

Validation of pre-operative proteinuria for post cardiac surgery acute kidney injury prediction in infants

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Research Article

Keywords:

Posted Date: June 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9404267/v1>

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Additional Declarations: No competing interests reported.

Abstract

Objective:

To validate a clinical prediction model for acute kidney injury (AKI) in infants undergoing cardiac surgery by integrating pre- and post-operative urinary albumin-to-creatinine ratio (ACR) with established clinical variables, including age, sex, prior cardiac surgeries, surgical type, RACHS-1 score, cardiopulmonary bypass time, and baseline kidney function.

Design:

Prospective observational study.

Setting:

Cardiothoracic unit of a tertiary care hospital in India.

Participants:

Infants aged 1 month to 1 year undergoing elective cardiac surgery. Exclusion criteria included neonates, children > 1 year, pre-existing kidney dysfunction, structural renal abnormalities, prior kidney transplant, and incomplete data.

Measurements and Main Results:

Patients were followed through hospital discharge (up to 11 days). AKI was defined using KDIGO criteria. Urine ACR was measured at 6 hours post-operatively and daily for two days. Among 66 infants, AKI incidence was 45.5% (n = 30), with onset at median postoperative day 2 (IQR 1–2). The pre-operative clinical model demonstrated strong predictive performance (AUC 0.838 [0.732–0.944]), exceeding ACR alone (pre-operative: 0.829; post-operative: 0.711) and combined ACR measures without clinical integration (0.829). Incorporating pre-operative ACR into the clinical model improved performance (sensitivity 80.0%, specificity 94.4%, PPV 92.1%, NPV 85.0%). A multivariable logistic regression–based nomogram incorporating eight predictors, including pre-operative ACR, showed good discrimination (AUC 0.805 derivation; 0.925 validation).

Conclusions:

Integration of albuminuria with clinical parameters improves prediction of cardiac surgery–associated AKI in infants. This combined model and accompanying nomogram provide a practical approach for

early risk stratification and may be particularly valuable in resource-limited settings.

Research in Context

- Prior studies have identified the high variability in AKI risk among infants undergoing cardiac surgery, with limited tools for accurate prediction in this subgroup.
- We studied 66 infants undergoing cardiac surgery at our institution and analyzed the albumin-to-creatinine ratios before and after surgery.
- Using both the pre-operative and post-operative albumin-to-creatinine ratios, we validated a predictive model and novel nomogram which shows promise in detecting AKI outcomes.

Introduction

Acute kidney injury following pediatric cardiac surgery (CS-AKI) is a common complication, with an incidence of around 40–60% [1, 2]. CS-AKI is associated with increased morbidity, mortality, prolonged hospital stays, ventilator dependency, healthcare costs, and a higher risk of chronic kidney disease (CKD) and hypertension [3–9]. The mechanisms of CS-AKI, including hemodynamic instability, inflammation, coagulation, and neurohumoral dysregulation, highlight its complex pathogenesis [10]. Factors such as age, renal immaturity, weight, preoperative renal function, serum albumin levels, pulmonary and cyanotic heart conditions, RACHS-1 score, sepsis, CPB use and duration, and aortic cross-clamp time contribute to this risk [11–15]. Despite the significant impact of AKI, current diagnostics like serum creatinine levels detect it too late [16], highlighting the need for early identification and preventive measures.

Compounding the issue, standardized AKI risk models are lacking. Small cohort sizes and insufficient validation have hindered the adoption of pediatric AKI prediction models [6, 17, 18]. Previous studies have explored various biomarkers for early CS-AKI detection and risk stratification [16], but high costs, lack of standardization, and limited generalizability limit their use. Innovative strategies are needed for risk assessment, especially in infants undergoing cardiac surgery. The urinary albumin: creatinine ratio (ACR) is a cost-effective, widely available alternative that reflects tubular or glomerular damage [19]. Additionally, simple nomograms have shown promise in predicting CS-AKI in adults [20–23], and similar approaches are emerging for pediatric patients [24–26].

Given the variability in albumin excretion among younger patients [27, 28], we previously conducted a single-center, prospective observational study to derive a 'Risk Prediction Scoring' system incorporating preoperative and postoperative albuminuria [29]. No prior models existed for predicting AKI exclusively in infants undergoing cardiac surgery. The previous prediction model demonstrated promising predictive accuracy for CS-AKI in a pediatric setting, combining clinical models with preoperative ACR for quick identification of at-risk infants in high-pressure healthcare settings [29]. In this current study, we validated the existing model and developed a novel nomogram based on collected data from 66 infants treated at our institution.

Methods

Ethical Approval

and Informed Consent:

The study adhered to the Institutional REB and the Helsinki Declaration of 1975. Approval was obtained from the Institutional Review Board (IRB) of Medanta - The Medicity (approval number 1491/2022) on January 10, 2023. Informed consent was obtained from all parents or guardians before participation.

