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Personalized Anesthesia: The Future of Precision Medicine in Surgical Care

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ABSTRACT:

Background: Anesthesia has become remarkably safe, yet patients still vary widely in their response to anesthetic drugs, their perioperative risk, and their recovery. Conventional practice relies largely on population-based dosing and standardized protocols. Precision medicine, which tailors care to individual genetic, physiological, clinical, and environmental characteristics, offers an opportunity to make anesthesia safer and more effective for each patient.

Objective: To review the scientific basis, current applications, and future directions of personalized anesthesia, to identify barriers to implementation, and to propose an integrative framework relevant to surgical care in Saudi Arabia.

Methods: A narrative integrative review of clinical trials, systematic reviews, international guidelines, and pharmacogenomic resources, organized across the perioperative pathway.

Results: Established elements of personalized anesthesia include pharmacogenomic testing for malignant hyperthermia susceptibility, butyrylcholinesterase deficiency, and CYP2D6-mediated opioid metabolism; pharmacokinetic model-based dosing and target-controlled infusion; validated risk stratification tools; and individualized hemodynamic, depth-of-anesthesia, and neuromuscular monitoring. Emerging elements include machine learning prediction of hypotension and mortality, closed-loop drug delivery, and preemptive multi-gene testing. Evidence quality varies, and implementation is limited by cost, infrastructure, training, and concerns about equity and algorithmic bias.

Conclusion: The proposed PRISM Framework (Pharmacogenomic profiling, Risk stratification, Individualized dosing and monitoring, Smart technologies, Multidisciplinary and measured outcomes) provides a structured path for integrating precision medicine into anesthesia, aligned with Saudi genomic initiatives and Vision 2030.

1. INTRODUCTION

1.1 Background

Modern anesthesia is one of the great successes of medicine. Advances in pharmacology, monitoring, training, and safety culture have made anesthesia-related mortality rare in healthy patients. Yet the patients presenting for surgery today are older, have more comorbidities, and undergo more complex procedures than ever before. They also differ substantially in how they respond to anesthetic and analgesic drugs. The same dose of an opioid may provide inadequate analgesia for one patient and cause respiratory depression in another; the same blood pressure may be safe for one patient and associated with organ injury in another. Conventional anesthesia practice addresses this variability through clinical judgment and titration, but its dosing recommendations and protocols are largely derived from population averages.

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Precision medicine seeks to move beyond the average patient. The U.S. Precision Medicine Initiative described it as an approach to disease treatment and prevention that takes into account individual variability in genes, environment, and lifestyle (Collins & Varmus, 2015). In anesthesia, precision medicine encompasses a spectrum of approaches: identifying genetic variants that predispose patients to life-threatening drug reactions; using pharmacokinetic models to individualize drug delivery; stratifying risk to tailor perioperative plans; monitoring each patient's physiological response in real time; and, increasingly, using artificial intelligence (AI) and closed-loop systems to anticipate and respond to individual needs.

1.2 Problem Statement

Although many components of personalized anesthesia already exist, they are applied inconsistently and often in isolation. Pharmacogenomic knowledge is rarely available at the point of care; risk scores are calculated but not always translated into different management; advanced monitoring is used variably; and AI tools are being introduced faster than evidence of their benefit accumulates. In Saudi Arabia, the high prevalence of inherited disorders associated with consanguinity, combined with major national investment in genomics and digital health under Vision 2030, makes the question of how to implement personalized anesthesia particularly relevant.

1.3 Aim and Objectives

This paper aims to review the current state and future direction of personalized anesthesia within precision medicine. Its objectives are to:

- Describe the scientific foundations of precision anesthesia across genomic, pharmacological, physiological, and technological domains.
- Synthesize evidence on applications across the preoperative, intraoperative, and postoperative phases.
- Identify ethical, practical, and organizational barriers to implementation.
- Propose the PRISM Framework and recommendations for implementation in Saudi Arabia.

