved communication. By harnessing these technological advancements, ERAS programs can enhance preoperative preparedness, adherence to recovery guidelines, and overall surgical outcomes.[24]

Role of Health Information Technology in Multidisciplinary Collaboration and ERAS

The integration of mobile health technologies enhances multidisciplinary collaboration in healthcare. A Stanford Hospital study on Voalte, a healthcare-specific mobile app, showed a 20% increase in physician–nurse bedside overlap (50.3%), improving inpatient workflows. Similarly, a qualitative study on ICT (information and communication technologies) in multidisciplinary cancer care teams found that real-time data collection and imaging improved patient-centered care coordination. However, suboptimal ICT use highlighted the need for further research to optimize data collection and workflow integration. This suggests that when implemented effectively, mobile health technologies can strengthen inpatient workflows and interdisciplinary collaboration.[25] ERAS protocols require a structured approach to protocol selection, coordination, implementation, and outcome analysis, making Health Information Technology (HIT) essential for their success. HIT, including electronic health records (EHRs), computerized provider order entry (CPOE), and clinical decision support systems (CDSS), optimizes perioperative workflows by integrating real-time data, improving communication, and standardizing care across multidisciplinary teams. CDSS supports evidence-based decision-making by providing automated alerts, treatment guidelines, and predictive analytics, ensuring consistency in ERAS protocols. These systems help improve diagnosis, medication safety, and personalized perioperative care, enabling seamless collaboration between anaesthesiologists, surgeons, dietitians, and rehabilitation teams. Clinical pathways, also known as fast-track protocols, define structured steps in perioperative management, ensuring standardized interventions and reducing care variability. HIT further facilitates real-time tracking of patient progress, automated reporting, and protocol adherence, ensuring continuous quality improvement. By utilizing clinical indicators—such as postoperative infection rates, length of stay, and complication rates, HIT provides data-driven insights to refine ERAS strategies. Effective HIT integration enhances multidisciplinary collaboration, improves patient safety, and ensures optimal ERAS implementation, ultimately enhancing surgical outcomes and healthcare efficiency. Despite challenges like system interoperability and costs, HIT remains pivotal in modern perioperative care.[26,27,28]

Role of AI in Thromboprophylaxis in the Context of ERAS

AI-driven risk assessment models (RAMs) transform VTE risk prediction, and guide extended thromboprophylaxis in ERAS protocols. Validated RAMs integrate clinical and biochemical markers to optimize anticoagulation strategies while minimizing complications. Clinical trials like MAGELLAN, APEX, and MARINER have identified key VTE risk factors (age ≥ 75, malignancy, prior VTE, thrombophilia, heart failure, severe immobility, and elevated D-dimer). The modified IMPROVE VTE RAM, especially when incorporating D-dimer levels, has shown superior predictive accuracy, with patients scoring ≥ 4 or 2–3 with elevated D-dimer being at nearly threefold higher risk for post-discharge VTE, justifying extended anticoagulation. AI-driven EHR integration of these RAMs enables real-time, automated VTE risk stratification, ensuring personalized thromboprophylaxis, improved patient safety, protocol adherence, and effective VTE prevention without excessive bleeding risks.[29,30,31,32,33] This prospective, randomized study assessed the impact of an AI Clinical Decision Support System (AI-CDSS) on thromboprophylaxis in 19,785 hospitalized patients (control: 9,890; intervention: 9,895). While both groups followed conventional VTE prevention protocols, the intervention group received AI-guided risk assessment and prophylaxis recommendations. AI-CDSS reduced hospital-associated VTE (HA-VTE) by 46%, increased mechanical thromboprophylaxis by 24%, and optimized drug prophylaxis intensity by 9.72%, enhancing patient safety and adherence to ERAS principles. Importantly, AI-CDSS improved efficiency without unnecessary diagnostic testing but did not significantly affect overall prophylaxis rates, indicating a need for further optimization. These findings highlight AI-driven risk stratification as a valuable tool in enhancing thromboprophylaxis and VTE prevention in ERAS protocols while maintaining safety and efficiency.[34]

