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Article

Perioperative Diagnosis, Risk Stratification and Organ-Protective Management of Cardiac Surgery–Associated Acute Kidney Injury in Infants and Young Children with Congenital Heart Disease: A Narrative Review

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Abstract: Acute kidney injury (AKI) remains one of the most frequent and clinically significant complications following congenital heart surgery in infants and young children. Cardiac surgery–associated acute kidney injury (CSA-AKI) is associated with prolonged mechanical ventilation, extended intensive care unit stay, increased need for vasoactive support and renal replacement therapy, and worse short-term clinical outcomes. The burden of CSA-AKI is particularly high in neonates and infants undergoing complex procedures or prolonged cardiopulmonary bypass. Although traditional diagnostic criteria based on serum creatinine and urine output remain clinically essential, their sensitivity for early detection is limited. This has stimulated growing interest in multimodal risk stratification strategies that integrate perioperative hemodynamic parameters, tissue perfusion markers, and renal and cardiac biomarkers. Current evidence increasingly supports a comprehensive organ-protective approach that includes optimized anesthesia, goal-directed perfusion during cardiopulmonary bypass, echocardiography-guided hemodynamic management, careful fluid stewardship, and timely initiation of peritoneal dialysis in selected high-risk patients. This narrative review summarizes current evidence on the epidemiology, perioperative risk factors, diagnostic challenges, and evolving preventive and therapeutic strategies for CSA-AKI in infants and young children with congenital heart disease.

Keywords: congenital heart disease; infants; young children; acute kidney injury; cardiac surgery; cardiopulmonary bypass; biomarkers; KDIGO; peritoneal dialysis.

Introduction

Congenital heart disease (CHD) remains a major cause of infant morbidity and early childhood hospitalizations worldwide. Advances in perioperative care and surgical techniques have significantly expanded the number of neonates and infants undergoing increasingly complex cardiac procedures [1]. As pediatric cardiac surgery has become more widely available and survival rates have improved, clinical attention has progressively shifted from operative survival alone toward the prevention of major postoperative complications.

Among these complications, cardiac surgery–associated acute kidney injury (CSA-AKI) has emerged as one of the most clinically significant conditions because of its strong association with multiorgan dysfunction, prolonged intensive care unit stay, and increased healthcare resource utilization [2]. Recent pediatric literature emphasizes that CSA-AKI should not be viewed solely as an isolated renal complication but rather as a manifestation of systemic perioperative stress involving ischemia–reperfusion injury, inflammatory activation, hemodynamic instability, hemolysis, and impaired oxygen delivery during cardiopulmonary bypass [3].

In infants and young children, the clinical significance of CSA-AKI is further amplified by developmental renal vulnerability, limited cardiovascular reserve, and the high prevalence of cyanotic and anatomically complex CHD requiring early surgical correction [4]. These characteristics make perioperative kidney injury both more likely to occur and more difficult to detect at a subclinical stage.

Consequently, contemporary approaches to CSA-AKI in pediatric cardiac surgery are increasingly moving beyond traditional diagnostic markers such as serum creatinine and urine output alone. Current research highlights the importance of integrated perioperative risk assessment that incorporates hemodynamic monitoring, tissue perfusion markers, early renal biomarkers, and targeted organ-protective strategies [5].

The aim of this review is to summarize current evidence regarding the epidemiology, perioperative risk factors, diagnostic and prognostic tools, and contemporary prevention and management strategies for cardiac surgery–associated acute kidney injury in infants and young children undergoing surgery for congenital heart disease.

Materials and Methods

This narrative review was based on the analysis of contemporary scientific literature addressing cardiac surgery–associated acute kidney injury in infants and young children with congenital heart disease. A structured literature search was conducted in the PubMed, Scopus, and Web of Science databases for studies published between 2010 and 2025.

The search strategy included the following key terms: cardiac surgery–associated acute kidney injury, pediatric cardiac surgery, congenital heart disease, cardiopulmonary bypass, biomarkers, and peritoneal dialysis. Priority was given to systematic reviews, meta-analyses, randomized clinical trials, and large observational studies involving pediatric cardiac surgery populations.

Selected publications were analyzed to summarize current evidence regarding the epidemiology, perioperative risk factors, diagnostic approaches, and preventive and therapeutic strategies for CSA-AKI in infants and young children undergoing surgery for congenital heart disease. Only articles published in English were included in the analysis.

Results of the Review

Epidemiology of CSA-AKI in Pediatric Cardiac Surgery

The incidence of CSA-AKI after pediatric cardiac surgery ranges from approximately 30% to 60%, while severe AKI develops in 5–15% of patients depending on the diagnostic criteria used. CSA-AKI is a common complication after pediatric cardiac surgery and remains one of the major contributors to complicated postoperative recovery. Contemporary reviews and cohort studies consistently demonstrate that acute kidney injury develops in a substantial proportion of children undergoing cardiopulmonary bypass (CPB), with the highest incidence observed in neonates and infants undergoing complex surgical procedures [6].

