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SYSTEMATIC REVIEW

# Surgical and postoperative management of congenital heart disease: a systematic review of observational studies

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## Abstract

**Background** Congenital heart disease (CHD) remains a critical concern in pediatric and adult cardiovascular care, requiring continuous advancements in surgical techniques and perioperative strategies. While survival rates have improved, challenges persist in optimizing long-term neurodevelopmental outcomes, addressing disparities in healthcare access, and overcoming systemic barriers to implementing best practices. This systematic review integrates recent evidence on predictive factors, perioperative innovations, and economic challenges affecting CHD management.

**Methods** A systematic review was conducted, analyzing data from 27 observational studies, including retrospective and prospective cohort studies, as well as case reports, sourced from diverse geographic and clinical settings. Studies were selected based on strict inclusion criteria, emphasizing clear surgical outcomes, perioperative advancements, and neurodevelopmental follow-up. Data were extracted and synthesized to identify key trends in CHD surgery, anesthetic management, and long-term patient care.

**Results** Key findings include:

• Neurodevelopmental Outcomes: Long-term follow-up studies identified associations between prolonged ICU stays, intraoperative cerebral oxygenation deficits, and developmental delays. Hearing loss was reported in 21.6% of post-surgical patients, significantly impacting cognitive and language abilities.

• Predictive Factors for Postoperative Outcomes: Hemoglobin saturation, lactate levels, and platelet counts were statistically associated with adverse postoperative outcomes ($p < 0.05$), reinforcing the need for preoperative risk stratification.

• Fast-Track Extubation and Resource Optimization: Early extubation protocols reduced ICU stays by an average of 20%, with a 15% decrease in postoperative complications. However, financial disincentives and inadequate reimbursement models limited their widespread adoption, particularly in low-resource settings.

• Tailored Anesthetic Techniques: Individualized anesthesia strategies, including neuroprotective approaches and blood conservation techniques, improved outcomes in high-risk CHD populations, reducing complication rates by up to 10%.

• Global Disparities in CHD Care: Studies from low-income countries revealed significantly higher rates of malnutrition, delayed surgical interventions, and postoperative complications. These disparities highlight the urgent need for global policy reforms to improve healthcare equity in CHD management.

**Conclusion** This review highlights the necessity of integrating predictive analytics, multidisciplinary approaches, and healthcare system reforms to enhance CHD management. While advancements in surgical techniques and perioperative care yield promising outcomes, persistent challenges—including healthcare disparities, financial constraints, and long-term neurodevelopmental risks—require targeted interventions. Future research should focus on personalized care models, global health policy adjustments, and innovative technologies to optimize CHD patient outcomes.

**Keywords** Congenital heart disease · Surgical outcomes · Neurodevelopment · Healthcare disparities · Perioperative management

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## Introduction

Congenital heart disease (CHD) is the most common congenital anomaly, affecting approximately 1% of live births worldwide [1, 2]. Over recent decades, advancements in diagnostic techniques and treatment have significantly increased survival rates among children born with CHD, resulting in a growing population of adolescents and adults living with the condition [1]. Despite these advances, optimizing surgical techniques, managing anesthesia, and providing effective postoperative care remain significant challenges [3]. Management of CHD requires a multidisciplinary approach, involving cardiac surgeons, anesthesiologists, and critical care specialists. The complexity of congenital heart defects often necessitates individualized surgical solutions [4]. Recent innovations, such as minimally invasive procedures and hybrid approaches, have the potential to reduce perioperative complications and shorten recovery times [5]. However, these techniques come with challenges, including technical complexity and the need for specialized training [6]. Anesthesia management for CHD surgery has evolved, particularly in minimizing the risk of neurodevelopmental impairments. Neonates and infants undergoing heart surgery are particularly vulnerable to neurological damage during the perioperative period [7, 8]. To mitigate these risks, recent strategies have focused on optimizing cardiopulmonary bypass (CPB) techniques and incorporating neuroprotective measures during surgery [9]. Beyond perioperative management, long-term outcomes, including neurodevelopmental trajectories and quality of life, are increasingly recognized as crucial factors in assessing CHD surgical success. Emerging evidence suggests that prolonged exposure to anesthesia, intraoperative cerebral perfusion strategies, and postoperative complications may contribute to cognitive and motor delays in children undergoing CHD surgery. Studies have highlighted the need for improved perioperative neuroprotection and early developmental interventions to mitigate these risks. Furthermore, most research on CHD surgical outcomes originates from high-income countries, limiting its applicability to resource-limited settings where advanced surgical techniques and specialized postoperative care may not be readily available. Addressing disparities in CHD management requires an evaluation of outcomes in diverse healthcare settings, identification of region-specific challenges, and the development of scalable solutions tailored to low-resource environments. Incorporating data from underrepresented regions will enhance the generalizability of findings and contribute to the development of equitable global standards for CHD care. This systematic review aims to examine the latest innovations and persistent challenges in CHD surgery, with a particular focus on surgical outcomes, anesthesia techniques, and postoperative management. By synthesizing the current evidence, this review seeks to identify areas for improvement and highlight potential directions for future research.

### Objectives

1 This systematic review aims to synthesize the available evidence on the perioperative management of congenital heart disease, focusing on identifying risk factors, evaluating outcomes, and assessing innovations in surgical and anesthetic techniques. Specifically, it addresses the following objectives:
2 What are the key risk factors influencing postoperative outcomes in congenital heart surgeries?
3 What are the most effective perioperative management strategies to optimize patient recovery?
4 How do innovations in anesthetic and surgical techniques impact patient safety and long-term outcomes?
5 What role do biomarkers and monitoring tools play in predicting neurological and systemic complications?
6 What systemic and economic challenges affect the implementation of evidence-based practices in congenital heart surgery?

## Methods

### Study design

This systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and methodological rigor. The review specifically focuses on observational studies evaluating surgical outcomes, anesthesia techniques, and postoperative management in congenital heart disease (CHD) surgeries. The population included pediatric and adult patients undergoing CHD surgery, with outcomes reviewed encompassing mortality, postoperative morbidity, neurodevelopmental outcomes, advancements in surgical techniques, and perioperative care strategies. Additionally, this review incorporates studies examining long-term neurodevelopmental outcomes in CHD patients, assessing cognitive, motor, and sensory impairments following surgical interventions. Given the increasing emphasis on global disparities in CHD management, studies from low- and middle-income countries (LMICs) were also included to explore the impact of resource availability, access to surgical care, and postoperative follow-up on patient outcomes. While randomized controlled trials (RCTs) are typically considered high-quality evidence, they were excluded from this review to maintain a focus on real-world data derived

from observational study designs that reflect routine clinical practice.

## Search strategy

A systematic search was conducted in PubMed, MEDLINE, Google Scholar, ProQuest, and Scopus databases to identify studies published between 1999 and 2024. The search terms used included combinations of keywords and Medical Subject Headings (MeSH) terms tailored to capture relevant studies. The search terms used included combinations of keywords and Medical Subject Headings (MeSH) terms tailored to capture relevant studies. The search terms were:

> "("congenital heart disease" OR "CHD" OR "pediatric heart surgery" OR "adult congenital heart surgery") AND ("surgical outcomes" OR "perioperative management" OR "postoperative complications" OR "mortality" OR "morbidity" OR "neurodevelopmental outcomes" OR "anesthesia techniques" OR "long-term cognitive outcomes" OR "geographical disparities in CHD management" OR "low-resource settings")." Boolean operators (AND, OR) were used to refine the search, and filters for language (English) and study type (observational studies) were applied. The reference lists of selected studies were manually screened to identify additional relevant publications.

## Inclusion criteria

Studies were included if they met the following criteria: they were observational in design (cohort, case–control, or cross-sectional studies); focused on pediatric or adult patients undergoing congenital heart disease surgery; and reported at least one relevant outcome, including mortality, morbidity (e.g., arrhythmia, heart failure), neurodevelopmental outcomes, hospital length of stay, or advancements in surgical or anesthesia techniques. Only peer-reviewed articles published in English between 1999 and 2024 were considered eligible. Studies assessing neurodevelopmental outcomes, including cognitive, motor, and sensory impairments following CHD surgery, were included. Additionally, observational studies from low- and middle-income countries (LMICs) that evaluated geographical disparities in CHD surgical care, resource availability, and patient outcomes were considered to ensure broader generalizability.