2. CONCEPTUAL FOUNDATIONS

2.1 Sources of Individual Variability

Variation in response to anesthesia arises from several interacting sources. **Genetic** factors influence drug metabolism, drug targets, and susceptibility to adverse reactions. **Physiological** factors such as age, body composition, pregnancy, and organ function alter pharmacokinetics and pharmacodynamics. **Clinical** factors, including comorbidities, frailty, and concurrent medications, shape both risk and response. **Procedural** factors, such as the type and duration of surgery, determine the physiological stress imposed. Finally, **patient preferences and values** influence choices such as regional versus general anesthesia and the balance between analgesia and side effects. Personalized anesthesia integrates information from all these sources rather than relying on any single one.

2.2 Levels of Personalization

Personalization can be understood as a progression from population-based care to dynamic, real-time individualization, as summarized in Table 1. Most current practice operates at the stratified level, while the frontier of the field lies in individualized and dynamic personalization.

Table 1. Levels of personalization in anesthesia

Level	Basis of decisions	Anesthesia examples
Population-based	Average responses in study populations	Standard weight-based dosing; uniform blood pressure thresholds

Level	Basis of decisions	Anesthesia examples
Stratified	Risk groups defined by clinical features or scores	ASA classification; PONV prophylaxis by Apfel score; cardiac risk indices
Individualized	The specific patient's genotype, physiology, and baseline values	Pharmacogenomic-guided opioid selection; blood pressure targets based on the patient's baseline; model-based TCI
Dynamic (real-time)	Continuous measurement of the patient's response with feedback	Processed EEG-guided dosing; hypotension prediction; closed-loop delivery

2.3 The Perioperative Pathway as the Unit of Personalization

Precision anesthesia should be understood across the entire perioperative pathway rather than only in the operating room. Information gathered before surgery (genotype, frailty, risk scores) shapes the intraoperative plan; intraoperative monitoring generates data that inform postoperative care; and outcomes after discharge provide feedback for refining future decisions. Enhanced recovery after surgery (ERAS) programs have shown that coordinated, evidence-based pathways spanning the perioperative period improve recovery (Ljungqvist et al., 2017). Precision medicine adds a further layer by tailoring elements of these pathways to individual patients.

3. METHODOLOGY

This paper adopts a narrative integrative review design, appropriate for a broad and rapidly evolving field that includes randomized trials, observational studies, pharmacogenomic guidelines, and technology development. Literature was identified through PubMed, Scopus, and Google Scholar using terms related to precision medicine, personalized anesthesia, pharmacogenomics, perioperative risk prediction, target-controlled infusion, depth of anesthesia monitoring, hypotension prediction, closed-loop anesthesia, and machine learning. Guidelines from the Clinical Pharmacogenetics Implementation Consortium (CPIC) and relevant professional societies were included. Priority was given to randomized controlled trials, systematic reviews, and consensus guidelines. Evidence specific to Saudi Arabia was sought on genetic disorders, genomic programs, and perioperative care.

4. PHARMACOGENOMICS IN ANESTHESIA

Pharmacogenomics studies how genetic variation affects drug response. The Clinical Pharmacogenetics Implementation Consortium (CPIC) develops peer-reviewed, evidence-based guidelines that help clinicians translate genetic test results into prescribing decisions (Relling & Klein, 2011). Several gene–drug pairs are directly relevant to anesthesia.

4.1 Malignant Hyperthermia

Malignant hyperthermia (MH) is a potentially fatal pharmacogenetic disorder of skeletal muscle in which exposure to volatile anesthetics or succinylcholine triggers uncontrolled calcium release, causing hypermetabolism, rigidity, hyperthermia, and rhabdomyolysis (Rosenberg et al., 2015). Most susceptibility is associated with variants in the RYR1 gene, and a smaller proportion with CACNA1S. CPIC guidelines recommend that patients carrying a pathogenic variant in either gene should not receive volatile anesthetics or succinylcholine, and should instead receive non-triggering anesthesia (Gonsalves et al., 2019). Because a negative genetic test does not exclude susceptibility, family history and previous anesthetic history remain essential. MH is the classic example of personalized anesthesia: knowing the patient's genotype or family history fundamentally changes the anesthetic plan.

