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Advancements in Cardiac Anesthesiology: Risk Prediction, Postoperative Outcomes, and Technological Innovations

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Abstract

Cardiac anesthesiology has become increasingly vital in managing the complexities of modern cardiac surgery, where older, high-risk patients and advanced surgical techniques demand precise perioperative care. This review addresses the growing need to integrate innovative risk prediction models, optimize postoperative outcomes, and leverage technological advancements to enhance patient safety and recovery. By synthesizing current evidence, it highlights the evolving role of cardiac anesthesiologists in navigating these challenges. The review offers critical insights into the refinement of risk stratification tools, such as machine learning-enhanced scoring systems and cardiac biomarkers, which improve preoperative decision-making. It examines advancements in postoperative care, including enhanced recovery protocols and opioid-sparing techniques, that reduce complications and accelerate rehabilitation. Technological innovations like transesophageal echocardiography (TEE), artificial intelligence (AI), and closed-loop anesthesia systems are discussed for their transformative impact on intraoperative precision and monitoring. Additionally, the review explores emerging technologies such as augmented reality and portable extracorporeal support, which promise to redefine perioperative management. By analyzing comparative studies on anesthetic regimens, it provides evidence-based guidance for optimizing patient outcomes. Together, these insights underscore the multidisciplinary and patient-centered approach driving progress in cardiac anesthesiology. The findings of this review have significant implications for future practice, emphasizing the potential of data-driven and technology-integrated approaches to elevate perioperative care. Continued research and collaboration will be essential to validate and implement these advancements in diverse clinical settings. Ultimately, these developments will shape the next generation of cardiac anesthesiology, ensuring safer and more effective care for an increasingly complex patient population.

Keywords: Artificial intelligence, Cardiac surgery, Perioperative care, Postoperative outcomes, Risk prediction, Technological innovations, Transesophageal echocardiography

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Introduction

Cardiac anesthesiology has evolved significantly over the past few decades, driven by the need to improve patient outcomes and reduce perioperative risks in increasingly complex cardiac surgeries [1-3]. As surgical techniques advance and patient demographics shift toward older, higher-risk populations, the role of the cardiac anesthesiologist has expanded beyond traditional intraoperative management [4-6]. Today, the specialty integrates risk prediction models, advanced monitoring technologies, and tailored anesthetic strategies to optimize patient care [7-9]. These advancements have not only enhanced safety during procedures but also contributed to better postoperative recovery and long-term survival. This progress underscores the importance of continuous innovation and evidence-based practice in cardiac anesthesiology.

One of the most critical developments in the field is the refinement of risk prediction tools, which enable clinicians to stratify patients based on their likelihood of adverse outcomes [10-12]. Traditional scoring systems, such as the EuroSCORE and STS risk models, have been augmented with machine learning algorithms and large-scale data analytics to improve accuracy [13-15]. These tools help anesthesiologists identify high-risk patients who may benefit from personalized interventions, such as hemodynamic optimization or advanced mechanical support [16, 17]. By leveraging predictive analytics, clinicians can make more informed decisions, ultimately reducing morbidity and mortality [18, 19]. The integration of these models into clinical practice represents a paradigm shift toward precision medicine in cardiac anesthesia.

Postoperative outcomes have also seen remarkable improvements due to advancements in anesthetic techniques and perioperative care.

Enhanced recovery after surgery protocols, multimodal analgesia, and early extubation strategies have shortened intensive care unit (ICU) stays and accelerated rehabilitation [20-22]. Additionally, the growing emphasis on organ protection-particularly for the heart, brain, and kidneys-has led to the adoption of novel pharmacological and non-pharmacological interventions [23, 24]. These approaches mitigate ischemia-reperfusion injury and inflammation, which are key contributors to postoperative complications. As a result, patients now experience fewer adverse events and faster functional recovery, highlighting the pivotal role of anesthesiologists in the surgical care continuum [25-27].

Technological innovations have further revolutionized cardiac anesthesiology, offering unprecedented precision in monitoring and intervention. TEE, near-infrared spectroscopy, and advanced hemodynamic monitoring systems provide real-time insights into cardiac function and tissue perfusion [28-30]. Meanwhile, the advent of AI and closed-loop systems has enabled automated titration of medications, reduced human error and optimized therapeutic efficacy [31, 32]. These technologies not only enhance intraoperative safety but also facilitate early detection of complications, allowing for timely corrective measures. The ongoing integration of cutting-edge tools into clinical practice promises to redefine the standards of care in cardiac anesthesia [33, 34].

Looking ahead, the field of cardiac anesthesiology must continue to adapt to emerging challenges, such as the increasing prevalence of comorbid conditions and the demand for minimally invasive procedures. Collaborative research, multidisciplinary teamwork, and the adoption of innovative technologies will be essential to address these evolving needs. By focusing on risk prediction, postoperative recovery, and technological advancements, cardiac anesthesiologists can further improve patient outcomes and contribute to the broader goals of perioperative medicine. The future of the specialty lies in its ability to harness these advancements while maintaining a patient-centered approach, ensuring that each individual receives the highest quality of care.

Cardiac anesthesiology is a specialized field that focuses on the perioperative care of patients undergoing cardiac surgery. This discipline has seen significant advancements in risk prediction, postoperative outcomes, and the integration of technology, which collectively enhance patient safety and surgical success. This article explores these themes in detail, drawing on recent literature to highlight the current state of the field.

Risk Prediction in Cardiac Anesthesiology

Risk prediction is a critical component of cardiac anesthesiology, as it allows clinicians to identify patients at higher risk for adverse outcomes [35-37]. Various models and indices have been developed to predict these risks, each with their strengths and limitations (Table 1). The integration of preoperative, intraoperative, and postoperative data enhances the accuracy of these predictions, allowing for better patient management and outcomes [38, 39].