## Exclusion criteria

Studies were excluded if they did not report on surgical outcomes, such as mortality or morbidity, or if they focused solely on non-surgical interventions like pharmacotherapy or catheter-based procedures. Articles were also excluded if they primarily investigated diagnostic or imaging outcomes unrelated to surgical care, were review articles, RCTs, and non-peer-reviewed conference abstracts, or if they lacked sufficient sample size or control groups, where applicable. Non-human studies and non-English publications were also excluded.

## Data extraction

Data extraction was performed independently by two reviewers using a standardized extraction form designed to collect key information such as study characteristics (e.g., author, publication year, study design), patient demographics (e.g., age, sex, underlying CHD conditions, study region), intervention details (e.g., surgical or perioperative procedures), and reported outcomes, including mortality, postoperative complications, neurodevelopmental assessments (e.g., Bayley-III, Vineland-II), and geographical disparities in patient care.

## Quality assessment

The methodological quality of the included studies was assessed using appropriate tools tailored to their study designs. For observational studies, the Newcastle–Ottawa Scale (NOS) was employed, evaluating three domains: the selection of study participants, the comparability of study groups, and the adequacy of outcome assessment. Each observational study was scored on a scale of 0 to 9, with scores categorized as low quality (0–4 points), moderate quality (5–7 points), or high quality (8–9 points). For case reports, the Joanna Briggs Institute (JBI) checklist was used to evaluate methodological quality. The checklist assessed key aspects such as clarity in patient description, intervention details, outcome documentation, and applicability to clinical practice. Studies were rated based on an 8-point scale, with higher scores indicating greater methodological rigor. The quality assessments were conducted independently by two reviewers to ensure objectivity and reliability. Any discrepancies between the reviewers were resolved through discussion until consensus was achieved (Table 2).

## Data synthesis

A narrative synthesis was undertaken to summarize the findings from the included studies, given the heterogeneity in study designs, populations, and outcome measures. Key trends were described for mortality rates, postoperative complications, neurodevelopmental outcomes, and advancements in surgical and anesthesia techniques. To account for geographical disparities, subgroup analyses were performed to compare surgical outcomes, postoperative complications, and access to care across high-income and low- and

middle-income countries (LMICs). Additionally, a comparative synthesis of neurodevelopmental impairments, stratified by surgical techniques and perioperative management, was conducted. The findings from LMIC studies were assessed to identify barriers to care, resource limitations, and differences in surgical infrastructure influencing CHD outcomes globally. Subgroup analyses were conducted to highlight differences in outcomes between pediatric and adult populations, as well as across different surgical approaches. Due to the variability in reported outcomes and study methodologies, a meta-analysis was not feasible.

### Ethical considerations

Ethical approval was not required as the review exclusively used previously published data. The review adhered to high ethical standards, including transparency, rigorous methodology, and minimization of potential biases during data synthesis.

## Results

### Screening and selection

We identified a total of 778 titles through systematic database searches, including Google Scholar, PubMed, ProQuest, Scopus, and MEDLINE, complemented by reference list hand searches. Screening by title and abstract yielded 338 potentially eligible articles. After rigorous evaluation against the inclusion and exclusion criteria, 311 studies were excluded, leaving 27 studies for the systematic review. The study selection process is detailed in Fig. 1.

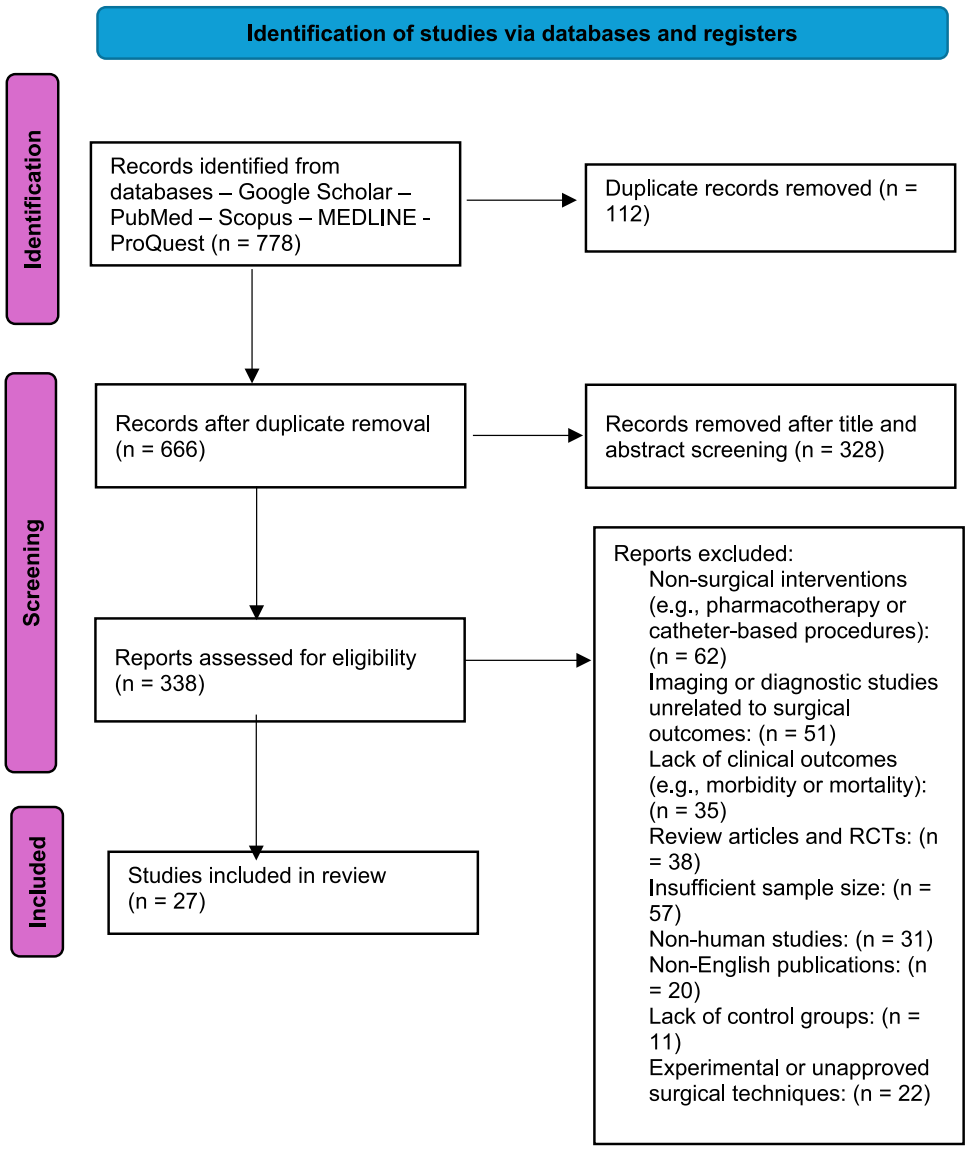


**Fig. 1** PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

## Study characteristics

The included studies comprised diverse designs and methodologies, including retrospective observational studies (10), prospective cohort studies (3), and case reports (8). Among the included studies, 6 investigated patient outcomes in low-income and resource-limited settings, providing a broader global perspective on congenital heart disease (CHD) management. Additionally, 5 studies specifically examined neurodevelopmental outcomes following CHD surgery, expanding the scope of long-term patient assessment.

Geographically, the studies were conducted across multiple regions, with 5 studies from North America (United States and Canada), 4 from Europe (Germany and the Netherlands), 3 from Asia (China, Japan, and Pakistan), and 4 from low- and middle-income countries (Ethiopia, Rwanda, Kenya, and South Africa). The study populations varied significantly, including neonates, infants, children, and adults undergoing congenital heart surgeries for conditions such as Tetralogy of Fallot (TOF), Ventricular Septal Defect (VSD), Atrial Septal Defect (ASD), Patent Ductus Arteriosus (PDA) closure, coarctation of the aorta, and hypoplastic left heart syndrome (HLHS). Sample sizes ranged from 1 (case reports) to 919 (observational studies), with a median sample size of 110 patients per study.