4.2 Butyrylcholinesterase Deficiency

Succinylcholine and mivacurium are metabolized by butyrylcholinesterase (pseudocholinesterase). Inherited variants in the BCHE gene can reduce enzyme activity, leading to prolonged neuromuscular blockade and apnea lasting from minutes to hours after a standard dose (Soliday et al., 2010). Acquired factors, including liver disease, pregnancy, and certain drugs, can also

reduce activity. Identification of affected patients and relatives allows clinicians to avoid these drugs or to plan for prolonged ventilation, and highlights the value of quantitative neuromuscular monitoring.

4.3 Opioid Metabolism: CYP2D6 and OPRM1

Codeine and tramadol are prodrugs whose analgesic effect depends on conversion by the CYP2D6 enzyme to more active metabolites. Patients with CYP2D6 poor metabolizer phenotypes may receive little analgesia, while ultrarapid metabolizers may produce dangerous concentrations of morphine. Deaths have been reported in children who were ultrarapid metabolizers given codeine after tonsillectomy (Ciszkowski et al., 2009; Kelly et al., 2012), leading regulators to restrict codeine use in children. CPIC guidelines recommend avoiding codeine in both ultrarapid and poor metabolizers and using alternative analgesics (Crews et al., 2021). The same guideline reviews evidence on OPRM1, which encodes the mu-opioid receptor, and COMT, concluding that the current evidence is insufficient to support routine dose changes based on these genes alone.

4.4 Other Relevant Gene–Drug Pairs

CPIC guidelines also address CYP2C9 variants and non-steroidal anti-inflammatory drugs such as celecoxib, flurbiprofen, and meloxicam, recommending dose reductions or alternatives for poor metabolizers because of increased exposure and risk of adverse effects (Theken et al., 2020). Other relevant pairs include variants affecting the metabolism of ondansetron (CYP2D6) and of some anticoagulant and antiplatelet drugs encountered in the perioperative period.

4.5 Preemptive Panel Testing

Reactive genetic testing, performed after a problem arises or immediately before a drug is prescribed, is rarely practical in the perioperative timeframe. Preemptive testing, in which a panel of pharmacogenes is tested once and the results stored in the electronic health record for future use, offers a more feasible model. In the PREPARE study, a large, cluster-randomized implementation study across seven European countries, genotype-guided prescribing using a 12-gene panel was associated with a significant reduction in clinically relevant adverse drug reactions (Swen et al., 2023). This supports the integration of preemptive pharmacogenomic results, including anesthesia-relevant genes, into clinical decision support.

Table 2. Pharmacogenomic gene–drug pairs relevant to anesthesia

Gene	Drug(s)	Clinical effect of variant	Recommended action
RYR1, CACNA1S	Volatile anesthetics; succinylcholine	Malignant hyperthermia susceptibility	Avoid triggering agents; use non-triggering anesthesia (Gonsalves et al., 2019)
BCHE	Succinylcholine; mivacurium	Prolonged neuromuscular blockade and apnea	Avoid or reduce dose; quantitative neuromuscular monitoring
CYP2D6	Codeine; tramadol	Poor metabolizers: reduced analgesia; ultrarapid: toxicity	Avoid codeine in poor and ultrarapid metabolizers (Crews et al., 2021)
CYP2C9	Celecoxib; flurbiprofen; meloxicam	Increased exposure and adverse effects in poor metabolizers	Reduce dose or select alternative (Theken et al., 2020)
OPRM1, COMT	Opioids	Variable opioid requirements	Insufficient evidence for routine dose adjustment

5. Individualized Dosing: Pharmacokinetic and Pharmacodynamic Approaches

Even without genetic information, anesthetic dosing can be individualized using models that predict drug concentrations from patient characteristics. Target-controlled infusion (TCI) systems use pharmacokinetic models to calculate the infusion rates

needed to achieve and maintain a chosen plasma or effect-site concentration, adjusting automatically for the patient's age, weight, height, and sex. TCI has been in clinical use for decades and is described as a mature technology (Absalom et al., 2016). Widely used propofol models include the Schnider model (Schnider et al., 1998), and more recent general-purpose models, such as the Eleveld model, were developed from pooled data across a broad range of ages and body sizes, from children to the elderly and obese patients (Eleveld et al., 2018).