A meta-analysis published in 2022 identified several reproducible pediatric risk factors and confirmed that the development of AKI is strongly associated with adverse postoperative outcomes following congenital heart surgery [7]. Importantly, pediatric-focused reviews have also emphasized that the reported incidence of CSA-AKI varies considerably depending on patient age, surgical complexity, and the diagnostic criteria applied. Nevertheless, across most studies the incidence remains sufficiently high to justify routine risk-oriented surveillance during the early postoperative period [8].

The neonatal population deserves particular attention. In a multicenter North American analysis of the NEPHRON network focusing on patients undergoing the Norwood procedure, severe CSA-AKI was associated with significantly increased mortality risk. These findings highlight that kidney injury in neonatal cardiac surgery should not be viewed merely as a laboratory abnormality but rather as a major determinant of postoperative outcomes [9].

This issue is especially relevant in infants and young children with complex congenital heart disease, in whom even moderate reductions in renal perfusion may rapidly progress to clinically significant kidney injury due to limited physiological reserve and immature renal function [10].

Perioperative Risk Factors

CSA-AKI in pediatric cardiac surgery has a multifactorial pathogenesis involving both patient-related and procedure-related factors. Recent meta-analytic evidence indicates that pulmonary hypertension, cyanotic congenital heart disease (CHD), univentricular physiology, a RACHS-1 score ≥3, vasopressor exposure, cardiopulmonary bypass (CPB) use, reoperation, and postoperative sepsis are among the most consistently identified risk factors [11]. These findings support the concept that the risk of perioperative kidney injury reflects the interaction between underlying patient vulnerability and surgical complexity.

Among procedural factors, prolonged CPB duration, hemodilution, low nadir hemoglobin levels, inflammatory activation, and impaired systemic oxygen delivery appear to play particularly important roles in the development of CSA-AKI. These observations have stimulated renewed interest in perfusion strategies that focus on oxygen delivery targets rather than conventional flow-based approaches alone [12].

A recent randomized pediatric trial demonstrated that maintaining indexed oxygen delivery (Do_2i) at or above 360 mL/min/m² during CPB significantly reduced the incidence of postoperative AKI compared with conventional perfusion management. These findings support the concept of goal-directed perfusion as a practical kidney-protective strategy during pediatric cardiac surgery [13].

In the postoperative period, several additional factors may further increase the risk of kidney injury. Low cardiac output syndrome, venous congestion, fluid overload, and high vasoactive-inotropic requirements are recognized contributors to renal hypoperfusion and subsequent AKI development [14]. The importance of perioperative hemodynamic optimization is further highlighted by recent neonatal and pediatric studies demonstrating that elevated lactate levels, a high vasoactive-inotropic score, and impaired systemic perfusion are associated with more severe forms of CSA-AKI and worse clinical outcomes (fig.1).

Taken together, these findings emphasize that CSA-AKI risk in pediatric cardiac surgery arises from the combined effects of patient-related vulnerability, intraoperative perfusion disturbances, and postoperative hemodynamic instability.

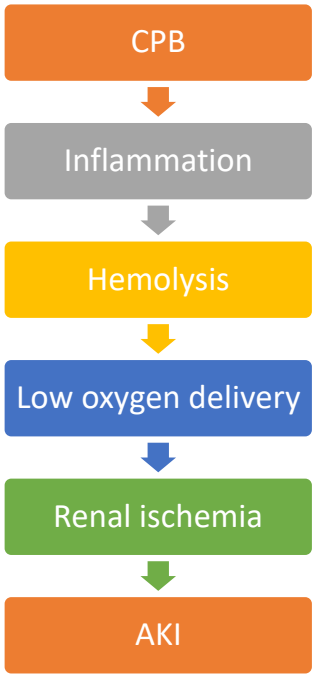

Figure 1. Pathophysiology of cardiac surgery–associated acute kidney injury (CSA-AKI).

Diagnostic Challenges

Current CSA-AKI diagnosis in children still relies mainly on KDIGO-based changes in serum creatinine and urine output. Although these criteria remain the clinical standard, they are intrinsically limited in infants because serum creatinine is influenced by age, low muscle mass, dilutional effects, and delayed kinetics after tubular injury. In infant cardiac surgery, recent work comparing different definitions of AKI has shown that incidence and staging vary substantially depending on the classification used, which reinforces the need for better early discrimination of clinically significant injury [15].

For this reason, there is increasing support for a multimodal diagnostic framework that combines conventional KDIGO staging with early injury biomarkers and hemodynamic context. Recent reviews emphasize that no single marker is sufficient in isolation; instead, the most informative approach is one that integrates renal biomarkers, markers of cardiac strain, perfusion indices, and bedside imaging.

Biomarkers and Expanded Risk Stratification

Among contemporary biomarkers, urinary NGAL remains the most extensively studied in pediatric cardiac surgery. A 2022 meta-analysis concluded that NGAL had the best overall diagnostic performance among the most frequently investigated biomarkers in children undergoing cardiac surgery, supporting its role as an early indicator of tubular injury before creatinine rises [16].