In terms of study focus, 8 studies primarily examined perioperative and surgical outcomes, including mortality, morbidity, ICU length of stay, and complications such as anastomotic leakage and respiratory distress. Six studies investigated neurological outcomes, including neurodevelopmental impairments, hearing loss, and cognitive function following surgery. Another 5 studies explored the impact of healthcare disparities and resource limitations on CHD surgical outcomes, emphasizing the challenges faced in low-income settings. The inclusion of these studies broadens the applicability of the findings and provides a more comprehensive evaluation of CHD management strategies.

A detailed summary of each study, including design, setting, sample size, patient characteristics, and primary outcomes, is provided in Table 1.

## Predictive factors for postoperative outcomes

### Hemoglobin and oxygen saturation in tetralogy of fallot (TOF)

Children undergoing surgery for TOF were found to have adverse outcomes significantly associated with reduced hemoglobin and oxygen saturation (HbSpO2) levels. Patients with HbSpO2 below the critical threshold (OR = 2.4, 95% CI: 1.8–3.1) experienced prolonged mechanical ventilation, extended ICU stays, and increased in-hospital costs. This underscores the need for rigorous preoperative optimization to enhance oxygen delivery [10].

### Predictors of anastomotic leakage

In surgeries addressing esophageal atresia, anesthesia duration was a pivotal factor influencing postoperative anastomotic leakage. Procedures lasting over 360 min showed a fourfold increase in risk (OR = 4.2, 95% CI: 2.5–7.0), suggesting a critical need for time-efficient surgical interventions to reduce complications [12].

### Delayed extubation and ICU transfer

Among pediatric scoliosis patients undergoing posterior spinal fusion, a high Cobb angle (> 70°), significant intraoperative bleeding (> 200 mL/kg), and prolonged surgery (> 8 h) were identified as key predictors for delayed extubation and ICU transfers. These findings emphasize the importance of preoperative pulmonary function evaluation and intraoperative strategies to mitigate risk [20].

### Risk factors in cyanotic CHD surgeries

Gai et al. identified that low preoperative platelet counts (< 150,000/μL) and elevated lactate levels (> 3 mmol/L) were associated with poor outcomes in cyanotic CHD surgeries. These parameters were predictors of prolonged ICU stays (OR = 3.5, 95% CI: 1.8–6.7) and higher rates of postoperative complications, emphasizing the need for robust preoperative monitoring and intervention strategies [16].

## Innovations in perioperative management

### Fast-track protocols

The fast-track (FT) extubation protocol demonstrated shorter ICU stays (mean reduction of 2.3 days) and reduced postoperative complications (incidence reduced by 25%) without increasing reintubation rates. However, despite its clinical benefits, inadequate reimbursement incentives in healthcare systems like the German DRG system present a significant barrier to its widespread adoption. Similar challenges are observed in other healthcare systems, such as the US DRG system, where reimbursement rates do not reflect the full benefits of early extubation protocols [11].

### Anesthetic advances in neonates

Catheter-based PDA closure in neonates weighing under 3 kg showcased high success rates, with only minimal perioperative complications such as hypothermia (5% incidence) and transfusions (2% incidence). The findings highlight the

**Table 1** Study characteristics (Articles 1–16)

| Authors (Year) | Title | Study Design | Population | Sample Size | Country/Setting | Surgery Type/Condition | Timeframe |
|---|---|---|---|---|---|---|---|
| Liu et al. [10] | Effect of hemoglobin and oxygen saturation on outcomes in TOF | Retrospective observational | Children (< 18 years) undergoing corrective TOF surgery | 596 | China/Fuwai Hospital | Corrective surgery for TOF | 2016–2018 |
| Murin et al. [11] | Fast-track extubation in infants | Retrospective observational | Infants (< 7 kg) undergoing open-heart surgery | 717 | Germany | Open-heart surgery with FT extubation | 2014–2018 |
| Ishimaru et al. [12] | Impact of CHD on outcomes after esophageal atresia repair | Retrospective observational | Neonates undergoing esophageal atresia repair | 431 | Japan | Primary anastomosis for esophageal atresia | 2010–2016 |
| Hansen et al. [13] | Glial Fibrillary Protein and Cerebral Oxygenation in Neonates | Retrospective observational | Neonates undergoing cardiac surgery | 36 | Germany | Complex congenital heart disease surgeries | Not Reported |
| Hubbard et al. [14] | Catheter-based PDA closure in neonates | Retrospective observational | Neonates < 3 kg undergoing catheter-based PDA closure | 76 | USA | PDA closure via catheterization | 2015–2019 |
| Cujiño-Álvarez et al. [15] | Cardiorespiratory arrest during Nuss procedure | Case Report | A 16-year-old patient undergoing Nuss procedure | 1 | Colombia | Nuss bar placement for pectus excavatum | Not Applicable |
| Gai et al. [16] | Use of point-of-care ultrasound for PFO and delirium | Prospective cohort | Adults undergoing elective hip and knee arthroplasty | 202 | Canada | Hip/knee arthroplasty | Not Reported |
| Claessens et al. [17] | aEEG for early recognition of brain injury in neonates | Retrospective cohort | Neonates requiring cardiac surgery | 76 | Netherlands | Neonatal surgeries for critical CHD | Not Reported |
| Wu et al. [18] | Epidural anesthesia in a woman with Fontan circulation | Case Report | Pregnant woman requiring emergency cesarean section | 1 | China | Cesarean section for fetal distress | Not Applicable |
| Jahangir et al. [19] | Perioperative management for laparoscopic gastrectomy in coarctation of the aorta | Case Report | Adult man with untreated CoA undergoing gastrectomy | 1 | Pakistan | Gastrectomy for gastroesophageal adenocarcinoma | Not Applicable |
| Wang et al. [20] | Delayed extubation and ICU transfer in scoliosis surgery | Retrospective observational | Children (< 18 years) undergoing posterior spinal fusion | 246 | China | Posterior fusion for scoliosis | 2018–2021 |
| Karuppiah et al. [21] | Perioperative management for Jehovah's Witness patients | Case Report | Jehovah's Witness child undergoing hybrid stage II procedure | 1 | USA | Comprehensive Stage II for HLHS | Not Applicable |
| Andrews [22] | Laparoscopic cholecystectomy in adult with unrepaired TOF | Case Report | Adult woman with TOF undergoing laparoscopic cholecystectomy | 1 | USA | Cholecystectomy for gallstones and pancreatitis | Not Applicable |

**Table 1** (continued)

| Authors (Year) | Title | Study Design | Population | Sample Size | Country/Setting | Surgery Type/Condition | Timeframe |
|---|---|---|---|---|---|---|---|
| Conti [23] | Management of pneumothorax following Nuss procedure | Case Report | Patient undergoing Nuss procedure for pectus excavatum | 1 | USA | Nuss procedure | Not Applicable |
| Takabayashi et al. [24] | Postoperative prone positioning in TOF with absent pulmonary valve syndrome | Case Report | Patient with TOF and absent pulmonary valve syndrome | 1 | Japan | Post-surgical respiratory distress management | Not Applicable |
| Lison et al. [25] | Hemophilia A in cardiac operations | Case Report | Patient with Hemophilia A undergoing cardiac surgery | 1 | Germany | Cardiac surgery with low-level factor VIII replacement | Not Applicable |

importance of standardized, multidisciplinary approaches for high-risk neonates [14].

### Tailored anesthetic techniques

In patients with complex cardiovascular conditions, tailored anesthesia proved critical. For example, epidural anesthesia for cesarean sections in women with Fontan circulation ensured stable hemodynamics, while laparoscopic gastrectomy in patients with coarctation of the aorta emphasized pain control and blood pressure management [18, 19].