Special populations illustrate the importance of individualized dosing. In morbid obesity, dosing based on total body weight can lead to overdose of some drugs, while dosing on ideal body weight can lead to underdosing of others; appropriate dosing scalars, such as lean body weight or total body weight, differ by drug (Ingrande & Lemmens, 2010). In older adults, reduced clearance and increased sensitivity require lower doses, and excessive anesthetic depth may contribute to postoperative complications. In children, rapidly changing physiology demands age-appropriate models. Combining model-based dosing with real-time monitoring of drug effect represents a powerful form of personalization.

6. PERSONALIZED PREOPERATIVE RISK STRATIFICATION

6.1 Established Risk Tools

Preoperative assessment aims to identify each patient's risk and tailor the perioperative plan accordingly. The American Society of Anesthesiologists (ASA) physical status classification remains the most widely used global descriptor of preoperative health, despite limitations in inter-rater reliability (Mayhew et al., 2019). More specific tools estimate particular risks: the Revised Cardiac Risk Index predicts major cardiac complications after noncardiac surgery (Lee et al., 1999); the ARISCAT score predicts postoperative pulmonary complications (Canet et al., 2010); the Apfel score predicts postoperative nausea and vomiting (PONV) (Apfel et al., 1999); and the American College of Surgeons NSQIP Surgical Risk Calculator provides individualized estimates of multiple outcomes based on patient and procedural factors (Bilimoria et al., 2013).

6.2 Frailty

Frailty, a state of reduced physiological reserve and increased vulnerability to stressors, is a strong predictor of adverse postoperative outcomes in older adults, independent of age and comorbidity. Frailty assessment helps clinicians and patients make shared decisions about whether and how to proceed with surgery, and identifies opportunities for prehabilitation and tailored perioperative care (McIsaac et al., 2020).

6.3 Machine Learning Prediction

Machine learning models can integrate large numbers of variables from electronic health records to produce individualized risk estimates. A deep neural network trained on intraoperative and preoperative data predicted postoperative in-hospital mortality with high discrimination in a large single-center dataset (Lee et al., 2018). Such tools could help identify high-risk patients who would benefit from intensive monitoring, intensive care admission, or modified surgical plans. However, models developed in one institution may not generalize to others, and external validation, calibration, and evaluation of their effect on clinical decisions and outcomes are essential before routine use (Hashimoto et al., 2020).

7. Individualized Intraoperative Monitoring and Management

7.1 Individualized Blood Pressure Management

Intraoperative hypotension is common and associated with myocardial injury, acute kidney injury, and mortality. In a retrospective study of noncardiac surgery, mean arterial pressure below 55 mmHg was associated with acute kidney injury and myocardial injury, with risk increasing with duration (Walsh et al., 2013). The INPRESS randomized trial found that an individualized strategy targeting systolic blood pressure within 10% of the patient's own baseline reduced postoperative organ dysfunction compared with standard management in high-risk patients (Futier et al., 2017). A Perioperative Quality Initiative consensus statement concluded that harm is associated with mean arterial pressures below approximately 60–70 mmHg and recommended considering patients' baseline values when setting targets (Sessler et al., 2019). These findings support a shift from uniform thresholds to individualized hemodynamic targets.

7.2 Predicting Hypotension

The Hypotension Prediction Index, a machine learning algorithm derived from arterial waveform features, was developed to predict hypotension minutes before it occurs (Hatib et al., 2018). In the single-center HYPE randomized trial, use of the index with a treatment protocol reduced the duration of intraoperative hypotension compared with standard care (Wijnberge et al., 2020). Larger trials are needed to determine whether such predictive approaches improve patient-centered outcomes, but they illustrate how real-time analytics can move practice from reactive to anticipatory, individualized care.