At the same time, newer reviews continue to highlight cystatin C as a valuable complement to NGAL because it better reflects changes in glomerular filtration and is less dependent on muscle mass than serum creatinine, which is especially relevant in infants and young children. Recent biomarker reviews note that NGAL and cystatin C remain among the most clinically useful pediatric candidates for earlier AKI prediction in the setting of ischemia-reperfusion and CPB-related injury [17].

A rational extension of this evidence is the use of combined renal and cardiac biomarkers, such as urinary NGAL, serum cystatin C, estimated GFR based on cystatin C, and NT-proBNP, together with perioperative echocardiographic assessment. Such integration is particularly attractive in infants because CSA-AKI often develops within a cardiorenal continuum rather than as isolated kidney injury [18]. Machine-learning work published in 2024 also supports the concept that multimarker, multivariable prediction models may improve identification of moderate-to-severe postoperative CSA-AKI.

Role of Echocardiography and Hemodynamic Monitoring

Hemodynamic assessment is central to modern CSA-AKI prevention because low cardiac output, venous congestion, and impaired tissue oxygen delivery are major drivers of perioperative renal hypoperfusion [19]. Echocardiography offers real-time insight into ventricular performance, filling conditions, outflow, and pulmonary pressures, allowing clinicians to individualize inotropic and vasoactive support rather than relying on static blood pressure targets alone. Recent reviews on pediatric cardiac surgery and neonatal hemodynamic monitoring emphasize that perfusion-oriented monitoring is essential for organ protection, especially in the immediate postoperative period [20].

This is highly relevant to infants and young children, where even modest reductions in cardiac index may translate into clinically meaningful renal hypoperfusion. Therefore, an integrated strategy combining biomarker surveillance with echocardiography-guided hemodynamic optimization appears more suitable than a creatinine-centered approach alone.

Prevention and Organ-Protective Perioperative Management

Current evidence supports a staged and multidisciplinary prevention strategy. First, anesthetic and perfusion management should prioritize oxygen transport, hemodynamic stability, and avoidance of excessive hemodilution. Second, CPB should be conducted using organ-protective targets whenever feasible, including goal-directed perfusion based on indexed oxygen delivery [21]. Third, postoperative management should focus on adequate cardiac output, avoidance of fluid overload, timely correction of congestion, and close surveillance for subclinical kidney injury. Recent adult and pediatric reviews converge on these themes, even though pediatric-specific randomized data remain limited.

The recent pediatric randomized trial of goal-directed perfusion is especially important because it provides direct evidence that maintaining $Do_2i \geq 360$ mL/min/m² during CPB can reduce postoperative AKI after pediatric cardiac surgery. This supports the incorporation of oxygen delivery targets into organ-protective perfusion protocols for high-risk children.

Peritoneal Dialysis in High-Risk Children

Peritoneal dialysis remains the preferred renal replacement modality in many infants and young children because it is technically feasible, better tolerated hemodynamically than extracorporeal modalities, and useful for fluid control in the postcardiotomy setting. Recent pediatric ICU data emphasize that AKI is a major indication for emergent peritoneal dialysis and support earlier initiation in selected high-risk cardiac patients, although outcomes remain strongly dependent on overall disease severity.

From a practical standpoint, this supports a proactive rather than delayed approach: in infants with a high-risk phenotype defined by hemodynamic instability, biomarker elevation, fluid accumulation, and poor renal recovery trajectory, peritoneal dialysis should be considered as part of a broader cardiorenal rescue strategy rather than only as salvage therapy.

Discussion

The modern view of CSA-AKI in infants and young children has shifted from a creatinine-defined renal event to a complex, perioperative cardiorenal syndrome. Recent literature suggests that clinically meaningful progress is most likely to come not from a single biomarker or a single therapy, but from integrated pathways that combine:

1. early risk stratification,
2. perfusion-oriented CPB management,
3. echocardiography-guided hemodynamic support,
4. biomarker-based detection of subclinical injury, and
5. timely renal support in selected patients.

For infants and young children with CHD, this integrated approach is particularly important because renal immaturity, complex anatomy, and postoperative hemodynamic fragility often coexist. Accordingly, future studies should focus on validating multimarker prediction models, refining pediatric-specific perfusion thresholds, and testing protocolized cardiorenal protection bundles in prospective multicenter settings.

Conclusion

Cardiac surgery-associated acute kidney injury remains a major determinant of postoperative morbidity in infants and young children undergoing surgery for congenital heart disease. Recent evidence confirms that risk is driven by a combination of disease complexity, perioperative hemodynamic stress, CPB-related oxygen delivery failure, and early postcardiotomy instability. Although KDIGO-based criteria remain indispensable for clinical staging, earlier and more precise detection requires integration of renal biomarkers, cardiac biomarkers, echocardiography, and tissue perfusion parameters. A contemporary organ-protective strategy should therefore include optimized anesthesia, goal-directed perfusion, hemodynamic personalization, fluid stewardship, and early consideration of peritoneal dialysis in high-risk patients.

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