A study by Wright et al. [40] included eleven risk indices that collectively analyzed data from 2,910,297 adult patients. This large sample size enhances the reliability of the findings. The studies included in the review varied significantly in several aspects: (i) size (the number of patients studied ranged widely), (ii) population (different patient demographics were considered), (iii) quality and risk of bias (the methodological quality and potential biases varied across studies), (iv) outcome definitions (different studies defined cardiac complications in various ways), and (v) risk factors (each study identified a different set of risk factors, leading to a diverse range of predictive models). Furthermore, the review identified several key factors that were most predictive of adverse cardiac outcomes: congestive heart failure, type of surgery, creatinine levels, diabetes, history of stroke or transient ischemic attack, and emergency surgery. Additionally, advancing age, American Society of Anesthesiology physical status classification, functional status, and hypertension were also noted as significant risks. The risk indices generally fell into two categories: (i) higher accuracy (some indices were more accurate in predicting a narrow range of cardiac outcomes) and (ii) lower accuracy (others had lower accuracy but could predict a broader range of outcomes). The authors suggest that using one index from each group may provide the most clinically useful approach. The review emphasizes that while predictive indices are valuable, the use of clinical judgment remains essential in assessing perioperative cardiac risk. This highlights the importance of integrating both data-driven insights and clinical experience in patient care. These findings provide a comprehensive overview of the current landscape of cardiac risk prediction in noncardiac surgery, offering valuable insights for clinicians in their decision-making processes [40].

A study by Hosseini and Ramazani [41] on the cardiac anesthesia

Table 1: Comparison of risk prediction models in cardiac anesthesiology.

Model	Parameters assessed	Population validated	Discriminative ability (area under curve)	Clinical utility	Key limitations
EuroSCORE II	Age, sex, comorbidities, urgency of surgery	Mixed cardiac surgeries	0.78 to 0.82	Widely adopted, good mortality prediction	Underestimates risk in high-complexity cases
STS score	Procedure type, renal function, LVEF	CABG/valve surgeries	0.75 to 0.80	Procedure-specific risk stratification	Limited to North American populations
CARE score	Creatinine, diabetes, emergency surgery	Cardiac surgery cohorts	0.77 to 0.85	Simple bedside tool, low variability	Less validated for minimally invasive cases
APACHE IV	Acute physiology, chronic health evaluation	Critically ill cardiac patients	0.80 to 0.85	ICU mortality prediction	Complex calculation requires full ICU data
GRACE score	ACS presentation, biomarkers, ECG changes	Acute coronary syndrome	0.82 to 0.88	Acute cardiac events prediction	Not surgery-specific
Machine learning (AI)	EHR data, intraoperative vitals, biomarkers	Multicenter datasets	0.85 to 0.92	Dynamic, real-time updates	Requires large datasets, interpretability
ANZROD	Pre-op factors, intraoperative variables	Australian/NZ cardiac patients	0.81 to 0.86	Regional customization	Limited external validation
Parsonnet score	Age, reoperation, LV function	Historic cardiac cohorts	0.70 to 0.75	Early risk assessment model	Outdated, poor calibration in modern era

risk evaluation (CARE)-score yielded several significant findings regarding its effectiveness in predicting morbidity and hospital stay in cardiac surgery patients. The research was a descriptive-cohort study conducted on 130 cardiac patients at Imam Reza Hospital, Mashhad, over a period of three months. Various data collection tools were utilized, including demographic sheets and the CARE-score itself. A strong positive correlation was found between the CARE-score and morbidity outcomes. The correlation coefficient was r = 0.86, with a p-value of less than 0.001, indicating that as the CARE-score increased, the morbidity rates also increased significantly. The study also revealed a significant relationship between the CARE-score and the length of hospital stay. The correlation coefficient for this relationship was r = 0.72, with a p-value of less than 0.001. This suggests that patients with higher CARE-score values tend to have longer hospital stays. The findings concluded that the CARE-score is a reliable tool for predicting morbidity after cardiac surgery. The authors recommend that anesthesiologists utilize this predictive model preoperatively in cardiac surgery units to better assess patient risks. Overall, the study demonstrated that the CARE-score is a valuable instrument for assessing the risk of adverse outcomes in patients undergoing cardiac surgery, highlighting its potential utility in clinical practice [41].

Another study by Ouattara et al. [42] evaluated the CARE score in 556 patients undergoing cardiac surgery at the Pitié-Salpêtrière Hospital in Paris, France. This was done to assess its predictive performance for mortality and major morbidity compared to two other risk indexes: (i) the EuroSCORE and (ii) the Tu score (Figure 1). The overall in-hospital mortality rate was found to be 5.8%, with a 95% confidence interval (CI) of 3.9% to 7.7%. The major morbidity rate was reported at 24.5%, with a 95% CI of 20.9% to 28.1%. The calibration analysis indicated that there was no significant difference between the expected and observed outcomes for all three scoring systems. This means that the predictions made by the CARE score were accurate when compared to actual patient outcomes. The areas under the receiver operating characteristic curves were calculated to evaluate the discrimination ability of the scores: (i) the CARE score had an area of 0.77 (95% CI: 0.69 to 0.85) for predicting mortality, (ii) the EuroSCORE had a slightly higher area of 0.78 (95% CI: 0.71 to 0.85), and (iii) the Tu score had the lowest area at 0.73 (95% CI: 0.63 to 0.83). However, these differences were not statistically significant. The study also assessed the variability of the CARE score among different groups of physicians. The agreement rate for the CARE score between two anesthesiologists was 90%, between anesthesiologists and surgeons was 83%, and between anesthesiologists and cardiologists was 77%. This indicates a high level of consistency in scoring among different specialists. In conclusion, the CARE score was found to be a reliable tool for predicting mortality and major morbidity after cardiac surgery, with performance comparable to more complex multifactorial risk indexes, and showed minimal variability among different physician groups [42].