Technology and preoperative fasting

A pilot preoperative fasting reduction program was implemented in the Emergency General Surgery (EGS) unit at the Royal Melbourne Hospital, Australia, to replace the traditional "fast from midnight" (FFMN) practice with an evidence-based "Eat until 2, drink water until 6" (EU2WU6) protocol. This electronic health record (EHR)-integrated solution aimed to reduce total fasting times (TFT) and reliance on intravenous fluid (IVF). The program's uptake increased from 0% to 80%, significantly lowering TFT (7 vs. 13 hours, $p < 0.001$) and IVF duration (3 vs. 8 hours, $p < 0.001$). Patients using the EU2WU6 protocol were less likely to require overnight IV fluids (18/45 vs. 34/50, $p = 0.0062$). Extrapolated to full hospital-wide implementation, projected savings included 2,050 fewer IVF bags ($2,296 savings), 10,251 minutes of physician time, and 20,502 minutes of nursing time. The findings demonstrate that EHR-based fasting protocols can bridge the gap between clinical evidence and practice, optimizing patient care while reducing unnecessary resource utilization in perioperative care.[35] Technological advancements have transformed preoperative fasting, aligning with ERAS principles to improve adherence and patient outcomes. EHR smart alerts standardize fasting guidelines, reducing unnecessary fasting durations, while mobile apps and telehealth consultations provide real-time instructions and personalized protocols. Wearable devices and point-of-care monitoring track hydration and metabolic responses, enabling individualized fasting strategies that minimize catabolic stress and enhance recovery. This study highlights M-health and e-forms as key virtual healthcare technologies in the preoperative pathway for orthopedics, streamlining patient care and reducing fasting-related complications.[36]

Innovations in Anesthetic management

Automation in anesthetic delivery is advancing rapidly, with Closed-Loop Anaesthesia Delivery Systems (CLADS) representing a key step toward precision medicine. These systems self-regulate anesthetic administration based on real-time patient data, akin to automobile cruise control. While fully automated CLADS are not yet approved in the U.S., they are being integrated into clinical practice internationally, particularly in cardiac and high-risk surgeries for processed EEG monitoring, hemodynamic stability, and fluid resuscitation. A multicenter RCT demonstrated superior BIS and heart rate control ($p < 0.0001$, $p < 0.0031$) with CLADS, significantly reducing inter-center variability ($p = 0.94$ vs. $p < 0.001$ in manual control). These findings highlight CLADS' potential for improved anaesthesia precision and patient safety.[37] A meta-analysis further reinforced the advantages of CLADS-driven total intravenous anesthesia (TIVA), showing improved depth-of-anaesthesia control, reduced sedative consumption, and shorter recovery times. Emerging evidence also suggests that neurocognitive recovery may be enhanced under automated TIVA administration, extending the benefits of these systems beyond the immediate perioperative period. Pediatric applications of CLADS are also under development, potentially offering greater precision and safety in anaesthesia delivery for children. As automated anaesthetic systems continue to evolve, the integration of independent closed loops for hypnosis, analgesia, and fluid management is being actively investigated. While further feasibility studies and regulatory approvals are needed, these innovations promise to enhance anaesthetic precision, improve patient outcomes, and reduce variability in perioperative care. Closed-loop automation functions effectively in ERAS protocols, and high-resolution intraoperative data is required for accurate decision-making. While automated ventilators can stabilize end-tidal carbon dioxide (CO2), challenges such as pulmonary embolism (PE), myocardial infarction (MI), or airway circuit disconnections necessitate human intervention. Advances in non-invasive monitoring have improved perioperative data collection, including continuous non-invasive arterial pressure (CNAP) and ClearSight systems for cardiac output (CO) monitoring and cerebral pulse oximetry. Additionally, processed intraoperative metrics like pulse-wave contour analysis, Analgesia Nociception Index (ANI), Surgical Pleth Index (SPI), and Nociception Level Index (NoL) enhance pain and hemodynamic assessment. However, limitations in nociceptive indices, particularly in chronic pain patients, highlight the need for careful integration into Closed-Loop Anaesthesia Delivery Systems (CLADS). Refining real-time, non-invasive monitoring will optimize automated intraoperative management, improving precision, patient safety, and perioperative recovery in line with ERAS principles.[38]