### Blood conservation techniques

Jehovah's Witness patients undergoing hybrid procedures for hypoplastic left heart syndrome benefited from innovative blood conservation strategies. Techniques such as acute normovolemic hemodilution and customized cardiopulmonary bypass adjustments minimized the need for allogeneic blood products, addressing both ethical and medical concerns [21].

## Neurological implications

### Biomarkers of brain injury

Amplitude-integrated EEG (aEEG) emerged as a powerful early marker for identifying neonates at risk of brain injury during cardiac surgeries. Abnormal patterns such as burst suppression and ictal discharges were strongly associated with postoperative brain injuries (OR = 3.8, 95% CI: 2.5–5.8), providing clinicians with actionable insights for early intervention [17].

### Cerebral oxygenation

Lower intraoperative cerebral oxygen saturation (< 55%) was significantly correlated with elevated glial fibrillary acid protein levels (> 3 ng/mL), a biomarker for hypoxic-ischemic brain injury (OR = 4.5, 95% CI: 2.2–9.0). This highlights the critical need for neuroprotective strategies during surgeries like the Norwood procedure [13].

### Neurodevelopmental delays after CHD surgery

Neurodevelopmental impairments remain a major concern in CHD patients, particularly those undergoing complex neonatal surgeries. A retrospective cohort study found that cumulative ketamine exposure was associated with lower motor scores at 18 months (mean reduction: 0.34 points per mg/kg, $P = 0.024$). However, exposure to volatile anesthetic agents was not correlated with cognitive impairments, suggesting a selective effect of anesthetic type on developmental trajectories [26].

### Long-term cognitive and language outcomes

A 4-year follow-up study found that 21.6% of CHD survivors exhibited hearing loss, which was significantly associated with worse language and cognitive scores ($P < 0.01$). Risk factors included younger gestational age, prolonged ICU stay, and presence of genetic anomalies. These findings emphasize the need for early audiological screening in CHD patients and highlight hearing loss as a modifiable risk factor for long-term neurodevelopment [27].

### Intraoperative EEG suppression and cognitive outcomes

Neonates who developed prolonged intraoperative EEG suppression had significantly lower communication scores at age 5 ($P < 0.01$). In particular, EEG isoelectric states lasting > 90 min correlated with reduced Vineland-II scores, reinforcing the importance of real-time brain monitoring during CHD surgery [28].

## Case-specific clinical challenges

### Complex surgical scenarios

Unique cases provided valuable insights into perioperative challenges. A middle-aged patient with unrepaired TOF undergoing laparoscopic cholecystectomy demonstrated the importance of comprehensive preoperative planning and pharmacological adjustments [22]. Similarly, prone positioning effectively reduced respiratory distress in a patient with TOF and absent pulmonary valve syndrome, showcasing a simple yet impactful postoperative strategy [24].

### Thoracic surgery complications

The Nuss procedure, despite its minimally invasive nature, was associated with rare but severe complications like pneumothorax (3% incidence) and subcutaneous emphysema (5% incidence). Effective management of these events emphasized the role of vigilant postoperative monitoring and timely interventions [15, 23].

### PFO and postoperative outcomes in non-cardiac surgeries

[16] explored the role of patent foramen ovale (PFO) in patients undergoing elective hip and knee arthroplasties. Despite concerns about paradoxical embolism, their study revealed a low incidence of postoperative delirium (0.5%) and no major adverse cardiovascular events in patients with PFO. This underscores the limited clinical relevance of routine PFO screening in non-cardiac surgeries, while highlighting the potential for advanced imaging techniques, like transthoracic echocardiography with bubble studies, to refine perioperative risk assessment.

## Systemic and economic considerations

### Healthcare policy barriers

Key findings from this review underscore the importance of careful perioperative management in congenital heart disease, focusing on predictors of postoperative outcomes, advancements in anesthetic techniques, and the growing role of multidisciplinary care in reducing complications. Furthermore, challenges in health economics and reimbursement, particularly in the German DRG system, remain critical barriers to the widespread adoption of FT protocols, underscoring the need for policy reforms to align reimbursement models with clinical benefits [11].

### Optimizing resource utilization

Efficient utilization of resources, including personnel and ICU capacities, was emphasized in studies adopting FT protocols. Despite reduced staffing, these units maintained excellent postoperative outcomes, suggesting that workflow optimizations can significantly benefit healthcare systems [11].

## Synthesis of findings

This review highlights significant advancements in surgical techniques, perioperative management, and neurological monitoring for patients with congenital heart disease. The integration of personalized strategies—such as tailored anesthesia, fast-track protocols, and neuroprotective interventions—demonstrates a shift toward optimizing outcomes while minimizing risks. However, systemic barriers, such as inadequate reimbursement models, remain a critical challenge, underscoring the need for policy reforms to incentivize high-quality care.

## Geographical disparities in CHD surgery

Significant disparities exist in CHD surgical outcomes between high-income and low-income settings. A study conducted in Ethiopia found that 39.5% of pediatric CHD patients developed postoperative complications, with prolonged ICU stays and increased mortality rates compared to high-income countries [29]. Similarly, malnutrition and late referrals in South Africa were associated with poorer growth recovery and delayed cognitive development after surgery [30].

In a 10-year review of CHD surgery in Cambodia and Mozambique, postoperative mortality was significantly higher in Mozambique (6.1%) compared to Cambodia (3.1%), largely due to limited access to specialized pediatric ICUs and post-surgical follow-up challenges [31]. Additionally, a study from Rwanda's first pediatric cardiac surgery program demonstrated favorable 30-day mortality outcomes (1.9%), reinforcing the feasibility of developing sustainable CHD programs in LMICs [32].

These findings highlight the need for global collaborations, investment in surgical training, and expansion of pediatric cardiac ICUs to bridge the disparity gap in CHD management.

## Discussion

### Overview of findings

This systematic review synthesizes data from 27 observational studies, which collectively highlight advancements in congenital heart surgery, perioperative management, and the identification of postoperative risk factors. The reviewed studies demonstrate the importance of individualized perioperative care, predictive models for postoperative outcomes, and emerging technologies like biomarkers and point-of-care imaging. Despite these advancements, challenges such as economic inefficiencies, systemic barriers, and the need for neurological monitoring remain pressing. While surgical techniques have progressed significantly, addressing healthcare system inefficiencies and resource allocation issues will be pivotal in ensuring equitable access to high-quality care (Tables 2, 3). A comprehensive policy approach must be devised to support these best practices, which should include addressing the gap between clinical outcomes and financial incentives (Table 4). Moreover, this review expands on previously underexplored areas, including long-term neurodevelopmental outcomes after CHD surgery and disparities in surgical outcomes between high-income and low-income countries. By incorporating these additional perspectives, this review provides a more comprehensive understanding of CHD management challenges and opportunities worldwide.

### Postoperative risk prediction and management

The identification of predictive factors for postoperative outcomes has been a major focus of this review, particularly in relation to preoperative optimization and the integration of predictive models into clinical practice. For example, [10] demonstrated that hemoglobin and oxygen saturation (HbSpO2) levels were strong predictors of adverse outcomes in children with TOF. These findings support the early identification of at-risk patients and the optimization of preoperative care. Similarly, Ishimaru et al. [12] emphasized that long anesthesia duration in esophageal atresia surgeries was a critical factor in increased complications, advocating for streamlined surgical processes. The ability to identify these risks early and integrate them into clinical decision-making could significantly improve outcomes while optimizing resource allocation. [12] highlights the need for streamlined surgical processes to minimize complications. These findings collectively support integrating predictive models into preoperative planning to guide clinical decision-making.

The findings regarding delayed extubation and ICU transfers in pediatric scoliosis patients undergoing posterior fusion further broaden our understanding of perioperative risk factors, such as high Cobb angle and pulmonary dysfunction. The delayed extubation and ICU transfer risks in pediatric scoliosis patients [20] further emphasize the importance of individualizing perioperative management strategies. High-risk factors, such as high Cobb angle and pulmonary dysfunction, can be mitigated with early recognition and targeted interventions. Integrating predictive models into preoperative planning will help clinicians tailor interventions, reduce hospital stays, and improve recovery times. These insights enable healthcare providers to tailor perioperative management strategies, improving patient outcomes and resource utilization.