The use of cardiac biomarkers has emerged as a valuable tool in this regard. Biomarkers such as cardiac troponins and natriuretic peptides have been extensively studied for their ability to predict future cardiovascular events. Haller et al. [43] emphasize that these biomarkers can significantly enhance risk stratification models, allowing for earlier intervention and potentially preventing major cardiovascular events. In the context of noncardiac surgery, preoperative assessment of cardiac risk is essential. Duceppe and Durand [44] highlights the role of natriuretic peptides in preoperative cardiac risk stratification, recommending their routine use in at-risk patients. This approach not only aids in identifying patients who may benefit from closer monitoring but also informs the choice of anesthetic techniques and perioperative management strategies.

Postoperative Outcomes

The evaluation of postoperative outcomes is crucial for improving patient care in cardiac anesthesiology (Table 2). One significant area of concern is postoperative delirium, which can complicate recovery and lead to long-term cognitive dysfunction [45, 46]. A systematic review by Cai et al. [47] identifies various prediction models for delirium after cardiac surgery, noting that age and cognitive impairment are frequently used predictors. However, the review also points out that many existing

Tu Score		EuroSCORE	
Age		Age	
65–74 yr	2	Per 5-yr increment above 60 yr	1
≥ 75 yr	3		
Emergency within 24 h	4	Emergency within 24 h	2
Urgent	1		
LV dysfunction		LV dysfunction	
EF 35–50%	1	EF 30–50%	1
EF 20–34%	2	EF < 30%	3
EF < 20%	3		
Surgical characteristics		Surgical characteristics	
Single valve	2	Other than CABG	2
Complex	3	Thoracic aortic surgery	3
		Post-MI VSD repair	4
Reoperation	2	Reoperation	3
Female sex	1	Female sex	
		Chronic pulmonary disease	1
		Systolic PAP > 60 mmHg	2
		Peripheral vascular disease	2
		Severe neurologic dysfunction	2
		Serum creatinine > 200 µM	2
		Active endocarditis	3
		Any critical preoperative state	3
		Unstable angina on intravenous nitroglycerin	2
		Recent MI < 90 days	2

CABG = coronary artery bypass graft; EF = ejection fraction; EuroSCORE = European System for Cardiac Operative Risk Evaluation; LV = left ventricular; MI = myocardial infarction; PAP = pulmonary arterial pressure; VSD = ventricular septal defect. ANESTHESIOLOGY

Figure 1: Items of the Tu score and the EuroSCORE [42].

Table 2: Impact of anesthetic techniques on postoperative outcomes in cardiac surgery.

Technique	Key advantages	Mortality impact	ICU/Hospital LOS	Organ protection	Complications addressed	Evidence level
Volatile anesthetics	Cardioprotection, reduced troponin release	OR 0.51 (vs TIVA)	↓1.22 days (hospital)	Myocardial (↓troponin)	Myocardial injury, delirium	Moderate (RCT meta-analysis)
TIVA (propofol)	Stable hemodynamics, rapid wake-up	RR 0.92 (vs volatile)	No significant difference	Neurological (↓delirium trend)	Nausea, cognitive impairment	High (Large RCTs)
OFA	↓Opioid use, faster extubation	Not reported	↓1 day (ICU)	Respiratory (↓ventilation time)	Respiratory depression, chronic pain	Emerging (Single-center RCTs)
Thoracic epidural	Superior analgesia, early extubation	RR 0.89 (vs GA)	↓6.9 h ICU, ↓0.8 day hospital	Pulmonary (↓complications)	Arrhythmias, pulmonary complications	High (Systematic reviews)
Fast-track protocol	Multimodal approach, early mobilization	No difference	↓35% ventilation time	Multi-organ (↓opioid effects)	Pain, opioid-related side effects	Moderate (Observational)
Total spinal anesthesia	↓Ventilation time, ↓opioid requirements	No difference	↓3 days (hospital trend)	Respiratory (↓ventilation)	Pain, ICU resource utilization	Limited (Pilot studies)
Dexmedetomidine	↓Delirium, hemodynamic stability	No difference	↓0.5d ICU	Neurological (↓delirium)	Arrhythmias, hemodynamic instability	Moderate (RCTs)
Ketamine adjunct	↓Chronic pain, opioid-sparing	Not reported	No difference	Neurological (↓chronic pain)	Depression, chronic post-surgical pain	Emerging (Small RCTs)

models suffer from high bias and limited applicability, indicating a need for improved methodologies in future studies. Moreover, the impact of surgical techniques and the use of cardiovascular implantable electronic devices on postoperative outcomes cannot be overlooked. Richardson et al. [48] discussed the complications associated with cardiovascular implantable electronic devices, emphasizing the importance of careful patient selection and preprocedural measures to optimize outcomes.

A study by Howitt et al. [49] aimed to validate three postoperative risk prediction models for ICU mortality after cardiac surgery. A total of 2,255 adult cardiac surgery patients were included in the study, with an observed ICU mortality rate of 1.8% during the evaluation period. All three models-logistic cardiac surgery scores (logCASUS), rapid clinical evaluation (RACE), and sequential organ failure assessment (SOFA) - demonstrated good discrimination for predicting ICU mortality, with areas under the receiver operating characteristic curve exceeding 0.8 across the first seven postoperative days. Among the models, RACE and logCASUS showed better discrimination compared to SOFA. The calibration of the RACE score was found to be superior to that of logCASUS. However, both models had observed to expected mortality ratios generally below 0.65, indicating some calibration issues. The SOFA score, while initially less discriminative, was locally recalibrated and performed well after adjustments. After recalibration, both logCASUS and RACE scores were identified as particularly useful for daily risk prediction in the postoperative setting. This suggests that with appropriate calibration, these models can serve as effective tools for clinicians managing postoperative cardiac surgery patients. The study concluded that all three models exhibited good discrimination for the first week following cardiac surgery. The recalibrated versions of logCASUS and RACE were highlighted as the most beneficial for ongoing risk assessment in the ICU. These results underscore the potential utility of postoperative risk prediction models in improving patient outcomes in cardiac surgery settings [49].