Study Design:

We conducted a prospective, observational study at our Pediatric Cardiothoracic unit with infants greater than 1 month up to 1 year of age scheduled for elective cardiac surgery utilizing cardiopulmonary bypass over one year from January 2023–2024. We followed the STROBE (Strengthening the reporting of observational studies in epidemiology) guidelines and checklist for this analysis.

Inclusion Criteria:

Infants greater than 1 month old up to 1 year old scheduled for elective cardiac surgery.

Exclusion Criteria:

1. Neonates (< 1 month of age)
2. Children older than 1 year of age
3. Infants with pre-existing kidney dysfunction ($\text{eGFR} < 60 \text{ mL/min/1.73 m}^2$), structural kidney and urinary tract abnormalities, post kidney transplant, or incomplete data.

Data Collection:

Data on demographics, heart disease diagnosis, previous surgeries, and estimated GFR using the revised bedside Schwartz formula were recorded [30]. Pre-operative urine was collected through urine sample and ACR was measured. Intraoperative details, including procedure duration, cardiopulmonary bypass length, and aortic cross-clamp times, were documented. Each child was classified according to the RACHS-1 category, an easily applicable tool designed to assess short-term mortality risk in pediatric congenital heart disease surgeries [31]. Following surgery, we monitored serum creatinine levels during the ICU stay starting at post-operative day 1 and once again the day before hospital discharge, defining AKI according to KDIGO guidelines [32]. We also tracked daily and cumulative fluid balances based on a standardised method utilizing fluid intake and output [33]; ventilator support duration, the use of NSAIDs or nephrotoxic drugs, hospital stay length, ICU stay lengths, sepsis development (presence of positive blood culture), transaminitis occurrence (more than two times the upper limit of normal), in-hospital mortality, and signs of low output cardiac syndrome (symptoms and signs of poor systemic perfusion

such as tachycardia, cold extremities or development of acidosis such as increase in base deficit > 4 or increase in lactate by > 2 mmol/L in consecutive blood gas analysis) [34]. Patients did not receive albumin products for fluid resuscitation. We defined prolonged ventilation as duration of mechanical ventilation > 7 days [35]. Hematological complications, such as anemia or thrombocytopenia, were noted throughout the admission. Diuretics or kidney replacement therapy were administered as needed based on institutional protocols. Urine ACR was measured the morning of surgery, 6 hours post-surgery and daily for two days using immunoturbidimetry. For our analysis, we defined post-operative ACR as the measurement taken 6 hours post-surgery. AKI recovery was defined as an absence of AKI by evaluating creatinine following KDIGO criteria within seven days of AKI diagnosis [36]. Mortality was defined as all deaths occurring in the same hospitalization as the operation or within 30 days of the operation [37]. Standardized protocols were used for data collection.

Statistical Analyses:

Data were recorded in Microsoft Excel and analyzed using SPSS version 22. Normality was tested with the Kolmogorov-Smirnov test. Outcomes included AKI incidence, length of ICU and hospital stay, and mortality. Categorical variables were summarized as frequencies and percentages, and continuous variables as median and interquartile range (IQR; 25th to 75th percentiles). Associations were assessed using chi-square or Fisher exact tests for categorical variables and Mann-Whitney U or Kruskal-Wallis tests for continuous variables. A generalized linear model calculated the unadjusted and adjusted relative risks (RRs) of pre- and post-operative ACR for predicting AKI. The pre-operative ACR is categorized as ACR < 10 mg/g, ACR 10–30 mg/g and ACR > 30 mg/g; while the first post-operative ACR is categorized a priori based on its tertile values, with 1st tertile (< 55 mg/g), 2nd tertile (55– 117.9 mg/g), and 3rd tertile (≥ 118 mg/g) [in-line with our previous study Nautiyal A et al., 2021 [29] and Zappitelli M et al., 2012 [39]]. Adjusted analyses controlled for age, gender, pre-operative creatinine, type of heart surgery, previous surgeries, RACHS-1 score, and cardiopulmonary bypass time.

In our study, we used a derivation model by Nautiyal et al., 2021 [29] in a prospective observational study to predict AKI among children aged < 2 years with pediatric cardiac surgery. This model comprised of multiple predictors such as age (continuous in month); gender (categorical: male vs. female); previous cardiac surgeries (categorical: yes vs. no); type of heart surgery (categorical: cyanotic vs. acyanotic); RACHS-1 score (categorical: ≥ 3 vs. < 3); cardiopulmonary bypass time (categorical: < 120 vs. ≥ 120 min); pre-operative creatinine (continuous in mg/dL) and pre-operative estimated glomerular filtration rate (eGFR; continuous in mL/min/1.73 m²). The model was developed based on patient characteristics with the greatest risk associated with AKI. The patient characteristics data from Nautiyal et al. (derivation cohort) was compared with the data derived from our current cohort, which includes ACR measurements (validation cohort).