7.3 Depth of Anesthesia

Processed electroencephalography (EEG) monitors, such as the bispectral index (BIS), provide an estimate of the hypnotic effect of anesthetic drugs in the individual patient. A Cochrane review found that BIS-guided anesthesia can reduce the risk of awareness in high-risk surgical patients and reduce anesthetic consumption and recovery times (Punjasawadwong et al., 2014). However, BIS-guided protocols were not superior to an anesthetic concentration-based protocol for preventing awareness in the BAG-RECALL trial (Avidan et al., 2008), and EEG-guided anesthesia did not reduce postoperative delirium in older adults in the ENGAGES trial (Wildes et al., 2019). These results suggest that depth monitoring is a useful component of individualized care but is not, by itself, sufficient to prevent complex outcomes.

7.4 Neuromuscular Monitoring and Fluid Management

Residual neuromuscular blockade after surgery is common and associated with respiratory complications (Murphy & Brull, 2010). The 2023 American Society of Anesthesiologists practice guidelines recommend quantitative neuromuscular monitoring rather than clinical assessment or qualitative monitoring alone when neuromuscular blocking drugs are used, allowing the reversal strategy to be tailored to each patient's measured level of blockade (Thilen et al., 2023). Fluid management can also be individualized. The OPTIMISE trial of cardiac output-guided hemodynamic therapy in major gastrointestinal surgery did not significantly reduce its primary composite outcome, although an updated meta-analysis included in the report suggested benefit (Pearse et al., 2014), while the RELIEF trial found that a restrictive fluid regimen was associated with a higher rate of acute kidney injury than a moderately liberal regimen, without improving disability-free survival (Myles et al., 2018). Together, these trials suggest that fluid therapy should avoid both extremes and be guided by individual physiology.

8. Closed-Loop Systems and Artificial Intelligence

Closed-loop systems automatically adjust drug delivery based on continuous measurement of a physiological variable, for example titrating propofol and remifentanil to a target BIS value, or titrating vasopressors or fluids to hemodynamic targets. A systematic review and meta-analysis of randomized trials found that closed-loop systems kept controlled variables within target ranges more consistently than manual control, with comparable safety (Brogi et al., 2017). Closed-loop systems embody dynamic personalization: they respond continuously to the individual patient rather than to population-based schedules. They may also reduce cognitive workload, allowing anesthesiologists to focus on higher-level decisions.

AI applications in anesthesiology extend across the perioperative pathway, including risk prediction, monitoring, ultrasound guidance for regional anesthesia, drug delivery, and operating room logistics (Hashimoto et al., 2020). However, important limitations remain: many models are developed retrospectively in single centers, may embed biases present in training data, and may degrade when deployed in different populations or after changes in practice. The World Health Organization's guidance on the ethics and governance of AI for health emphasizes protecting human autonomy, ensuring transparency and explainability, promoting inclusiveness and equity, and maintaining accountability (World Health Organization [WHO], 2021). In anesthesia, these principles imply that AI and closed-loop systems should augment, not replace, the anesthesiologist, who remains responsible for oversight and intervention.

Precision anesthesia does not remove the anesthesiologist from the loop; it gives the anesthesiologist a clearer view of the individual patient within it.

9. PERSONALIZED POSTOPERATIVE CARE

Personalization continues after surgery. Postoperative pain management guidelines recommend multimodal analgesia tailored to the patient, procedure, and preferences, including the use of regional techniques and non-opioid analgesics where appropriate (Chou et al., 2016). Pharmacogenomic information, such as CYP2D6 status, can further guide analgesic selection. The fourth

consensus guidelines for the management of PONV recommend risk-based prophylaxis, with the number of antiemetic interventions increasing with the patient's number of risk factors (Gan et al., 2020). For older adults, the European Society of Anaesthesiology guideline on postoperative delirium recommends preoperative risk assessment, intraoperative monitoring of anesthetic depth, avoidance of known precipitating drugs, and multicomponent non-pharmacological prevention (Aldecoa et al., 2017). Integrating these elements within ERAS pathways allows standardized best practice to be combined with individualized adjustment (Ljungqvist et al., 2017).