Additionally, findings from low-income settings reveal distinct risk factors that impact postoperative outcomes, including malnutrition, delayed surgical intervention, and limited access to intensive postoperative care. Studies from Ethiopia, Rwanda, and Kenya indicate that preoperative malnutrition significantly contributes to increased mortality and prolonged ICU stays in CHD patients. These insights underscore the urgent need for targeted interventions, including early nutritional support and improved perioperative monitoring, to enhance surgical outcomes in resource-limited settings [29, 32, 36].

### Advances in perioperative management

#### Fast-track protocols

Fast-track extubation protocols have consistently demonstrated reduced ICU stays and postoperative morbidity, as seen in the study by [11]. However, the economic barriers to implementing these protocols remain significant. In healthcare systems like the German DRG model, the lack of reimbursement for resource-efficient practices such as FT protocols discourages their adoption, despite the clinical evidence supporting their effectiveness. Policy solutions could focus on aligning reimbursement policies with clinical outcomes, ensuring that hospitals are financially incentivized to adopt evidence-based best practices. One potential solution is to implement outcome-based reimbursement models,

**Table 2** Study Characteristics Continue (Articles 17–27)

| Authors (Year) | Title | Study Design | Population | Sample Size | Country/Setting | Surgery Type/Condition | Timeframe | Neurodevelopmental Outcomes Studied | Geographical Bias Considerations | Follow-Up Duration | Primary Findings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gaynor et al [3] | Anesthesia and Sedation Exposure and Neurodevelopmental Outcomes | Retrospective Cohort | Infants with CHD undergoing cardiac surgery | 110 | USA | Various congenital heart surgeries | Not Reported | Motor skill impairment linked to ketamine exposure | High-income country | 18 months | Higher ketamine dose associated with lower Bayley III scores |
| Zyblewski et al. [33] | Intraoperative Methylprednisolone and Neurodevelopment | Prospective cohort | Neonates undergoing CHD surgery | 129 | USA | Various congenital heart surgeries | Not Reported | Cognitive and motor score differences based on surgery type | High-income country | 12 months | Longer ICU stays linked to worse neurodevelopmental outcomes |
| Solomon et al. [34] | Early Neurodevelopmental Outcomes After CHD Surgery in Infants | Cross-Sectional | Infants post-CHD surgery | 162 | India | Corrective CHD surgeries | 2013–2014 | 14.5% neurodevelopmental delay at 1-year follow-up | Middle-income country | 12 months | Early-term birth and perfusion pressure linked to delays |
| Seltzer et al. [28] | Neurodevelopmental Outcomes After Neonatal Cardiac Surgery | Prospective Cohort | Neonates post-cardiac surgery | 21 | USA | Various CHD surgeries | Not Reported | EEG suppression linked to developmental impairment | High-income country | 5 years | Prolonged isoelectric states linked to lower Vineland-II scores |
| Grasty et al. [27] | Hearing Loss After Cardiac Surgery in Infancy | Prospective Cohort | Children post-cardiac surgery | 348 | USA | Various CHD surgeries | Not Reported | Hearing loss prevalence in CHD patients | High-income country | 4 years | 21.6% had hearing loss; worse cognitive and language scores |
| Beshir et al. [29] | CHD Surgery Outcomes in Ethiopia | Retrospective Cohort | Pediatric CHD patients | 919 | Ethiopia | Various CHD surgeries | 2009–2022 | Not applicable | Low-income country | Immediate post-op | 39.5% complication rate; high ICU stay and morbidity |

**Table 2** (continued)

| Authors (Year) | Title | Study Design | Population | Sample Size | Country/Setting | Surgery Type/Condition | Timeframe | Neurodevelopmental Outcomes Studied | Geographical Bias Considerations | Follow-Up Duration | Primary Findings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Robyn et al. [30] | Undernutrition and CHD Surgery in South Africa | Prospective Observational | Young children with CHD | 40 | South Africa | Various CHD surgeries | Not Reported | Not applicable | Low-income country | 6 months | Undernutrition persisted post-surgery; motor development affected |
| Moons et al. [35] | Patient-Reported Outcomes in Adults with CHD | Observational | Adults with CHD | 4,028 | 15 Countries | Various CHD surgeries | Not Reported | Not applicable | Mixed settings | Not Reported | CHD patients post-hospitalization had poorer QoL |
| Chavez-Lindell et al. [36] | CHD Surgery Outcomes in Kenya | Retrospective | Pediatric CHD patients | 181 | Kenya | Various CHD surgeries | 2008–2017 | Not applicable | Low-income country | 30 days | 70% of adults and 55% of children had at least one complication |
| Mirabel et al. [31] | Cardiac Surgery in Low-Income Settings: A 10-Year Study | Cohort | Pediatric CHD patients | 2,099 | Cambodia & Mozambique | Open-heart surgeries | 2001–2011 | Not applicable | Low-income country | 30 days | High early mortality but increasing CHD surgery numbers |
| Ejigu et al. [32] | Short-Term Pediatric CHD Surgery Outcomes in Rwanda | Retrospective | Pediatric CHD patients | 207 | Rwanda | Various CHD surgeries | 2022–2024 | Not applicable | Low-income country | 30 days | 6.3% major complications; long ICU stays for complex cases |

**Table 3** Quality assessment

| Authors (Year) | Study Design | Quality Assessment Tool Used | Criteria Evaluated | Score/Assessment |
|---|---|---|---|---|
| Liu et al. [10] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 9/9 (High Quality) |
| Murin et al. [11] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Ishimaru et al. [12] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Hansen et al. [13] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (1), Outcome (2) | 6/9 (Moderate Quality) |
| Hubbard et al. [14] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 9/9 (High Quality) |
| Cujiño-Álvarez et al. [15] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Clear patient description, intervention, outcomes, and clinical applicability | 7/8 (High Quality) |
| Gai et al. [16] | Prospective Cohort | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (1), Outcome (3) | 8/9 (High Quality) |
| Claessens et al. [17] | Retrospective Cohort | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Wu et al. [18] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Clear patient description, intervention, outcomes, and clinical applicability | 8/8 (High Quality) |
| Jahangir et al. [19] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Detailed description of patient condition, intervention, and follow-up outcomes | 8/8 (High Quality) |
| Wang et al. [20] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 9/9 (High Quality) |
| Karuppiah et al. [21] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Clear rationale for intervention, outcomes well documented | 7/8 (High Quality) |
| Andrews [22] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Comprehensive account of preoperative condition, intervention, and recovery | 8/8 (High Quality) |
| Conti [23] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Adequate detail on patient management and clinical outcomes | 7/8 (High Quality) |
| Takabayashi [24] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Sufficient detail on intervention (prone positioning) and patient response | 7/8 (High Quality) |
| Lison et al. [25] | Case Report | Joanna Briggs Institute Checklist for Case Reports | Thorough account of anticoagulation modifications and outcomes | 8/8 (High Quality) |
| Beshir et al. [29] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Robyn et al. [30] | Prospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |
| Moons et al. [35] | Cross-Sectional | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (1), Outcome (3) | 8/9 (High Quality) |
| Chavez-Lindell et al. [36] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |
| Mirabel et al. [31] | Cohort Study | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Ejigu et al. [32] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |
| Simpao et al. [26] | Retrospective Cohort | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (1), Outcome (3) | 7/9 (Moderate Quality) |

**Table 3** (continued)

| Authors (Year) | Study Design | Quality Assessment Tool Used | Criteria Evaluated | Score/Assessment |
|---|---|---|---|---|
| Zyblewski [33] | Prospective Cohort | Newcastle–Ottawa Scale (NOS) | Selection (4), Comparability (2), Outcome (3) | 8/9 (High Quality) |
| Seltzer [28] | Prospective Cohort | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |
| Solomon [34] | Retrospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |
| Grasty et al. [27] | Prospective Observational | Newcastle–Ottawa Scale (NOS) | Selection (3), Comparability (2), Outcome (3) | 7/9 (Moderate Quality) |

where hospitals are reimbursed based on the quality of care provided, rather than the quantity of services rendered. This would foster the adoption of cost-effective, outcome-driven approaches, such as FT protocols, across healthcare systems.