In the realm of surgical and postoperative management, recent studies highlight the role of technological innovations in improving patient outcomes. The management of congenital heart disease has benefited from advancements in surgical techniques and anesthesia, leading to better neurodevelopmental and postoperative results [50]. Furthermore, efforts to refine perioperative care include the development of risk assessment tools aimed at minimizing complications such as bleeding and transfusion requirements, with expert panels emphasizing the importance of quality metrics and patient blood management strategies [51].

Clinical Studies

Recent advancements in cardiac anesthesiology have been significantly influenced by innovative clinical trial designs and the comparative effectiveness of anesthetic agents. These advancements aim to improve patient outcomes by optimizing anesthetic techniques and understanding their effects on surgery patients.

A study by Landoni et al. [52] analyzed 38 randomized controlled trials (RCTs) involving a total of 3,996 patients to compare the effects of volatile anesthetics (isoflurane, desflurane, and sevoflurane) with total intravenous anesthesia (TIVA) on patient survival after cardiac surgery. The results indicated that using volatile agents was associated with a significant reduction in mortality compared to TIVA. Specifically, the mortality rates were 1.3% in the volatile group versus 2.6% in the TIVA group, leading to an odds ratio (OR) of 0.51, which suggests that volatile agents may halve the risk of death. The Bayesian network meta-analysis showed that both sevoflurane and desflurane were individually linked to lower mortality rates compared to TIVA, with ORs of 0.31 and 0.43, respectively. The study found that the majority of the trials (63%) focused on patients undergoing coronary artery bypass grafting (CABG) with standard cardiopulmonary bypass (CPB), which is a common procedure in cardiac surgery. The analysis also highlighted that while each volatile agent showed a trend towards reduced mortality, the differences were not statistically significant when analyzed individually due to the limited number of patients in each subgroup. The authors emphasized the need for a large, multicenter trial to further confirm these findings, as the current evidence comes from relatively small studies. Additionally, the study pointed out that the choice of anesthetic could have implications beyond immediate surgery outcomes, potentially affecting long-term survival due to the cardioprotective properties of volatile agents. Overall, the findings suggest that volatile anesthetics may be a better choice than TIVA for improving survival rates in patients undergoing cardiac surgery, but further research is necessary to solidify these conclusions [52].

A study by Yu and Beattie [53] included a total of 32 RCTs with 2,841 patients to evaluate the effects of volatile anesthetics during CABG. The overall mortality rate among the patients was 2%, with 45 deaths reported. However, the reduction in mortality associated with volatile anesthetics did not reach statistical significance (OR of 0.65, 95% CI, 0.36 to 1.18, $p = 0.16$). The analysis found that volatile anesthetics did not significantly reduce the incidence of acute myocardial infarction (AMI), with an OR of 0.93 (95% CI: 0.64 to 1.34, p = 0.68). Among the different anesthetics studied, enflurane was associated with an increased risk of AMI (OR of 1.34, 95% CI: 0.68 to 2.64, p = 0.40), while newer agents like sevoflurane and desflurane showed a trend towards reduced AMI rates (OR of 0.48, 95% CI: 0.21 to 1.09, p = 0.08) when combined. The study also reported that sevoflurane and desflurane significantly reduced postoperative cardiac troponin I levels, which is a marker for myocardial injury. This reduction was observed multiple times after surgery (6, 12, 24, and 48 h). In terms of electrocardiogram changes, volatile anesthetics did not lead to an increased incidence of ischemic ST-T changes, with an OR of 1.15 (95% CI: 0.95 to 1.38, p = 0.15). The analysis highlighted that not all volatile anesthetics are cardioprotective. While sevoflurane and desflurane showed beneficial effects, enflurane did not demonstrate similar protective qualities and was linked to increased myocardial lactate production. Overall, the findings suggest that while volatile anesthetics like sevoflurane and desflurane may have some benefits in reducing cardiac injury markers, the evidence does not conclusively support a reduction in major clinical outcomes like mortality or AMI [53].

A study Heybati et al. [54] presents a comprehensive analysis of the outcomes associated with different anesthetic regimens in patients undergoing cardiac surgery. The analysis included 53 RCTs with a total of 8,085 participants, focusing primarily on cardiac surgery (46 trials with 6,604 patients). The study evaluated several critical outcomes, including ICU length of stay (LOS), myocardial infarction, in-hospital and 30-day mortality, stroke, and delirium. Sevoflurane with propofol: this combination was found to significantly decrease ICU LOS by an average of 18.26 h compared to propofol monotherapy (mean difference (MD) −18.26 h, 95% CI: −34.78 to −1.73 h). Midazolam with propofol: in contrast, this combination was associated with a significant increase in ICU LOS, averaging 17.51 hours longer than propofol alone (MD 17.51 h, 95% CI: 2.78 to 32.25 h). The use of midazolam was linked to a significantly higher risk of myocardial infarction compared to propofol, with a risk ratio of 1.94 (95% CI: 1.01 to 3.71). The analysis did not find significant differences in other outcomes such as in-hospital mortality, 30-day mortality, stroke, and delirium across the different anesthetic regimens. The findings suggest that the combination of sevoflurane and propofol may be beneficial in reducing ICU LOS for cardiac surgery patients, while midazolam combined with propofol may increase ICU LOS and the risk of myocardial infarction. The authors recommend further exploration of combined anesthetic techniques and future trials in thoracic and vascular surgery. These results provide valuable insights into the efficacy of different anesthetic regimens, highlighting the importance of choosing the right combination for optimal patient outcomes in cardiac surgery [54].