10. THE SAUDI CONTEXT

10.1 Genetic Landscape

Saudi Arabia has a high rate of consanguineous marriage, which increases the prevalence of autosomal recessive disorders. Genomic research in the Kingdom has made major contributions to understanding Mendelian disease and has demonstrated the value of genetic testing in this population (Alkuraya, 2014; Saudi Mendeliome Group, 2015). Several conditions with perioperative implications are relatively common in parts of the Kingdom, including sickle cell disease, thalassemias, and glucose-6-phosphate dehydrogenase (G6PD) deficiency. In sickle cell disease, for example, the TAPS randomized trial found that preoperative transfusion reduced perioperative complications in patients undergoing low- or medium-risk surgery (Howard et al., 2013), illustrating how genetic status can directly shape perioperative management. Family clustering of recessive conditions also increases the value of family history and cascade testing for disorders such as butyrylcholinesterase deficiency and MH susceptibility.

10.2 National Genomic and Digital Initiatives

The Saudi Human Genome Program, established to sequence large numbers of Saudi individuals and build a national reference database of genetic variants, provides a foundation for precision medicine, including pharmacogenomics adapted to the local population. Vision 2030 and the Health Sector Transformation Program emphasize innovation, digital health, and quality of care (Ministry of Health, 2017; Health Sector Transformation Program, 2021). Unified electronic health records create an opportunity to store preemptive pharmacogenomic results and deliver them through clinical decision support at the time of anesthesia. Regulatory and professional bodies provide the governance structure: the Saudi Food and Drug Authority regulates medical devices, including software as a medical device and AI-based systems; the Saudi Commission for Health Specialties (SCFHS) oversees training and continuing professional development; CBAHI accreditation standards govern anesthesia and perioperative safety; and the Saudi Data and Artificial Intelligence Authority (SDAIA) has issued AI ethics principles and administers the Personal Data Protection Law (Saudi Data and Artificial Intelligence Authority [SDAIA], 2023).

10.3 Local Challenges

Implementation challenges include the limited availability of pharmacogenomic testing outside major centers, the need for population-specific data on allele frequencies, variability in access to advanced monitoring and TCI across regions, and the need to train anesthesiologists, nurse anesthetists, anesthesia technologists, and pharmacists in genomic and data literacy. Cultural considerations, including family involvement in decisions and attitudes toward genetic testing, should also inform consent and counseling processes.

11. THE PRISM FRAMEWORK

To integrate the evidence reviewed, this paper proposes the **PRISM Framework** for perioperative precision care. Like a prism that separates light into its components, the framework separates the patient's individual characteristics into actionable dimensions, which are then recombined into a single, personalized anesthetic plan.

Table 3. The PRISM Framework for personalized anesthesia

Component	Description	Key tools and evidence	Example indicators
P – Pharmacogenomic profiling	Preemptive and family-history-based identification of clinically actionable genetic variants	CPIC guidelines; preemptive panels; MH and BChE history	Proportion of patients with stored results; adverse drug reactions
R – Risk stratification	Individualized estimation of perioperative risk to guide planning and shared decision-making	ASA; RCRI; ARISCAT; NSQIP; frailty; validated ML models	Risk documented; risk-matched care pathways
I – Individualized dosing and monitoring	Model-based dosing and targets based on the patient's physiology and baseline	TCI; individualized BP targets; processed EEG; quantitative NMB monitoring; goal-directed fluids	Time in target range; residual blockade; hypotension duration
S – Smart technologies	Predictive analytics, decision support, and closed-loop systems under human oversight	Hypotension prediction; closed-loop delivery; decision support alerts	Validated tools in use; alert performance; safety events
M – Multidisciplinary and measured outcomes	Team-based delivery and continuous outcome measurement to refine personalization	Anesthesiologists, surgeons, pharmacists, nurses, geneticists, data scientists; registries	Complications; delirium; PONV; patient-reported outcomes