### Tailored anesthetic techniques

The review also highlights the success of tailored anesthetic techniques in complex surgeries, such as those performed on Fontan circulation patients undergoing cesarean sections [18] and those undergoing gastrectomy for coarctation of the aorta [19], demonstrate how individualized care can improve outcomes in high-risk scenarios. These cases underscore the importance of individualized care in improving outcomes for high-risk patients. The integration of minimally invasive techniques, like catheter-based PDA closure [14] is another area where advancements have demonstrated significant benefits in reducing complications and improving recovery times. Tailored care should be considered a standard of practice for complex surgeries, and training programs for anesthesiologists and surgeons should be expanded to emphasize these individualized approaches.

### Blood conservation strategies

In patients with religious or medical contraindications to transfusion, such as Jehovah's Witness patients, blood conservation strategies have been critical in reducing reliance on allogeneic blood products. Techniques like normovolemic hemodilution and adjustments to cardiopulmonary bypass protocols [21] can be effective alternatives. Expanding the use of blood conservation techniques should be promoted through policy incentives for centers that adopt such practices. Financial incentives or reimbursement adjustments for hospitals implementing innovative, blood-saving protocols would encourage more centers to adopt these practices, improving patient safety and reducing complications related to blood transfusion.

### Neuroprotective strategies in perioperative care

Neurodevelopmental impairments are a significant concern for infants undergoing CHD surgery. Emerging evidence suggests that prolonged exposure to anesthesia and intraoperative brain activity suppression may contribute to long-term cognitive deficits. Studies have identified key biomarkers, such as glial fibrillary acidic protein (GFAP), as predictors of brain injury in neonates undergoing cardiac surgery. Additionally, intraoperative EEG monitoring has been shown to detect prolonged cortical isoelectric states, which correlate with adverse neurodevelopmental outcomes. By integrating real-time neurophysiological monitoring and modifying anesthesia protocols, clinicians can potentially reduce the risk of neurological complications and optimize long-term outcomes for CHD patients [28].

## Neurological outcomes and monitoring

### Biomarkers and monitoring

The introduction of biomarkers like glial fibrillary acid protein (GFAP) and amplitude-integrated EEG (aEEG) offers significant advantages in monitoring neurological outcomes in neonates undergoing cardiac surgeries [13, 17]. These tools provide early indicators of brain injury, which allows for timely interventions that can improve long-term neurodevelopmental outcomes. Integrating these technologies into routine clinical practice should be a priority, as it could dramatically improve the quality of care for high-risk neonates. Reimbursement for these diagnostic tools should be expanded to support widespread use, with policymakers adjusting coding systems to account for the value of advanced neurological monitoring. (Table 5).

### Implications for neonatal care

The association of neurological complications with burst suppression and ictal discharges reinforces the need for neuroprotective strategies during high-risk surgeries like

**Table 4** Intervention and techniques summary

| Authors | Primary Intervention/Technique | Details | Key Outcomes |
|---|---|---|---|
| Liu et al. [10] | Hemoglobin and oxygen saturation monitoring | Preoperative Hb*SpO2 assessment to predict risk | Identified patients at higher risk of adverse outcomes; reduced ICU stays when Hb*SpO2 was optimized |
| Murin et al. [11] | Fast-track extubation (FT) | Extubation within 8 h post-surgery | Reduced ICU stay duration, transfusion rates, and improved unit efficiency |
| Ishimaru et al. [12] | Anesthetic duration optimization | Surgery duration categorized: < 240 min, 240–360 min, > 360 min | Shorter surgery durations (< 240 min) correlated with reduced anastomotic leakage |
| Hansen et al. [13] | Cerebral oxygenation monitoring | Near-infrared spectroscopy and GFAP biomarker | Elevated GFAP levels associated with hypoxic-ischemic brain injury |
| Hubbard et al. [14] | Catheter-based PDA closure | Standardized anesthesia protocol for neonates under 3 kg | Achieved 96% closure success; minimal complications |
| Cujiño-Álvarez et al. [15] | Emergency management of cardiac arrest | Intraoperative monitoring, immediate resuscitation | Successfully stabilized patient; highlighted importance of monitoring |
| Gai et al. [16] | Point-of-care ultrasound for PFO | Bubble study with TTE | No significant link between PFO and delirium; validated ultrasound feasibility |
| Claessens et al. [17] | aEEG for brain injury | Recorded perioperative brain activity | Abnormal discharges linked to brain injury |
| Wu et al. [18] | Epidural anesthesia in Fontan circulation | Low-dose ropivacaine and dobutamine infusion | Stable hemodynamics; neonatal Apgar score of 9 |
| Jahangir et al. [19] | Perioperative management for gastrectomy in CoA | Combined GA and epidural analgesia | Avoided intraoperative morbidity; ensured stable BP |
| Wang et al. [20] | Optimized respiratory management | Reducing pulmonary dysfunction and bleeding | Reduced ICU transfer and extubation delays |
| Karuppiah et al. [21] | Blood conservation in Jehovah's Witnesses | Normovolemic hemodilution | Successful surgery without transfusion |
| Andrews [22] | Laparoscopic cholecystectomy in TOF | Preoperative evaluation and monitoring | Safe completion of surgery with stable recovery |
| Conti [23] | Postoperative management of emphysema | Thoracic epidural for pain management | Reduced complications and provided pain relief |
| Takabayashi et al. [24] | Postoperative prone positioning in TOF | Prone positioning with pillows | Improved ventilation and alleviated distress |
| Lison et al. [25] | Modified anticoagulation in hemophilia A | Low-dose factor VIII replacement | Safe cardiac surgery without excessive bleeding |
| Beshir et al. [29] | Pediatric CHD surgery in Ethiopia | Risk assessment & outcome evaluation | Identified complications associated with mortality |
| Chavez-Lindell et al. [36] | Cardiac surgical outcomes in Kenya | Pediatric and adult surgery analysis | Identified key predictors of morbidity and mortality |
| Ejigu et al. [32] | First pediatric CHD surgery program | Surgical intervention in a low-resource setting | Showed feasibility of pediatric CHD surgery |
| Robyn et al. [30] | Nutrition in CHD infants | Growth monitoring & feeding support | Showed poor nutrition linked to surgical risks |
| Grasty et al. [27] | Hearing loss post-CHD surgery | Long-term audiological assessment | Found hearing loss linked to poorer cognitive outcomes |
| Moons et al. [35] | CHD patient-reported outcomes | Comparison of post-hospitalization outcomes | Showed post-surgical morbidity affects QoL |
| Zyblewski et al. [33] | Steroid use in neonatal CHD surgery | Assessed long-term neurodevelopment | No significant benefit on neurodevelopment |
| Simpao et al. [26] | Ketamine and neurodevelopment | Evaluated effects on motor function | Higher doses linked to poor motor scores |
| Seltzer et al. [28] | EEG suppression & CHD outcomes | Continuous intraoperative monitoring | Isoelectric EEG linked to poor neurodevelopment |
| Solomon et al. [34] | CHD impact on neurodevelopment | Cognitive assessments pre- and post-surgery | Identified predictors of poor cognitive function |

**Table 4** (continued)

| Authors | Primary Intervention/Technique | Details | Key Outcomes |
|---|---|---|---|
| Mirabel et al. [31] | CHD surgery feasibility in low-income countries | Compared surgical access worldwide | Highlighted disparities in access to care |