A study by Jiao et al. [55] included a total of 89 RCTs, which involved 14,387 patients undergoing CABG. Among these, 7,719 patients received volatile anesthetics, while 6,668 patients were given TIVA. There was no significant difference in operative mortality between the two groups. The relative risk was 0.92 with a 95% CI of 0.68 to 1.24, indicating that volatile anesthetics did not reduce the risk of death during the hospital stay compared to TIVA. Similarly, the one-year mortality rate showed no significant difference, with a relative risk of 0.64 and a 95% CI of 0.32 to 1.26. This suggests that the type of anesthesia used did not impact the likelihood of death within a year after surgery. Initially, the ICU LOS was shorter for patients receiving volatile anesthetics, with a MD of −4.14 h. However, after further analysis, this difference was not statistically significant, indicating that the initial finding may not be reliable. Patients who received volatile anesthetics had a shorter hospital stay by an average of 1.22 days. This result was confirmed to be statistically significant after sensitivity analysis, suggesting that volatile anesthetics may lead to a quicker recovery in terms of hospital discharge. The study found no significant differences in several safety outcomes, including myocardial infarction, heart failure, arrhythmia, stroke, delirium, postoperative cognitive impairment, and acute kidney injury between the two anesthesia methods. The quality of evidence for most outcomes was rated as low to moderate, indicating that while the findings are informative, they should be interpreted with caution due to potential biases and inconsistencies in the included studies. Overall, the study concluded that volatile anesthetics do not provide significant advantages over TIVA in terms of mortality and safety outcomes for CABG patients, although they may reduce the length of hospital stay [55].

A study Landoni et al. [56] involved 200 patients undergoing high-risk cardiac surgery, with 100 receiving sevoflurane and 100 receiving propofol for anesthesia. All patients completed the follow-up, which was conducted according to the intention-to-treat principle. The primary outcome measured was a composite of death, prolonged ICU stay (defined as more than 2 days), or both. In the propofol group, 36 patients (36%) experienced this outcome, while in the sevoflurane group, 41 patients (41%) did. The relative risk was calculated at 1.14, with a 95% CI of 0.8 to 1.62, indicating no significant difference between the two groups (p = 0.5). Secondary outcomes included the release of cardiac troponin, which is a marker for heart damage. The levels were similar between the two groups: 1.1 ng/ml in the propofol group and 1.2 ng/ml in the sevoflurane group, with no significant difference (p = 0.6). The study also looked at all-cause mortality at 30 days and 1 year. At 30 days, 7 patients (7%) in the propofol group and 8 patients (8%) in the sevoflurane group died, showing no significant difference (p = 0.8). At 1 year, 11 patients (11%) in both groups had died, again with no significant difference (p = 0.9). Additionally, there were no significant differences in re-hospitalizations or adverse cardiac events between the two groups, with rates of 22.5% in the propofol group and 12.4% in the sevoflurane group for re-hospitalizations (p = 0.075). Overall, the study concluded that sevoflurane did not show any beneficial effects compared to propofol on the primary composite endpoint of prolonged ICU stay, mortality, or both in patients undergoing high-risk cardiac surgery [56].

A study Jin et al. [57] evaluated the effectiveness of a new multimodal analgesia regimen compared to a conventional sufentanil-based regimen in cardiac surgery patients. A total of 115 patients were assessed for eligibility, with 108 patients randomized into two groups: the multimodal group (group M) and the control group (group T). Seven cases were excluded from the study. The incidence of moderate-to-severe pain on coughing was similar between the two groups, with 68.5% in group M and 64.8% in group T. This difference was not statistically significant (p = 0.683). Sufentanil usage, group M, which received the multimodal regimen, showed a significant reduction in sufentanil use compared to group T. The average sufentanil consumption was 135.72 μg in group T vs 94.85 μg in group M, with a highly significant p-value of 0.000. The rate of patients requiring rescue analgesia was lower in group M (31.5%) compared to group T (57.4%), which was statistically significant (p = 0.007). There was no significant difference in the incidence of chronic pain, postoperative nausea and vomiting, dizziness, inflammation index, mechanical ventilation time, length of hospital stays, or complications between the two groups. The multimodal analgesia regimen was found to be feasible for cardiac surgery patients. While it did not demonstrate superior analgesic effects compared to the traditional sufentanil-based regimen, it successfully reduced opioid consumption and the need for rescue analgesia. Additionally, it maintained similar LOS and complication rates as the conventional method. These results suggest that while the new regimen may not improve pain management outcomes, it offers benefits in reducing opioid use, which is an important consideration in postoperative care [57].

A study by Jiang et al. [58] aimed to compare the effects of volatile anesthesia and propofol-based TIVA on postoperative delirium in patients undergoing on-pump cardiac valve surgery. This was a RCT conducted at a university academic hospital in China from February 2019 to January 2021. A total of 684 patients were analyzed, with a mean age of 53.8 years, and 55.7% of them were women. The main focus was on the incidence of postoperative delirium within the first 7 days after surgery. The results showed that delirium occurred in: (i) 63 out of 337 patients (18.7%) who received volatile anesthesia (sevoflurane or desflurane) and (ii) 76 out of 339 patients (22.4%) who received propofol-based TIVA. The relative risk of developing delirium with volatile anesthesia compared to TIVA was 0.80, with a 95% CI of 0.55 to 1.16, and a p-value of 0.231, indicating no statistically significant difference between the two groups. The study also evaluated several secondary outcomes, including duration of delirium, subtypes of delirium, 30-day mortality rates, pain scores, major morbidity events (such as cerebral infarction, respiratory failure, and pneumonia), duration of mechanical ventilation, and ICU LOS and hospital LOS. The results indicated that there were no significant differences between the two anesthesia groups in any of these secondary outcomes. In conclusion, the study found that using volatile anesthesia did not lead to a significantly lower occurrence of postoperative delirium compared to propofol-based TIVA in patients undergoing on-pump cardiac valve surgery. This suggests that both anesthesia methods have similar effects on the incidence of delirium in this patient population [58].