In our study, the different diagnostic characteristics (sensitivity, specificity, positive predictive value and negative predictive value) and area under the receiver operating characteristic curve (AUC; with 95% CI) was calculated to determine the predictive ability of a clinical model alone and when combined with ACR

measurements. A nomogram was also generated based on an 8-item score that included age at surgery, gender, pre-operative creatinine, RACHS-1 score, heart disease, previous cardiac surgeries, cardiopulmonary bypass time, and pre-operative ACR. The magnitude of the association of each variable with postoperative AKI was reflected by the assigned points. The total score for each participant was calculated to estimate the probability of postoperative AKI. The nomogram was created using the R software (Version 4.1.2) software. A two tailed p-value < 0.05 was considered to be statistically significant.

Results

Patient Characteristics

A total of 66 infants were included in our validation study. The overall incidence of AKI was 45.5% (n = 30) [stage 1 AKI (n = 18), stage 2 (n = 9) and stage 3 (n = 3)], measured by an acute increase in serum creatinine. The median (IQR) post-operative day of AKI development was 2 (1–2). Table 1 compares the patient characteristics by AKI staging. Median (IQR) age was significantly higher in infants with lower pre-operative ACR levels [ACR < 10 mg/g: 10 (5.5–12) months vs. ACR 10–30 mg/g: 5 (1.5–10) months vs. ACR > 30 mg/g: 3.5 (1-6.3) months; p = 0.016]. AKI incidence was significantly higher in infants with higher pre-operative ACR levels [ACR < 10 mg/g: 0% vs. ACR 10–30 mg/g: 20% vs. ACR > 30 mg/g: 68.4%; p < 0.001] (Table 2).

Table 1
Patient characteristics by AKI staging

Variable	No AKI (n = 36)	AKI stage 1 (n = 18)	AKI stage 2 (n = 9)	AKI stage 3 (n = 3)	p value
Age (months)*	5 (3.3–10)	3.5 (0.9–9)	3 (0.7–4.5)	3 (0–3)	0.034
Gender (Male)	25 (69.4%)	14 (77.8%)	7 (77.8%)	3 (100%)	0.648
Pre-operative creatinine (mg/dl)*	0.3 (0.3– 0.3)	0.3 (0.2– 0.3)	0.3 (0.2– 0.5)	0.7 (0.2– 0.8)	0.407
Type of heart disease (cyanotic)	16 (44.4%)	11 (61.1%)	7 (77.8%)	2 (66.7%)	0.269
Previous cardiac surgeries (yes)	2 (5.6%)	5 (27.8%)	0 (0%)	1 (33.3%)	0.044
RACHS staging (≥ 3)	1 (2.8%)	2 (11.1%)	4 (44.4%)	1 (33.3%)	0.005
CPB time (minute)*	61 (47–66)	78 (72–89)	141 (59–159)	116 (69–128)	< 0.001
ACC time (minute)*	45 (35–52)	55 (45–63)	84 (42–99)	69 (32–74)	0.008
ACC time (≥ 60 minute)	32 (88.9%)	12 (66.7%)	3 (33.3%)	1 (33.3%)	0.002
Post-operative day of developing AKI*	-	2 (1–2)	2 (1–2)	0 (0–3)	0.504
Sepsis (yes)	7 (19.4%)	5 (27.8%)	2 (22.2%)	2 (66.7%)	0.316
Haematological complications (yes)	7 (19.4%)	7 (38.9%)	3 (33.3%)	3 (100%)	0.023
Transaminitis (yes)	12 (33.3%)	9 (50%)	2 (22.2%)	2 (66.7%)	0.329
Re-exploration / 2nd operation (yes)	1 (2.8%)	2 (11.1%)	2 (22.2%)	1 (33.3%)	0.12
Prolonged ventilation (yes)	9 (25%)	5 (27.8%)	5 (55.6%)	1 (33.3%)	0.353
Re-intubation (yes)	5 (13.9%)	2 (11.1%)	2 (22.2%)	1 (33.3%)	0.707
Nephrotoxic antibiotics used (yes)	19 (52.8%)	13 (72.2%)	6 (66.7%)	3 (100%)	0.259
*Continuous variables reported as Median (IQR), while others as Categorical variables [n (%)]					

Variable	No AKI (n = 36)	AKI stage 1 (n = 18)	AKI stage 2 (n = 9)	AKI stage 3 (n = 3)	p value
Death (yes)	0 (0%)	0 (0%)	0 (0%)	2 (66.7%)	< 0.001
*Continuous variables reported as Median (IQR), while others as Categorical variables [n (%)]					

RACHS, risk adjustment in congenital heart surgery; AKI, acute kidney injury; RRT, Renal replacement therapy; ACC, aortic cross clamp; CPB, cardiopulmonary bypass; IQR, Interquartile range