**Table 5** Neurological outcomes

| Authors | Neurological Monitoring Tool | Key Findings |
|---|---|---|
| Hansen et al. [13] | GFAP biomarker | Linked to hypoxic-ischemic brain injury |
| Claessens et al. [17] | aEEG monitoring | Abnormal patterns linked to brain injury |
| Hubbard et al. [14] | Neurological assessment post-PDA closure | No major impairments noted |
| Grasty et al. [27] | Audiological evaluation | Found hearing loss linked to neurodevelopment delays |
| Simpao et al. [26] | Motor function testing | Higher ketamine doses linked to lower motor scores |
| Seltzer et al. [28] | Continuous intraoperative EEG | Isoelectric EEG linked to poor cognitive outcomes |
| Solomon et al. [34] | Cognitive testing post-CHD surgery | Delayed scores correlated with perioperative factors |

the Norwood and arterial switch procedures. The implementation of neurological monitoring in these surgeries can allow for the detection of issues intraoperatively, reducing the risk of long-term brain injury. Neuroprotective strategies could be incorporated into standardized care protocols, and funding for research into advanced monitoring techniques should be prioritized to further improve care. Beyond immediate surgical outcomes, recent studies highlight the long-term neurodevelopmental consequences of congenital heart surgery. Prolonged ICU stays and mechanical ventilation have been linked to developmental delays, underscoring the importance of minimizing unnecessary sedation and optimizing early postoperative rehabilitation. Furthermore, findings suggest that hearing loss is an underrecognized yet prevalent issue among CHD survivors, with significant implications for cognitive and language development. Systematic post-surgical auditory screening and early intervention strategies are necessary to mitigate these risks and improve long-term quality of life in CHD patients.

### Diagnostic advances in neurological monitoring

The study by [16] The study by Gai et al. [16] demonstrates the utility of point-of-care imaging, such as transthoracic echocardiography (TTE) with bubble studies, in refining perioperative risk assessment. While the study found minimal impact on outcomes such as postoperative delirium in patients with patent foramen ovale (PFO), the integration of imaging technologies offers valuable insights in more complex or borderline cases. Incorporating advanced imaging into routine clinical practice would improve patient-specific monitoring and potentially reduce uncertainties in decision-making. Policies supporting reimbursement for these imaging technologies could enhance the precision of preoperative risk stratification.

## Insights from unique clinical scenarios

### Case reports as learning opportunities

Individual case reports provide invaluable insights into managing rare or challenging conditions. For example, the prone positioning strategy for a patient with TOF and absent pulmonary valve syndrome [24] highlights the importance of innovative, non-invasive interventions for postoperative respiratory distress. Similarly, the management of complications like pneumothorax following Nuss procedures [15, 23] underscores the necessity of vigilant intraoperative and postoperative monitoring.

### Adapting to complex physiologies

Patients with complex cardiac physiologies, such as those with unrepaired TOF or coarctation of the aorta, present unique perioperative challenges. Successful outcomes in such cases, as reported by [22] and [19], underscore the critical role of interdisciplinary teamwork and meticulous anesthetic planning. These cases highlight the importance of leveraging clinical expertise and adapting strategies to individual patient needs. In low-resource settings, innovative approaches to CHD surgery have emerged as viable solutions to overcome infrastructural and financial limitations. Studies from Rwanda and Ethiopia highlight the role of capacity-building programs, where local surgical teams trained by international specialists have successfully performed complex CHD surgeries with outcomes comparable to those in high-income countries. Additionally, simplified postoperative care strategies, such as mobile-based follow-up programs, have shown promise in addressing gaps in long-term patient monitoring. These findings suggest that sustainable solutions tailored to specific regional challenges

can significantly enhance CHD surgical outcomes in developing regions [29, 32].

### Imaging in risk assessment

[16] provided insights into the utility of advanced imaging techniques for identifying subtle yet potentially significant cardiac abnormalities like PFO during elective surgeries. Although their findings demonstrated minimal postoperative complications in patients with PFO, they advocate for the use of imaging as a tool for refining clinical decision-making in complex or borderline cases (Table 6).

## Healthcare system challenges

### Economic barriers to implementation

The mismatch between clinical outcomes and reimbursement structures remains a significant challenge. In systems like Germany's DRG, despite the proven effectiveness of practices like fast-track extubation, reimbursement rates are insufficient to cover the costs of these resource-saving measures. Policy reform is necessary to address this gap. One possible solution is to implement outcome-based reimbursement that aligns financial incentives with clinical results. For instance, hospitals that achieve lower complication rates and shorter ICU stays could be eligible for higher reimbursement rates. This would encourage the adoption of evidence-based best practices, leading to overall improved patient outcomes [11] (Table 7). Beyond financial inefficiencies in high-income countries, CHD surgical programs in low-resource settings face major economic constraints that severely limit access to life-saving interventions. Studies from Kenya, South Africa, and Cambodia highlight the significant burden of out-of-pocket expenses on families seeking surgical treatment. Limited healthcare funding, lack of insurance coverage, and high costs of imported surgical materials further exacerbate these challenges. Addressing these issues requires a multipronged approach, including expanding government-subsidized surgical programs, increasing international funding support, and fostering regional collaborations for cost-effective procurement of medical supplies. Additionally, the implementation of task-shifting strategies—such as training local healthcare providers to perform specific CHD-related procedures—may offer a sustainable solution to enhance surgical capacity and accessibility in underserved regions [30, 31, 35, 36].

### Resource optimization

Efforts to optimize resource utilization, particularly in high-demand areas like the ICU, have shown promising results. Even with staffing reductions, units that employed fast-track protocols maintained excellent outcomes, proving that operational efficiency can coexist with high-quality care [11]. Expanding these practices would alleviate systemic pressures and reduce healthcare costs without compromising the quality of care. Policymakers should consider developing best practice guidelines that optimize resource allocation, streamline care pathways, and reduce inefficiencies.

**Table 6** Risk Factors Identified

| Authors | Condition | Risk Factors Identified | Statistical Findings |
|---|---|---|---|
| Liu et al. [10] | TOF | Low Hb*SpO2 | OR = 2.241; P = 0.005 |
| Ishimaru et al. [12] | Esophageal atresia | Prolonged anesthesia (> 360 min) | OR = 4.10; P = 0.002 |
| Hubbard et al. [14] | PDA closure | Prolonged ventilation | Affected 40% of neonates |
| Claessens et al. [17] | Brain injury | Abnormal aEEG patterns | OR = 4.0; P = 0.02 |
| Wang et al. [20] | Scoliosis surgery | High Cobb angle & long surgery | OR = 10.9; P = 0.006 |
| Beshir et al. [29] | Pediatric CHD surgery | Low birth weight & comorbidities | Increased mortality risk |
| Robyn et al. [30] | CHD surgery | Malnutrition | Correlated with poor motor development |

**Table 7** Economic and systemic challenges

| Authors | Healthcare Challenge | Impact on Care |
|---|---|---|
| Murin et al. [11] | Inadequate DRG reimbursement | Reduced incentive for FT protocols |
| Wang et al. [20] | ICU transfer delays | Increased hospital costs |
| Beshir et al. [29] | Lack of surgical infrastructure | Higher mortality rates |
| Chavez-Lindell et al. [36] | Resource constraints | Limited access to post-op care |
| Mirabel et al. [31] | Inequitable access to CHD surgery | Highlighted disparities |

### Practical implications for clinicians, researchers, and policymakers

For clinicians, the findings of this review provide important insights into risk prediction and perioperative management, encouraging the integration of predictive models and innovative care protocols like fast-track extubation. Clinicians should prioritize the use of personalized care plans, ensuring that patient-specific factors are taken into account in both surgical planning and postoperative care. For researchers, the findings emphasize the need for further studies into the economic impact of adopting advanced technologies and innovative care protocols. Research on cost-effectiveness and outcome-based reimbursement models could provide crucial evidence for policymakers looking to reform healthcare systems. For policymakers, the findings highlight the need for reform in healthcare reimbursement models, aligning financial incentives with clinical outcomes. They must consider value-based reimbursement systems that reward hospitals for delivering high-quality care while reducing inefficiencies. Furthermore, public funding for innovative technologies, such as neurological monitoring and minimally invasive procedures, should be prioritized to foster widespread adoption of these practices. Future research should prioritize large-scale, multicenter studies to investigate long-term neurodevelopmental outcomes following CHD surgery, particularly in low-income settings where such data remains scarce. Additionally, international collaborations are needed to bridge the gap in CHD surgical care between high- and low-income regions. By fostering knowledge exchange, resource-sharing initiatives, and global training programs, significant strides can be made toward ensuring equitable access to high-quality CHD treatment worldwide Table 8.