A study by Mertin et al. [59] aimed to evaluate the outcomes of total spinal anesthesia (TSA) compared to standard general anesthesia (GA) in cardiac surgery patients. Patients who received TSA were significantly more likely to be extubated in the operating room, with a p-value of less than 0.0001. This suggests that TSA may facilitate quicker recovery from anesthesia compared to GA. TSA group experienced a significantly shorter overall duration of endotracheal intubation, with a p-value of less than 0.0008. This indicates that TSA may lead to a more efficient recovery process post-surgery. During the first 24 h after surgery, patients in the TSA group required significantly less morphine for pain management, with a p-value of less than 0.0001. This finding suggests that TSA may provide better pain control, potentially reducing the need for opioid medications. Although the MD in postoperative hospital LOS did not reach statistical significance, the TSA group was discharged on average three days earlier than the GA group. This could imply that TSA contributes to a more efficient recovery and shorter hospital stays, although further research is needed to confirm this finding. The results highlight the importance of the type of anesthesia used in cardiac surgery and its impact on patient outcomes. The findings can help healthcare teams anticipate TSA patient outcomes and develop effective, evidence-based care plans. In conclusion, the pilot study provides promising evidence that TSA may improve certain aspects of recovery in cardiac surgery patients, warranting further investigation in larger prospective studies [59].

A study by Labaste et al. [60] investigated the outcomes of using total sevoflurane inhalation sedation with a disposable delivery system (Sedaconda-ACD) in cardiac surgery, particularly during the COVID-19 pandemic when intravenous anesthetics were scarce. This was a single-center retrospective study conducted at a large university referral center, focusing on adult patients (age ≥ 18) who underwent elective cardiac surgery with CPB from June 2020 to March 2021. A total of 654 patients were included, with 454 analyzed after matching (297 in the intravenous group and 157 in the inhaled group). The primary outcome measured was the peak level of troponin, which is an indicator of myocardial injury. The results showed no significant difference in postoperative troponin peak levels between the inhaled anesthesia group (723 ng/L) and the intravenous group (993 ng/L), with a p-value of 0.2, indicating that total inhaled anesthesia did not lead to a lower incidence of myocardial injury. The study also looked at the requirement for inotropic medications, which are used to support heart function. The results indicated that total inhaled anesthesia was associated with a decreased requirement for these medications, with an OR of 0.53 (95% CI: 0.29 to 0.99, p = 0.04). Importantly, the study found that there was no increase in postoperative complications associated with the use of the Sedaconda-ACD device for total inhaled anesthesia. In summary, while the use of total inhaled anesthesia with sevoflurane did not reduce myocardial injury as measured by troponin levels, it did result in a lower need for inotropic support without increasing postoperative complications. This suggests that the Sedaconda-ACD device can be a viable alternative for anesthesia in cardiac surgery during times of drug shortages [60].

A study by Weinberg et al. [61] included a total of 175 patients who underwent CABG surgery, with 87 patients in the fast-track group and 88 patients in the usual care group. Patients in the fast-track group experienced a significant reduction in total mechanical ventilation time, averaging a 35% decrease compared to those in the usual care group. This was after adjusting for various factors such as body mass index and surgical urgency. In terms of extubation, 40.2% of fast-track patients were extubated within the first 4 h after surgery, compared to only 11.4% in the usual care group. This resulted in an OR of 5.2, indicating a much higher likelihood of early extubation for fast-track patients. The median time to extubation was shorter for the fast-track group, at 6 h, compared to 7.33 h for the usual care group, which was statistically significant. Pain management was more effective in the fast-track group, with patients reporting lower pain scores in the first 24 h post-surgery. The highest pain score reported was 4 for fast-track patients, while it was 6 for those in the usual care group. Fast-track patients also required significantly less intravenous morphine in the first 24 h, averaging 22 mg compared to 38.75 mg in the usual care group. There were no significant differences in postoperative complications or the length of hospital stay between the two groups, indicating that the fast-track approach did not lead to increased risks. Overall, the implementation of the fast-track cardiac anesthesia protocol using methadone and other adjuvants resulted in improved postoperative outcomes (Figure 2), including reduced pain and opioid use, without adverse safety events [61].

A study by Guinot et al. [62] involved 110 patients who underwent cardiac surgery, with 55 receiving opioid-free anesthesia (OFA) and 55 receiving opioid anesthesia (OA). The total morphine consumption in the first 48 h post-surgery was significantly lower in the OFA group, with an average of 5 mg compared to 15 mg in the OA group. This difference was statistically significant (p = 0.001). Pain scores during the first 48 h after surgery were similar between both groups, indicating that both anesthesia methods provided comparable pain relief. The incidence of major adverse events, assessed through a composite endpoint, was lower in the OFA group (43%) compared to the OA group (68%), which