Table 2
Patient characteristics by preoperative ACR category

Variable	ACR < 10 mg/g (n = 8)	ACR 10–30 mg/g (n = 20)	ACR > 30 mg/g (n = 38)	p value
Age (months)*	10 (5.5–12)	5 (1.5–10)	3.5 (1–6.3)	0.016
Gender (Male)	5 (62.5%)	17 (85%)	27 (71.1%)	0.358
Pre-operative creatinine (mg/dl)*	0.3 (0.2–0.3)	0.3 (0.3–0.4)	0.3 (0.2–0.4)	0.767
Type of heart disease (cyanotic)	5 (62.5%)	10 (50%)	21 (55.3%)	0.881
Previous cardiac surgeries (yes)	1 (12.5%)	3 (15%)	4 (10.5%)	0.867
RACHS staging (≥ 3)	0 (0%)	2 (10%)	6 (15.8%)	0.650
CPB time (minute)*	61 (41–71)	61 (47–68)	77 (65–118)	0.002
ACC time (minute)*	41 (29–53)	46 (33–52)	54 (44–76)	0.020
ACC time (≥ 60 minute)	7 (87.5%)	18 (90%)	23 (60.5%)	0.030
Sepsis (yes)	1 (12.5%)	1 (5%)	14 (36.8%)	0.011
Haematological complications (yes)	3 (37.5%)	3 (15%)	14 (36.8%)	0.211
Transaminitis (yes)	2 (25%)	4 (20%)	19 (50%)	0.070
AKI (yes)	0 (0%)	4 (20%)	26 (68.4%)	< 0.001
AKI staging (≥ 2)	0 (0%)	1 (25%)	11 (42.3%)	0.632
AKI recovery (yes)	0 (0%)	3 (75%)	24 (92.3%)	0.360
Need for RRT (yes)	0 (0%)	1 (25%)	1 (3.8%)	0.253
Re-exploration / 2nd operation (yes)	0 (0%)	2 (10%)	4 (10.5%)	1.000
Prolonged ventilation (yes)	2 (25%)	4 (20%)	14 (36.8%)	0.473
Re-intubation (yes)	0 (0%)	2 (10%)	8 (21.1%)	0.373
Nephrotoxic antibiotics used (yes)	4 (50%)	9 (45%)	28 (73.7%)	0.080
*Continuous variables reported as Median (IQR), while others as Categorical variables [n (%)]				

Variable	ACR < 10 mg/g (n = 8)	ACR 10–30 mg/g (n = 20)	ACR > 30 mg/g (n = 38)	p value
Death (yes)	0 (0%)	1 (5%)	1 (2.6%)	1.000
*Continuous variables reported as Median (IQR), while others as Categorical variables [n (%)]				

RACHS, risk adjustment in congenital heart surgery; AKI, acute kidney injury; RRT, Renal replacement therapy; ACC, aortic cross clamp; ACR, albumin-to-creatinine ratio; CPB, cardiopulmonary bypass; IQR, Interquartile range

Association of Pre-operative and Post-operative ACR with AKI

Post-operative ACR was significantly higher than pre-operative ACR in patients with and without AKI. The median (IQR) ACR was significantly higher in those with AKI compared to those without AKI at different time-points such that ACR was during pre-operative [53 (37.8–76) vs. 15 (10.3–39) mg/g; $p < 0.001$], at post-operative day (POD) 0 [110 (86–242.7) vs. 53 (21.5–123.8) mg/g; $p = 0.003$], at POD 1 [368.4 (255.5–806.7) vs. 100 (65.4–267) mg/g; $p < 0.001$] and at POD day 2 [385 (200–602.5) vs. 83.1 (45.7–179.1) mg/g; $p < 0.001$] [Table 3].

Table 3
Comparison of pre-operative and post-operative ACR among infants with and without AKI

ACR	AKI Yes [n = 30]	AKI No [n = 36]	p value
Pre-operative	53 (37.8–76)	15 (10.3–39)	< 0.001
POD day 0	110 (86–242.7)	53 (21.5–123.8)	0.003
POD day 1	368.4 (255.5–806.7)	100 (65.4–267)	< 0.001
POD day 2	385 (200–602.5)	83.1 (45.7–179.1)	< 0.001
POD: Post-operative day; ACR: Albumin-to-creatinine ratio			

The pre-operative ACR > 30 mg/g was significantly associated with post-operative AKI development such that those with pre-operative ACR > 30 mg/g had a 13 times higher relative risk of post-operative AKI (unadjusted RR, 13.00; 95% confidence interval [95% CI], 3.69–45.84) and 28 times higher relative risk of post-operative AKI after adjusting for different confounders (adjusted RR, 27.64; 4.52–169.16). However, the pre-operative ACR > 30 mg/g was not significantly associated with the development of severe AKI [stage ≥ 2] in unadjusted analysis (RR, 2.2; 0.2–24.09) and after adjusting for different confounders (RR, 2.0; 0.07–60.88) [Table 4].