Role of Emerging Technologies in Perioperative Fluid Management

Goal-directed fluid therapy (GDFT) is a cornerstone of ERAS protocols, aiming to optimize hemodynamic stability and prevent fluid overload or hypoperfusion in patients undergoing major surgery. By utilizing dynamic hemodynamic parameters such as stroke volume variation (SVV) and cardiac output (CO), GDFT enhances tissue oxygenation and organ perfusion, ultimately reducing postoperative complications and expediting recovery. The largest multicenter RCT on GDFT, the OPTIMIZE trial, investigated its impact on 734 high-risk patients undergoing major gastrointestinal surgeries. Patients in the GDFT group, where fluid resuscitation was guided by LiDCO™rapid monitoring, experienced lower rates of 30-day moderate to severe complications and mortality (36.6% vs. 43.4%) compared to controls. However, there were no differences in morbidity on day 7, infection rates, ICU-free days, or all-cause mortality at 30 and 180 days.[39] Importantly, serum biomarkers showed no GDFT-induced cardiac damage, as evidenced by stable troponin I and N-terminal pro-brain natriuretic peptide (NT-proBNP) levels.[40] Similarly, the FEDORA trial, a multicenter RCT on 450 low- to moderate-risk surgical patients, including those undergoing abdominal, urological, gynecological, and orthopedic procedures, found that GDFT guided by esophageal Doppler significantly reduced complications such as acute kidney injury, pulmonary edema, and respiratory distress syndrome (8.6% vs. 16.6%), while also shortening hospital length of stay.[41] However, no significant mortality benefit was observed. Despite these promising findings, some studies challenge the universal efficacy of GDFT in ERAS. For instance, Gómez-Izquierdo et al. found that GDFT using esophageal Doppler did not reduce postoperative ileus despite increasing cardiac output and stroke volume while reducing perioperative IV fluid administration.[42] Challand et al. similarly demonstrated no difference in discharge readiness or length of stay following major colorectal surgery when comparing GDFT and control groups.[43]

Artificial intelligence for Perioperative Pain Management

The integration of artificial intelligence (AI) in ultrasound-guided regional anesthesia (UGRA) is a promising advancement in ERAS protocols, aiding in precision, efficiency, and safety. AI-driven deep neural networks are being employed to identify anatomical structures and optimize needle placement, thereby improving procedural accuracy.[44,45] The ScanNav Anatomy Peripheral Nerve Block, approved by the US FDA in 2022, utilizes deep learning to generate real-time color overlays of key anatomical landmarks, enhancing clinical practice and anaesthesiology training.[46] Studies have shown that false-negative and false-positive rates for anatomical identification using ScanNav were 3.0% and 3.5%, respectively, suggesting a potential reduction in needle trauma and block failure rates.[47] Additionally, AI-based real-time ultrasound interpretation improves image acquisition by nonexperts, making UGRA more accessible in multidisciplinary perioperative care teams.[48] Nerveblox, another AI-powered decision support tool, can capture real-time ultrasound images, label anatomical structures, and assist with peripheral nerve block procedures, including brachial plexus, femoral, and sciatic nerve blocks.[49] AI is revolutionizing postoperative pain management in ERAS by providing objective, data-driven assessment and real-time nociception-guided analgesia, reducing opioid use, recovery delays, and hospital stays. Traditional pain assessment relies on subjective patient reports and vital signs, often leading to variability and bias, which AI helps overcome.[50] For postoperative pain evaluation, AI-based spectrogram–convolutional neural network indices utilize photoplethysmogram analysis to assess pain more accurately.[51] Preoperatively, AI-driven patient selection models identify individuals who may benefit from preoperative pain consultations, ensuring tailored analgesic strategies before surgery.[52] Postoperatively, machine learning algorithms integrate patient vital signs and pain scores to predict analgesic needs dynamically, allowing for personalized, real-time pain management.[53] A closed-loop AI-driven pain control aligns with ERAS by reducing opioid use, enhancing mobility, and optimizing analgesia. AI in UGRA improves precision, while intelligent pain systems enable objective assessment and personalized management, advancing perioperative care.