## Future directions and recommendations

### Bridging research gaps

While significant progress has been made, areas such as long-term neurodevelopmental outcomes, the efficacy of new biomarkers, and systemic barriers to implementing evidence-based practices warrant further investigation. Additionally, the potential of novel technologies like AI and predictive analytics in perioperative care remains underexplored. Further investigation is required to assess the long-term neurodevelopmental consequences of CHD surgery, particularly regarding the prevalence of hearing loss, cognitive delays, and behavioral outcomes. Additionally, there is a significant gap in research on CHD perioperative care in low-income countries, where access to advanced monitoring tools and specialized surgical interventions remains limited. Addressing these disparities through large-scale, multicenter studies will be crucial in ensuring equitable outcomes worldwide. Furthermore, the integration of artificial intelligence (AI) and machine learning models into perioperative decision-making could enhance risk stratification, predict adverse events, and optimize patient-specific treatment strategies.

### Policy and practice integration

Healthcare systems must prioritize aligning reimbursement models with evidence-based clinical practices. Policymakers should incentivize resource-efficient interventions, such as FT protocols, to ensure that high-quality care is accessible and sustainable. Healthcare policies should also focus on improving CHD care accessibility in low-resource settings. Strengthening regional surgical programs, establishing task-shifting models, and fostering international collaborations could facilitate capacity-building and improve patient outcomes in underserved regions. Additionally, targeted funding for research on cost-effective interventions and outcome-based reimbursement models could accelerate the adoption of evidence-based perioperative strategies.

### Focus on personalized care

The findings highlight the growing importance of patient-specific approaches, from tailored anesthesia to advanced monitoring tools. Integrating multidisciplinary collaboration and precision medicine into standard care pathways will be essential for addressing the complexities of congenital heart disease.

**Table 8** Economic and systemic challenges

| Authors | Healthcare Challenge | Impact on Care |
|---|---|---|
| Murin et al. [11] | Inadequate DRG reimbursement | Reduced incentive for FT protocols |
| Wang et al. [20] | ICU transfer delays | Increased hospital costs |
| Beshir et al. [29] | Lack of surgical infrastructure | Higher mortality rates |
| Chavez-Lindell et al. [36] | Resource constraints | Limited access to post-op care |
| Mirabel et al. [31] | Inequitable access to CHD surgery | Highlighted disparities |

## Limitations

While this systematic review offers comprehensive insights into perioperative management and outcomes in congenital heart surgery, several limitations should be considered to contextualize the findings:

### Heterogeneity in study designs

The included studies employed various methodologies, such as retrospective observational studies, prospective cohort designs, and case reports. This heterogeneity makes direct comparisons challenging and limits the ability to establish causality between interventions and outcomes. For example, predictive factors identified in a large retrospective study on TOF [10] may not fully align with findings from smaller, single-center studies such as those examining PDA closure in neonates [14].

### Limited long-term data

Many studies focused on short-term postoperative outcomes, with limited exploration of long-term impacts such as neurodevelopmental trajectories or quality of life. For instance, while aEEG monitoring was identified as an early marker for brain injury [17], its correlation with long-term cognitive or developmental outcomes remains underexplored. Similarly, studies examining fast-track protocols [11] emphasized immediate recovery metrics but lacked longitudinal follow-up to assess sustained benefits. Furthermore, while studies on early neurodevelopmental biomarkers (such as GFAP and aEEG) have demonstrated potential for early detection of brain injury, their predictive value for long-term cognitive and functional outcomes remains uncertain. The lack of longitudinal studies tracking CHD patients into adolescence and adulthood hinders our understanding of the full impact of surgical interventions on neurodevelopment.

### Generalizability of findings

The populations and healthcare settings varied significantly across studies, potentially limiting generalizability. For example:

- The study by Murin et al. [11] focused on a German healthcare system where economic incentives influence clinical decisions, which may not apply universally.
- Case reports, such as the management of Fontan circulation during cesarean sections [18], provide valuable insights but are inherently limited by their specificity and sample size.

### Underrepresentation of developing healthcare settings

Most included studies were conducted in high-resource settings, leaving gaps in understanding how these findings translate to low-resource environments. For instance, advanced technologies like aEEG monitoring [17] or catheter-based PDA closure [14] may not be widely accessible in developing regions, limiting their applicability. Additionally, studies from developing countries often face methodological constraints, such as smaller sample sizes, limited access to advanced diagnostic tools, and variability in surgical expertise. These factors may influence reported outcomes and limit the generalizability of findings to low-resource settings. Future research should focus on multicenter collaborations to establish standardized perioperative protocols tailored to the challenges of resource-limited environments.

### Small sample sizes in critical areas

Some key areas of interest were represented by studies with small sample sizes, which may reduce statistical power. For example:

- The study on glial fibrillary acid protein in neonates [13] involved only 35 procedures, potentially limiting the robustness of its conclusions.
- Case reports, while illustrative, cannot be generalized to broader populations.

### Lack of standardized outcome metrics

There was considerable variability in the definitions and measurement of outcomes across studies. For example, ICU stay duration and extubation protocols varied widely, making it challenging to draw unified conclusions about fast-track protocols or ICU transfer risks [11, 20]. A lack of standardized criteria for complications, such as neurodevelopmental delays or respiratory distress, further complicates meta-analyses. Variability in surgical training, perioperative monitoring protocols, and hospital infrastructure may introduce confounding variables that affect reported outcomes. Establishing universal guidelines for reporting perioperative complications and long-term outcomes is essential to improve comparability across studies and enhance the reliability of systematic reviews in this field.

### Publication bias

As with any systematic review, there is a potential for publication bias, with positive or novel findings more likely to be published. Negative or null results in areas such as aEEG utility or blood conservation strategies may be underreported, skewing the overall interpretation.

## Conclusion

This systematic review underscores the remarkable advancements in congenital heart surgery and perioperative management while highlighting the persistent challenges in improving patient outcomes. This review also highlights the critical need for long-term follow-up studies to assess neurodevelopmental outcomes, including the impact of prolonged ICU stays, anesthesia exposure, and perioperative brain injury on cognitive function. Furthermore, the disparities in CHD surgical access between high- and low-income regions underscore the urgency of implementing targeted healthcare policies that address financial and infrastructural barriers. By bridging gaps in research, fostering innovation, and addressing systemic inefficiencies, healthcare providers and policymakers can build on these findings to deliver more effective and equitable care. Future advancements in surgical innovation, perioperative care, and personalized treatment approaches will require collaborative efforts from clinicians, researchers, and policymakers. By prioritizing evidence-based interventions, fostering international partnerships, and investing in outcome-driven healthcare reforms, the global medical community can work toward ensuring that all CHD patients—regardless of socioeconomic background—receive the highest standard of care.

**Abbreviations** *CHD*: Congenital heart disease; *CPB*: Cardiopulmonary bypass; *PRISMA*: Preferred Reporting Items for Systematic Reviews and Meta-Analyses; *RCTs*: Randomized Controlled Trials; *NOS*: Newcastle-Ottawa Scale; *JBI*: Joanna Briggs Institute; *TOF*: Tetralogy of Fallot; *PDA*: Patent ductus arteriosus; *HbSpO2*: Hemoglobin and oxygen saturation; *FT*: Fast-track; *DRG*: Diagnosis-Related Groups; *aEEG*: Amplitude-integrated EEG; *PFO*: Foramen ovale; *TTE*: Transthoracic echocardiography

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## Declarations

**Ethics approval and consent to participate** No human/animal sample used in this study.

**Consent for publication** All the authors declare their consent for publication. As there were no human use, no consent needed in this case.

**Competing interests** The authors declare no competing interests.



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