Table 4

Unadjusted and adjusted RRs for preoperative ACR to predict postoperative AKI or stage ≥ 2 AKI

Pre-operative ACR		Un-adjusted RR (95% CI)		p value	Adjusted RR (95% CI)	p value
AKI (yes)						
No. of events	30					
ACR ≤ 30 mg/g (n = 28)	4 (14.3%)	1		≤ 0.001	1	≤ 0.001
ACR > 30 mg/g (n = 38)	26 (68.4%)	13.00 (3.69–45.84)			27.64 (4.52–169.16)	
AKI ≥ stage 2						
No. of events	12					
ACR ≤ 30 mg/g (n = 4)^	1 (25%)	1		0.632	1	0.691
ACR > 30 mg/g (n = 26)^	11 (42.3%)	2.2 (0.2–24.09)			2.0 (0.07–60.88)	
^with AKI						

Adjusted for age (continuous), gender (categorical), creatinine (continuous), type of heart surgery (categorical), previous cardiac surgeries (categorical) and RACHS-1 score ≥ 3 versus < 3 (categorical)

RR: Relative risk; ACR: Albumin-to-creatinine ratio; AKI: Acute kidney injury

As compared to the patients with postoperative ACR in 1st tertile (< 55 mg/g), those in 2nd tertile (55–117.9 mg/g) (unadjusted RR, 12.66; 2.78–58.82) (adjusted RR, 80.45; 2.49–2605) or 3rd tertile (≥ 118 mg/g) (unadjusted RR, 8.26; 1.89–35.71) (adjusted RR, 35.06; 2.10–585.39) had a significantly higher risk of post-operative AKI. However, the first post-operative ACR tertiles were not significantly associated with the development of stage ≥ 2 AKI. The relative risk data was not available due to low sample size of patients with stage > 2 AKI post-stratification based on tertiles. [Table 5]

Table 5

Unadjusted and adjusted RRs for first postoperative ACR to predict postoperative AKI or stage ≥ 2 AKI

1st post-operative ACR		Un-adjusted RR (95% CI)	p value	Adjusted RR (95% CI)	p value
AKI (yes)					
No. of events	30				
1st tertile (< 55 mg/g; n = 22)	3 (13.6%)	1		1	
2nd tertile (55– 117.9 mg/g; n = 21)	14 (66.7%)	12.66 (2.78–58.82)	< 0.001	80.45 (2.49–2605)	0.013
3rd tertile (> = 118 mg/g; n = 23)	13 (56.5%)	8.26 (1.89–35.71)	0.003	35.06 (2.10–585.39)	0.013
AKI ≥ stage 2					
No. of events	12				
1st tertile (< 55 mg/g; n = 3)^	3 (100%)	1		1	
2nd tertile (55– 117.9 mg/g; n = 14)^	4 (28.6%)	NA	0.051	NA	0.999
3rd tertile (> = 118 mg/g; n = 13)^	5 (38.5%)	NA	0.200	NA	0.999
^with AKI					

Adjusted for age (continuous), gender (categorical), creatinine (continuous), type of heart surgery (categorical), previous cardiac surgeries (categorical) and RACHS-1 score ≥ 3 versus < 3 (categorical)

RR: Relative risk; ACR: Albumin-to-creatinine ratio; AKI: Acute kidney injury; RACHS: Risk adjustment in congenital heart surgery; NA: Not available [can't be calculated due to 0 in one of the cell of 2*2 table]

Association of ACR with Duration of Stay and Mortality

Median ICU stay duration increased significantly with higher pre-operative ($p = 0.008$), POD 1 ($p = 0.004$), and POD 2 ($p = 0.032$) ACR levels. Hospital stay duration also increased significantly with higher pre-operative ($p = 0.031$) and POD 2 ($p = 0.022$) ACR levels (Supplementary Table 1). Mortality did not differ significantly by pre-operative ACR level [ACR < 10 mg/g: 0%, ACR 10–30 mg/g: 5%, ACR > 30 mg/g: 2.6%; $p = 1.000$].

Added Benefit of Pre-operative and First Postoperative ACR to Clinical Predictors of AKI

The AUC of the pre-operative clinical model, which doesn't account for ACR values, for AKI prediction [0.838 (0.732–0.944)] was higher than pre-operative ACR AKI risk prediction alone [0.829 (0.728–0.930)], first post-operative ACR AKI risk prediction alone [0.711 (0.585–0.837)], or the AKI risk prediction of both pre-operative and first post-operative ACR values combined, independent of pre-operative clinical model [0.829 (0.725–0.932)]. The highest AUC was for the pre-operative clinical model integrated with pre-operative ACR [0.925 (0.864–0.986)], with no improvement by integrating first post-operative ACR values instead of or along with pre-operative ACR values. The sensitivity, specificity, PPV and NPV of clinical model + pre-operative ACR was observed to be 80.0%, 94.4%, 92.1% and 85.00%, respectively (Supplementary Table 2).