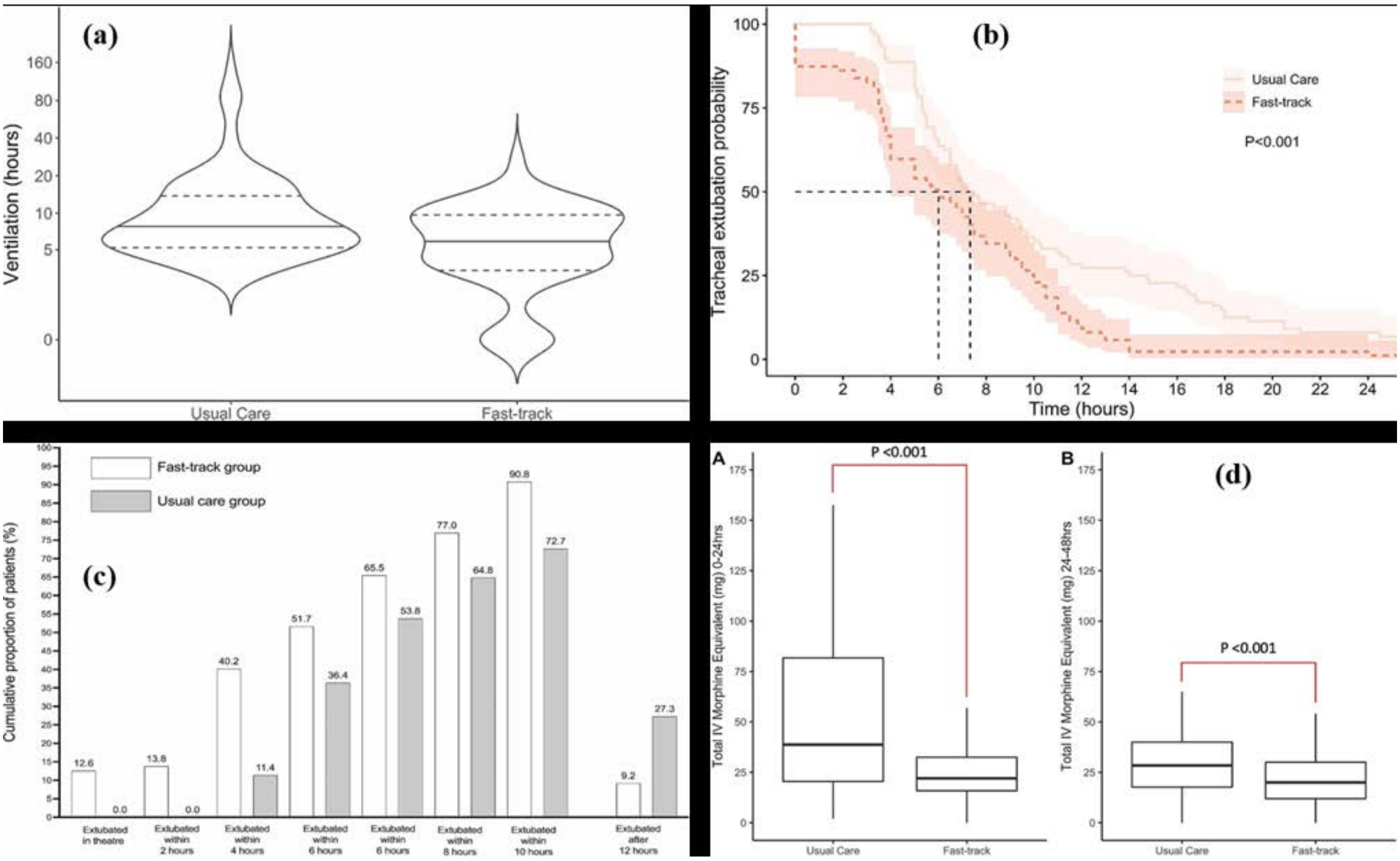

Figure 2: (a) Violin plot comparing total duration of mechanical ventilation (in hours) prior to extubation between the fast-track and standard care groups. **(b)** Kaplan-Meier survival curve illustrating time to tracheal extubation for both groups, with 95% CI based on a log hazard estimate. The graph focuses on the first 24 h to enhance visual clarity between groups. **(c)** Graph showing the cumulative proportion of patients extubated over time. And **(d)** Box plots comparing total intravenous morphine equivalent consumption at 24 h **(A)** and 48 h **(B)** after surgery between the fast-track and standard care groups [61].

was also statistically significant (p = 0.021). Patients in the OFA group experienced shorter times to extubation, averaging 3 h compared to 5 h in the OA group (p = 0.001). Additionally, the ICU LOS was shorter for the OFA group, averaging 2 days versus 3 days for the OA group (p = 0.037). Creatinine levels, which indicate kidney function, did not show significant differences between the two groups on the first postoperative day, suggesting that kidney function was not adversely affected by either anesthesia method. The overall hospital LOS did not differ significantly between the two groups, with the OFA group staying an average of 8 days and the OA group 10 days (p = 0.790). The study concluded that OFA was associated with lower morphine consumption and potentially beneficial effects on the postoperative course for patients undergoing cardiac surgery. These results suggest that using an opioid-free approach in cardiac surgery may lead to improved outcomes without compromising pain management [62].

A systematic review and meta-analysis by Chiew et al. [63] conducted in this paper yielded several important findings regarding the use of thoracic epidural anesthesia (TEA) in cardiac surgery compared to GA. TEA significantly reduced the ICU LOS by an average of 6.9 h (95% CI: −12.5 to −1.2, p = 0.018). Patients receiving TEA had a shorter hospital stay, with a reduction of 0.8 days (95% CI: −1.1 to −0.4, p < 0.0001). The extubation time was also significantly reduced by 2.9 h (95% CI: −3.7 to −2.0, p < 0.0001) for those who underwent TEA. The study found no significant difference in mortality rates between the TEA and GA groups, indicating that while TEA may improve recovery times, it does not affect survival rates. TEA was associated with a significant reduction in various postoperative complications, including pain scores, pulmonary complications, transfusion requirements, delirium, and arrhythmia. The risk of epidural hematomas was estimated to be less than 0.14%, indicating minimal complications. The trial sequential analysis indicated that the cumulative Z-curve passed the trial sequential analysis-adjusted boundary for ICU LOS, hospital LOS, and ET, suggesting a clinical benefit from TEA. In conclusion, the findings from this systematic review and meta-analysis support the use of TEA in cardiac surgery, highlighting its benefits in reducing recovery times and postoperative complications while maintaining safety. These results advocate for the broader adoption of TEA in cardiac surgical practices worldwide [63].