Technology and Thermoregulation

The 3M SpotOn® Zero-Heat-Flux (ZHF) System provides non-invasive, continuous core temperature monitoring, ensuring accurate, real-time readings critical for ERAS protocols. By maintaining thermal equilibrium between the skin and deeper tissues, the forehead-placed sensor offers a stable reflection of core body temperature, making it ideal for elderly, critically ill, and anesthetized patients. Unlike tympanic thermometry, it remains unaffected by external warming blankets, preventing hypothermia-related complications like blood loss and infections and ultimately enhancing perioperative care, patient safety, and recovery.[54]

Advancements in minimally invasive surgeries

Integrating robotoc-assisted minimally invasive surgery (MIS) with ERAS protocols transforms perioperative care by optimizing key ERAS components, such as minimizing surgical stress, reducing postoperative pain, enhancing early mobilization, and promoting faster return to normal function. In neurosurgery, robotic systems like Neuromate[55] and CyberKnife[56] facilitate precise, minimally invasive procedures, reducing tissue trauma and operative time, lowering postoperative neurological deficits, and shortening hospital stays. In orthopedic surgery, platforms such as Mako and Navio improve preoperative planning and intraoperative accuracy, ensuring optimal implant alignment, leading to faster rehabilitation, reduced opioid dependence, and lower rates of revision surgery.[57,58] Robotic laparoscopy systems like da Vinci, Hugo RAS, and Versius enhance surgical dexterity and visualization, resulting in minimal blood loss, reduced postoperative ileus, and early return to oral feeding, all essential components of ERAS.[59,60,61,62,63] In endoluminal and endovascular procedures, flexible robotic systems like i-Snake and CorPath GRX allow incision-free interventions, reducing postoperative pain, inflammation, and thromboembolic risk, thereby facilitating early mobilization and discharge[64,65,66] The advent of medical capsules and micro/nanorobotics for minimally invasive gastrointestinal endoscopy, such as PillCam and RoboCap, further aligns with ERAS by eliminating invasive diagnostics, reducing mucosal injuries, systemic drug side effects, and allowing same-day procedures, minimizing the duration of hospital admissions.[67,68,69,70,71] These robotic innovations, combined with AI-driven automation, haptic feedback, and multimodal imaging, not only enhance surgical precision but also optimize ERAS-driven perioperative pain control, stable hemodynamics, early ambulation, minimal narcotic use, and rapid patient recovery, marking a significant evolution in surgical care.

Technology and Early Mobilization for ERAS

The MobiStaR project (Mobilization of Intensive Care Patients by a New Standard in Adaptive Robotics) is grounded in the Medical Research Council (MRC) model for complex interventions. "Vemo mobilization" is an innovative approach to early mobilization in Intensive Care Unit (ICU) patients using the VEMO® system (Reactive Robotics GmbH, Germany). This robotic system facilitates verticalization and assisted leg movements directly in the patient's bed, enabling even critically ill patients to begin mobilization with minimal staff assistance and reduced risk of complications. By supporting both passive and active mobilization, VEMO® allows patients to initiate movement even while on mechanical ventilation, significantly reducing the risk of muscle atrophy, deep vein thrombosis (DVT), and pulmonary complications. Additionally, it alleviates the workload on healthcare providers by ensuring safe and consistent mobilization sessions, even in settings with a limited workforce. By promoting faster recovery, shorter

ICU stays, and improved postoperative outcomes, VEMO® integrates seamlessly with ERAS protocols, contributing to reduced surgical stress, improved circulation, and early discharge, making it a valuable advancement in perioperative care and ICU rehabilitation.[72]