Comparison of Validation and Derivation Cohorts

Our current validation cohort (n = 66) had a lower median age (4.5 months) than the previous derivation cohort (n = 93) (7 months; p = 0.001) and slightly lower pre-operative UACR (36.5 mg/g vs. 42 mg/g; p = 0.049). Differences in sepsis, transaminitis, prolonged ventilation, and nephrotoxic antibiotic use were significant. Hospital stay was shorter in the validation cohort (7 days vs. 9 days; p < 0.001) (Supplementary Table 3). In the derivation cohort, the clinical model alone had an AUC of 0.761 (95% CI: 0.657–0.866).

We first used the patient data in the derivation cohort to analyze ACR. For the derivation cohort, using pre-operative ACR values alone to predict AKI yielded an AUC to 0.729 (95% CI: 0.618–0.840). Using post-operative ACR values alone yielded an AUC of 0.704 (95% CI: 0.586–0.822). Combining pre-operative and first post-operative ACR values in the derivation cohort and analyzing the AKI risk prediction improved the AUC to 0.751 (95% CI: 0.645–0.856). When the previously developed clinical model was integrated with pre-operative ACR values in the derivation cohort, the AUC was highest at 0.805 (95% CI: 0.713–0.896), proving to be the most comprehensive model in the derivation cohort. The clinical model combined with only the first post-operative ACR values resulted in an AUC of 0.777 (95% CI: 0.676–0.879). Similar patterns were observed in the validation cohort, reaffirming the utility of these biomarkers (Supplementary Table 4).

Figure 1 shows the nomogram for predicting postoperative AKI probability based on the final logistic regression model. An 8-item score was generated that included age at surgery, gender, pre-operative creatinine, RACHS-1 score, heart disease, previous cardiac surgeries, cardiopulmonary bypass time, and pre-operative ACR. The magnitude of the association of each variable with postoperative AKI was reflected by the assigned points. The total score for each participant was calculated to estimate the probability of postoperative AKI.

Discussion

We conducted a prospective cohort study in India to validate Risk Prediction Scoring using preoperative and postoperative albuminuria in infants up to 1 year undergoing cardiac surgery[29]. This validation study confirmed that preoperative ACR is crucial for predicting AKI. In the validation cohort, younger infants with higher ACR levels had a significantly higher incidence of AKI. Integrating preoperative ACR with clinical models significantly improved AKI prediction. Our current study aligns with these insights by demonstrating the predictive significance of pre-operative and post-operative ACR levels for AKI. We observed that younger infants exhibited higher ACR levels, which correlated significantly with increased AKI incidence, mirroring findings in children under 2 years in the derivation cohort. This inverse relationship between infant age and ACR levels is consistent with normal renal maturation, as albuminuria levels fall as glomerular and tubular function mature (Okamoto et al, 2023). The predictive accuracy of preoperative ACR appears more pronounced in infants compared to older children, as when age was adjusted for (Table 4), there was a higher risk (adjusted RR, 27.64; 4.52–169.16), emphasizing age-specific risk assessment's importance.

Numerous studies have demonstrated an association between proteinuria and a higher CS-AKI risk [38, 39]. While adult studies have shown a positive correlation between pre-existing proteinuria and CS-AKI[38, 40], a pediatric study found no such association preoperatively, although postoperative albuminuria was linked to CS-AKI [41]. This relationship is seen in both cardiac and non-cardiac surgeries [42, 43], with Nishimoto et al. noting lower overall AKI risk in non-cardiac surgeries (6%) [42].

However, the additional benefit of including post-operative ACR values varied in our studies; it did not enhance the model's predictive power in our derivation cohort [29]. This contrasts with Zappitelli et al.'s findings, which showed no improvement by adding pre-operative ACR values to post-operative measurements [41]. Furthermore, our model showed higher AUC values than other studies[29, 41, 44]. Our clinical predictive model also took into account additional variables, including previous cardiac surgeries and the type of heart surgery, which were not as extensively considered in other studies [41, 44]. While Zappitelli et al.'s study included other biomarkers, our validation cohort indicated that combining pre-operative and first post-operative ACR with clinical models yielded a better AUC for AKI prediction. Our original CS-AKI risk prediction model, derived from a study on children aged 1 month to 18 years undergoing cardiac surgery, included 143 children, 36 of whom developed AKI [29]. Post-operative ACR predictive risk for AKI was higher than pre-operative ACR in both age groups. For children ≥ 2 years, the highest post-operative ACR tertile (> 75.8 mg/g) significantly predicted AKI, while in those < 2 years, it predicted AKI only in unadjusted analysis. The previous study concluded that albuminuria, especially when combined with clinical models, is a viable biomarker for predicting AKI post-cardiac surgery.