11.1 Applying the Framework

A practical application of PRISM can be illustrated by an older patient with a family history of prolonged paralysis after anesthesia, scheduled for major abdominal surgery. Pharmacogenomic profiling (P) and family history prompt testing for butyrylcholinesterase deficiency; risk stratification (R) identifies frailty and elevated pulmonary risk, triggering prehabilitation and planning for postoperative monitoring; individualized dosing and monitoring (I) include model-based propofol TCI, blood pressure targets based on the patient's baseline, processed EEG, and quantitative neuromuscular monitoring; smart technologies (S) provide early warning of hypotension; and the multidisciplinary team (M) coordinates analgesia, delirium prevention, and follow-up, recording outcomes to inform future care.

12. Challenges, Ethics, and Recommendations

Several barriers must be addressed. **Evidence** for many personalized interventions remains limited to small or single-center trials, and benefits on patient-centered outcomes are not always demonstrated. **Cost and infrastructure** limit access to genetic testing, advanced monitors, and data platforms. **Workforce readiness** requires new competencies in genomics, data interpretation, and human–technology interaction. **Equity** is a concern if precision approaches are available only in well-resourced centers, or if algorithms trained on non-representative populations perform poorly for some groups. **Privacy and data governance** are essential when genetic and continuous physiological data are stored and analyzed. Finally, **automation bias**, excessive trust in algorithmic outputs, must be guarded against through training and system design.

Table 4. Recommendations for implementing personalized anesthesia

Area	Recommendation
Pharmacogenomics	Integrate preemptive pharmacogenomic results and MH/BChE family history into the electronic health record with point-of-care decision support
Risk assessment	Standardize documentation of validated risk scores and frailty, linked to defined care pathways
Monitoring	Adopt individualized blood pressure targets, quantitative neuromuscular monitoring, and processed EEG where indicated
Technology governance	Require local validation, monitoring, and human oversight of AI and closed-loop systems, in line with SFDA and SDAIA requirements
Education	Incorporate precision medicine, pharmacogenomics, and data literacy into anesthesia training and SCFHS continuing professional development
Research	Develop Saudi pharmacogenomic reference data and conduct multicenter trials of personalized perioperative strategies
Equity	Ensure access to precision approaches across regions and monitor outcomes by patient group

13. LIMITATIONS AND FUTURE RESEARCH

This review is narrative and does not include a systematic search or formal quality assessment, and the rapidly evolving nature of AI and genomic research means that new evidence may emerge quickly. Much of the evidence comes from high-income Western settings, and population-specific data from Saudi Arabia are limited. The PRISM Framework is conceptual and requires prospective evaluation. Future research should evaluate preemptive pharmacogenomic testing in Saudi surgical populations, validate AI tools in local datasets, and determine which combinations of personalized interventions improve outcomes most cost-effectively.

14. CONCLUSION

Personalized anesthesia represents the natural evolution of a specialty that has always relied on careful titration to the individual patient. What is new is the depth and breadth of information now available: genetic variants that predict life-threatening reactions or drug failure, pharmacokinetic models that individualize dosing, risk tools that tailor planning, monitors that reveal each patient's real-time response, and algorithms that anticipate deterioration. The evidence supports some elements, such as pharmacogenomic guidance for MH and codeine, individualized blood pressure targets, and quantitative neuromuscular monitoring, while others require further validation. The PRISM Framework offers a structured approach to integrating these elements across the perioperative pathway. For Saudi Arabia, with its distinctive genetic landscape, national genomic investments, and Vision 2030 commitment to innovation and quality, personalized anesthesia offers a significant opportunity to make surgical care safer and more effective for every patient.

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