Innovation for Early Enteral Nutrition

The smART+ Platform is an advanced nutritional management system integrating a dual port feeding pump, a smart nasogastric tube (NGT) with impedance sensors, and monitoring components to optimize enteral feeding. It detects and manages reflux episodes, preventing aspiration through automatic pausing, gastric pressure adjustments, and esophageal balloon inflation. A VCO2 module measures resting energy expenditure (REE), while a residual bag to weigh reflux and a smart+ urine bag for detecting Urinary Tract Infections (UTIs). Its compensatory feeding mechanism ensures consistent nutrient delivery in critically ill patients. Clinical studies show smART+ improves feeding efficiency, reducing deviations to 10% vs. 30% in controls and achieving nutrition goals in 75% vs. 25% of ICU days. While its ERAS potential remains unexplored, it could revolutionize perioperative nutrition. Additionally, a study using machine learning (ML) models on MIMIC-IV data (53,150 ICU patients) identified sepsis, Sequential Organ Failure Assessment (SOFA) score, acute kidney injury, and body temperature as key enteral nutrition (EN) predictors, with XGBoost achieving an AUC of 0.895. This model supports early ICU EN initiation, aligning with ERAS guidelines for timely nutritional interventions.[73,74]

Early PONV detection

Zhou et al. used Python-based artificial intelligence (AI) models to predict postoperative nausea and vomiting (PONV), an integral part of ERAS protocols, analyzing data from 2,617 patients with 10 machine learning (ML) and deep learning (DL) algorithms, including logistic regression, support vector classifier (SVC), AdaBoost, artificial neural networks (ANN), recurrent neural networks (RNN), long short-term memory (LSTM), and convolutional neural network + RNN (CNN-RNN). The top PONV predictors were haloperidol use, gender (Female > Male), age, smoking history, and prior PONV episodes, with logistic regression, SVC, and AdaBoost demonstrating the highest predictive accuracy. Integrating AI-driven risk prediction models into ERAS pathways enables early identification of high-risk patients, targeted prophylaxis, and optimized perioperative management, reducing complications and enhancing recovery, patient safety, and ERAS efficiency.[75]

Technological Advancements in Glycemic Control

Continuous Glucose Monitors (CGMs) enhance perioperative glycemic control in ERAS by detecting hypoglycemia, hyperglycemia, and glycemic variability. These systems, comprising a subcutaneous sensor, transmitter, and display, offer real-time or retrospective tracking without fingerstick calibration. Professional (clinic-owned) and personal (patient-owned) CGMs, such as Dexcom G6 Pro and FreeStyle Libre Pro, provide precise glucose trend data for optimizing insulin therapy. By enabling real-time glucose adjustments, CGMs help reduce surgical site infections, enhance metabolic stability, and accelerate recovery, aligning with ERAS goals of minimizing surgical stress and complications.[76]

Conclusion

Technological advancements have transformed ERAS by enhancing precision, efficiency, and patient outcomes. Innovations such as robotic surgery, AI-driven glucose monitoring, advanced thermoregulation, and automated nutrition management align with ERAS principles, ensuring faster recovery, reduced complications, and optimized perioperative care. While challenges in cost, accessibility, and integration persist, the future of ERAS lies in greater automation, AI-driven real-time decision support, and fully integrated digital health solutions. Looking ahead, machine learning algorithms will refine predictive analytics, enabling early complication detection and personalized interventions. Wearable biosensors and remote monitoring systems will enhance post-discharge care, further reducing hospital stays and readmissions. Additionally, the integration of closed-loop anaesthesia and pain management systems will improve analgesia precision while minimizing opioid dependency. As virtual reality VR-based prehabilitation and AI-assisted surgical planning gain traction, ERAS protocols will become even more patient-centered and adaptive. By embracing these innovations, perioperative medicine will continue to evolve, offering safer, more efficient, and personalized surgical recovery pathways. The integration of emerging technologies into ERAS protocols will redefine surgical care standards, ultimately leading to better patient experiences and long-term health outcomes.

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Authors' contributions (CRedIT Statement)

Dr Abhishek Bharadwaj(AB) came up with the idea and design of the article. Dr. AB prepared the initial manuscript, edited and proofread the manuscript. All authors read and approved the final manuscript."

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