Albuminuria predicts multiorgan failure and increased mortality in critically ill patients [46, 47]. The ASSESS-AKI study found CS-AKI linked to higher hypertension rates in the first post-discharge year and CKD four years post-discharge, emphasizing albuminuria's role in long-term cardiovascular and renal risk [9]. In adults, various clinical and surgical factors have been explored to predict CS-AKI, often focusing on variables effective in predicting stage 3 AKI, characterized by a significant increase in serum

creatinine or the need for renal replacement therapy. Notable predictive models, such as the Cleveland Clinic score [48], the Mehta score [49] and the Simplified Renal Index [50], predominantly use preoperative risk factors to assess the likelihood of severe CS-AKI. Despite its effectiveness, the Cleveland Clinic score is not widely used in clinical practice, and its applicability in pediatric, especially infant populations, remains unclear. Tinica et al.'s systematic review noted that most clinical scores effectively identify severe forms of CS-AKI in adults but often overlook milder cases [51]. Zappitelli et al. identified a better CS-AKI prediction model using clinical variables, first post-operative ACR, and cystatin C [41], emphasizing the importance of integrating biomarkers like proteinuria into these scores.

In both studies, post-operative ACR values were higher in AKI patients, emphasizing its importance in indicating AKI risk. Higher first post-operative ACR levels were associated with significantly increased AKI risk, particularly in the top tertile, consistent with our derivation study and Zappitelli et al. [41]. Devarajan et al.'s research showed significant urinary protein increases post-surgery, detectable within 2 hours post-surgery [44]. This finding contrasts with the study by Zappitelli et., who found postoperative ACR predicted more severe AKI in children under 2 years [41]. This may be due to unique pathophysiological responses in infants to cardiac surgery. The ACR levels did not predict stage ≥ 2 , possibly due to a small sample size. Additionally, there was no significant association observed between the timing of AKI development and ACR.

Higher ACR levels were associated with longer ICU and hospital stays in both our derivation and validation cohorts [29]. This contrasts with Zappitelli et al., who found that in children under 2 years, the first postoperative ACR predicted longer hospital stays but not extended ICU stays [41]. Devarajan et al. also observed a link between elevated urine albumin and prolonged hospital stay and higher CS-AKI incidence [44]. Our data on mortality were inconclusive due to a small number of events (two), but consistently show that elevated ACR levels are associated with more severe clinical outcomes including the development of sepsis, transaminitis, and prolonged ventilation.

Recent advances in machine learning and deep learning have yielded highly accurate models for predicting CS-AKI in children [24–26]. However, the complexity of these models often limits their transparency and ease of use. More straightforward risk scores could offer comparable predictive capability without sacrificing user-friendliness. While such risk scores are well-established for adults [20–23], pediatric models are less common. A study analyzing 1,137 children with a median age of 3 developed a predictive nomogram using six variables, achieving AUCs of 0.739 and 0.755 for its development and validation cohorts [52]. Our nomogram, including eight parameters (age at surgery, gender, pre-operative creatinine, RACHS-1 score, type of heart disease, history of previous cardiac surgeries, cardiopulmonary bypass time, and pre-operative ACR), achieved AUCs of 0.805 and 0.925 for our development and validation cohorts, indicating robust differentiation of infants at risk of CS-AKI.

This study's strengths lie in its prospective nature, distinct sets of data for testing and validation, and focus on infants, a group where urine albumin excretion variability complicates the differentiation between no AKI and mild AKI. We employed standardized laboratory assessments for albuminuria and

evaluated urine ACR at four clinically relevant time points: preoperative and postoperative days 1, 2, and 3. The routine nature of urine ACR testing enhances timely clinical implementation but may increase costs if repeated measurements are needed. The study's small sample size limited our ability to assess severe AKI prediction, and as a single-center study, its generalizability is restricted. Additionally, we did not include other biomarkers such as NGAL, IL-18, or KIM-1, which might have provided more comprehensive insights. Our cohort mainly included individuals with pre-existing normal kidney function based on serum creatinine, indicating a need for future studies in high-risk groups, such as those with pre-existing kidney dysfunction or those undergoing nephrotoxic drug treatment. Furthermore, our AKI definition was based solely on serum creatinine increases. The unresolved role of microalbuminuria or albuminuria as direct contributors to cardiorenal disease suggests another direction for future research. Our study established practical ACR threshold values to identify infants at risk for AKI following cardiac surgery. These thresholds can aid in selecting candidates for future AKI-related clinical trials or preventive measures, such as avoiding fluid overload and nephrotoxins. Since urine ACR is a familiar and commonly used test, it is an actionable tool for early AKI diagnosis compared to other novel biomarkers.