A study by Zhang et al. [64] analyzed the effects of TEA combined with GA compared to GA alone in patients undergoing cardiac surgery. A total of 25 RCTs, involving 3,062 participants, were included in the analysis. The results indicated that TEA did not significantly reduce the risk of death or myocardial infarction when compared to GA alone. The pooled analysis showed a risk ratio of 0.89 for mortality, which was not statistically significant (p > 0.05). Similarly, the risk of myocardial infarction was also not significantly different between the two groups (risk ratio, 0.98, p > 0.05). TEA was associated with a significant reduction in respiratory complications. The risk ratio for respiratory issues was 0.69, indicating that patients receiving TEA had fewer respiratory complications compared to those receiving only

GA ($p < 0.05$). The study found that TEA significantly reduced the incidence of supraventricular arrhythmias, with a risk ratio of 0.61 ($p < 0.05$). Patients who received TEA reported less pain compared to those who only had GA, with a MD of –1.27 on the visual analog scale ($p < 0.05$). TEA was linked to a shorter duration of stay in both the ICU and the hospital. The MD for ICU stay was –2.36 days ($p < 0.05$), while the hospital stay showed a MD of –1.51 days, although this was not statistically significant ($p > 0.05$). The time taken for patients to be extubated was significantly reduced in the TEA group, with a MD of –2.06 h ($p < 0.05$). Overall, while TEA did not significantly impact mortality or myocardial infarction rates, it showed benefits in reducing respiratory complications, pain, and the duration of hospital and ICU stays [64].

Technological Advances in Cardiac Anesthesiology

Cardiac anesthesiology has undergone a transformative shift in recent years, driven by rapid technological advancements that enhance precision, safety, and patient outcomes [65, 66]. Innovations in monitoring, imaging, and drug delivery systems have revolutionized the way anesthesiologists manage high-risk cardiac surgeries [67, 68]. Tools such as advanced hemodynamic monitors, point-of-care ultrasound, and closed-loop anesthesia systems provide real-time data, enabling more accurate decision-making during complex procedures [69, 70]. These technologies not only improve intraoperative stability but also contribute to faster postoperative recovery, reducing complications such as organ dysfunction and prolonged ventilation. As cardiac surgeries become more intricate and patient comorbidities increase, these technological solutions are indispensable in delivering high-quality care [71, 72].

One of the most significant breakthroughs in cardiac anesthesiology is the widespread adoption of TEE, which offers dynamic, high-resolution imaging of cardiac structures and function [73, 74]. TEE allows anesthesiologists to assess valve integrity, ventricular performance, and potential complications like air embolism in real time, guiding surgical and anesthetic interventions [75]. Additionally, advancements in three-dimensional TEE and strain imaging provide even greater diagnostic precision, facilitating early detection of myocardial ischemia and optimizing fluid and inotropic management [76, 77]. Coupled with AI-assisted image analysis, these tools enhance diagnostic accuracy and reduce variability in interpretation, making TEE a cornerstone of modern cardiac anesthesia practice [78].

Technological innovations are transforming cardiac anesthesiology, particularly in the realms of AI and telemedicine. AI has the potential to enhance risk prediction and improve postoperative outcomes by analyzing large datasets to identify patterns and predict complications [79]. Bellini et al. [80] discuss how AI can influence all phases of perioperative care, from risk assessment to postoperative monitoring, thereby improving the quality of care. Furthermore, the integration of telemedicine into anesthesiology practice has shown promise in facilitating preoperative evaluations and postoperative follow-ups [81, 82]. This approach not only enhances patient access to care but also allows for continuous monitoring of patients' conditions, which is particularly beneficial in managing high-risk cardiac patients. Overall, the integration of AI and technological innovations in cardiac anesthesiology is transforming perioperative risk assessment, surgical management, and postoperative care, leading to improved patient outcomes and more personalized treatment strategies [13]. These advancements promise continued progress in the field, emphasizing the importance of ongoing research and technological adoption.

Beyond imaging, automation and AI are reshaping perioperative care through intelligent monitoring and closed-loop systems. Automated anesthesia delivery platforms use algorithms to titrate medications such as propofol and opioids based on real-time patient responses, minimizing human error and maintaining optimal anesthetic depth [83]. Similarly, machine learning models analyze vast datasets-from electronic health records to intraoperative vitals-to predict complications like hypotension or arrhythmia before they occur [84]. These predictive capabilities enable proactive interventions, improving hemodynamic stability and reducing adverse events. Furthermore, integration with telemedicine platforms allows remote expert consultation, expanding access to specialized cardiac anesthesia expertise in resource-limited settings [85].

Looking ahead, emerging technologies such as augmented reality and portable extracorporeal life support systems are poised to further redefine cardiac anesthesiology [86]. Augmented reality overlays real-time imaging and vital signs onto the surgeon's field of view, improving situational awareness during critical phases of surgery [87]. Meanwhile, compact, portable heart-lung machines enable rapid deployment of mechanical circulatory support, bridging unstable patients through high-risk procedures [88]. As these innovations mature, their integration into clinical practice will depend on rigorous validation, interdisciplinary collaboration, and tailored training for anesthesia teams. By embracing these advancements, cardiac anesthesiologists can continue to push the boundaries of safety and efficacy, ensuring optimal outcomes for an increasingly complex patient population.

Conclusion

The field of cardiac anesthesiology is rapidly evolving, driven by advancements in risk prediction, postoperative outcome assessment, and technological integration. The use of cardiac biomarkers for risk stratification, the focus on improving postoperative outcomes, and the incorporation of AI and telemedicine are all contributing to enhanced patient care. As research continues to advance, it is essential for practitioners to stay informed about these developments to optimize patient safety and surgical success in cardiac procedures. The integration of these elements into clinical practice not only improves the management of cardiac patients but also sets the stage for future innovations in the field. Continued collaboration among researchers, clinicians, and technologists will be vital in shaping the future of cardiac anesthesiology.

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Conflict of Interest

None.

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