Conclusion

This study highlights the potential role of pre-operative and post-operative albumin-to-creatinine ratio ACR levels in predicting CS-AKI among infants. The development of our nomogram, with a robust discriminating power in the development and validation cohorts, may provide clinicians in resource limited regions to quickly integrate these variables with clinical predictive models. Additionally, it highlights the importance of using age-specific strategies to assess and manage CS-AKI risk, promoting care that is better tailored to this vulnerable population. Further research in this area could provide additional insights into the optimization of perioperative care and improve outcomes in this high-risk population.

At the Bedside

- Incorporation of pre-operative and post-operative ACR into routine assessments could identify high-risk infants, allowing for tailored interventions.
- This study shows the potential benefits of combining ACR levels with clinical assessments for predicting AKI in infants post-cardiac surgery.
- Clinical bottom line: Clinicians should consider ACR levels and utilizing the nomogram and model to improve risk stratification and preventive care for infants undergoing cardiac surgery, optimizing perioperative management, and potentially reducing AKI-related complications.

Declarations

Funding:

The authors report no financial disclosures or conflicts of interest.

Author Contribution

M.G. and R.S. contributed equally to this work and were involved in study conception and design. M.G., R.S., A.B., and R.A. were responsible for patient recruitment, data acquisition, and clinical oversight. S.B.B., R.A., F.A.M., P.B., A.M., and S.S. contributed to data collection, surgical and perioperative data interpretation, and critical clinical input. A.M. (Adel Moideen) and S.K.S. contributed to study design refinement, data interpretation, and provided expert nephrology oversight. A.T. performed data analysis, interpretation of results, and drafted the initial manuscript. S.T. and M.R. assisted with data organization and literature review. S.K.S. supervised the overall project, contributed to study design, data interpretation, and critically revised the manuscript for important intellectual content. All authors reviewed, edited, and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to institutional and patient privacy considerations but are available from the corresponding author on reasonable request.

Competing interests: All the authors declared no competing interests.

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Figures

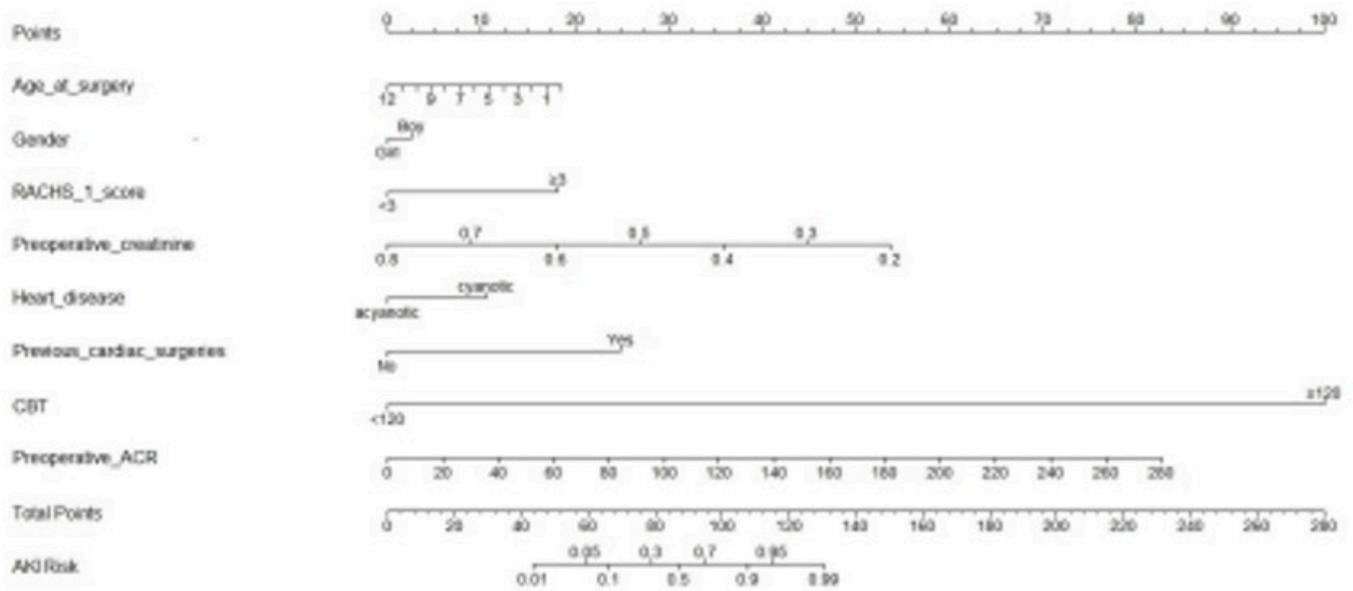


Figure 1

Normogram to calculate the probability of acute kidney injury in children after cardiac surgery

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