Cardiology in the Young

cambridge.org/cty

Periods of low renal perfusion pressure are associated with acute kidney injury following paediatric cardiac surgery

Jamie S. Penk[1], Katja M. Gist[2], Matthew Barhight[3], Karl Migally[1], Santiago Borasino[4], Wendy F. Torres[1], Siyuan Dong[5], Bradley S. Marino[6] and Catherine D. Krawczeski[7]

[1]Department of Pediatrics, Division of Cardiology, Ann and Robert H. Lurie Children's Hospital of Chicago, Chicago, IL, USA; [2]Department of Pediatrics, Division of Cardiology, Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA; [3]Department of Pediatrics, Division of Critical Care, Ann and Robert H Lurie Children's Hospital of Chicago, Chicago, IL, USA; [4]Department of Pediatrics, Division of Cardiology, Children's of Alabama, Burmingham, AL, USA; [5]Department of Preventive Medicine, Division of Biostatistics, Northwestern University, Chicago, IL, USA; [6]Department of Heart Vascular and Thoracic, Division of Cardiology and Cardiovascular Medicine, Cleveland Clinic Children's, Cleveland, OH, USA and [7]Department of Pediatrics, Division of Cardiology, Nationwide Children's Hospital, Columbus, OH, USA

Original Article

Cite this article: Penk JS, Gist KM, Barhight M, Migally K, Borasino S, Torres WF, Dong S, Marino BS, and Krawczeski CD (2024). Periods of low renal perfusion pressure are associated with acute kidney injury following paediatric cardiac surgery. *Cardiology in the Young*, page 1 of 6. doi: 10.1017/S1047951124025149

Received: 21 November 2023
Revised: 26 March 2024
Accepted: 22 April 2024

Keywords:
Paediatric cardiac surgery; acute kidney injury; renal perfusion pressure; cardiac critical care; mean arterial pressure; central venous pressure

Corresponding author:
J. S. Penk; Email: jpenk@luriechildrens.org

Abstract

Introduction: Acute kidney injury is associated with worse outcomes after cardiac surgery. The haemodynamic goals to ameliorate kidney injury are not clear. Low post-operative renal perfusion pressure has been associated with acute kidney injury in adults. Inadequate oxygen delivery may also cause kidney injury. This study evaluates pressure and oximetric haemodynamics after paediatric cardiac surgery and their association with acute kidney injury. *Materials and Methods:* Retrospective case–control study at a children's hospital. Patients were < 6 months of age who underwent a Society of Thoracic Surgery-European Association for Cardio-Thoracic Surgery Congenital Heart Surgery categories ≥ 3. Low renal perfusion pressure was time and depth below several tested thresholds. The primary outcome was serum creatine-defined acute kidney injury in the first 7 days. *Results:* Sixty-six patients (median age 8 days) were included. Acute kidney injury occurred in 36%. The time and depth of renal perfusion pressure < 42 mmHg in the first 24 hours was greater in acute kidney injury patients (94 versus 35 mmHg*minutes of low renal perfusion pressure/hour, $p = 0.008$). In the multivariable model, renal perfusion pressure < 42 mmHg was associated with acute kidney injury (aOR: 2.07, 95%CI: 1.25–3.82, $p = 0.009$). Mean arterial pressure, central venous pressure, and measures of inadequate oxygen delivery were not associated with acute kidney injury. *Conclusion:* Periods of low renal perfusion pressure (<42 mmHg) in the first 24 post-operative hours are associated with acute kidney injury. Renal perfusion pressure is a potential modifiable target that may mitigate the impact of acute kidney injury after paediatric cardiac surgery.

Acute kidney injury is common after paediatric cardiac surgery and is associated with well-described increased morbidity and mortality.[1–3] Attempts to ameliorate acute kidney injury post-operatively have had some success in adults, but even promising interventions still result in a significant rate of acute kidney injury.[4] A major limitation to acute kidney injury prevention is the lack of evidence regarding optimal haemodynamic goals in adults.[5] This is even more challenging in children given the variability in age-related normative haemodynamic parameters as well as thresholds that are associated with adverse outcomes. It is not even clear if driving pressure through the kidney or oxygen delivery is more important in supporting the kidneys nor have thresholds for adequate haemodynamics been established. Renal perfusion pressure, the difference between mean arterial pressure and central venous pressure, is not often considered in the post-operative management of children but may be more important than its individual components as it represents the driving pressure through the kidney. Inadequate oxygen delivery, which is often evaluated with renal near-infrared spectrometry, may also contribute to kidney injury.

The vast majority of literature on the effect of renal perfusion pressure has been studied during cardiac surgery. In a retrospective study of 513 adults on cardiopulmonary bypass, Hu et al found that more time spent at a renal perfusion pressure under the patient's own baseline was associated with subsequent acute kidney injury.[6] Lower renal perfusion pressure more powerfully predicted acute kidney injury than the average mean arterial pressure. A similar retrospective study by Bojan et al of 72 infants during cardiopulmonary bypass found that longer

duration of mean arterial pressures 40% below the patient's baseline was predictive of post-operative kidney tubular dysfunction.[7] Interestingly, Bojan did not find an association between decreased oxygen delivery and acute kidney injury. To adequately support the kidney, it is likely that both adequate pressure and adequate oxygen delivery are required. Renal near-infrared spectrometry could help guide therapy by detecting inadequate oxygen delivery assuming this impacts renal injury. Study results for an association between low renal near-infrared spectrometry and acute kidney injury are mixed, but promising.[8–10]

The literature provides less clarity for blood pressure and oxygen delivery targets *after* cardiopulmonary bypass in the cardiac ICU. Saito et al performed a small retrospective study of 76 adults after cardiac surgery.[11] They found that greater deficits in renal perfusion pressure compared to baseline, but not mean arterial pressure, predicted subsequent development of acute kidney injury. To that end, we sought to evaluate haemodynamics in infants after complex cardiac surgery and their association with subsequent acute kidney injury. We investigate differences in both pressures and oxygen delivery as variables that may drive kidney injury. Our primary hypothesis was that longer duration and depth of low renal perfusion pressure in infants after cardiac surgery would be associated with acute kidney injury.

Materials and methods

Study design

We performed a single-centre retrospective study among infants undergoing cardio-thoracic surgery at Ann & Robert H. Lurie Children's Hospital of Chicago between February 2019 and March 2020. A waiver was granted by the local Institutional Review Board on 8/11/2021.

Patient population

Infants were included if they were < 6 months of age and had a Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery score ≥ 3.[12] We included patients six months and younger so we could compare renal perfusion pressure within an age range with high rates of acute kidney injury and similar expected blood pressure. Infants were excluded if there were less than 20 hours of haemodynamic monitoring data available in the first 24 post-operative hours.

Data collection

Data were collected from three sources: the electronic medical record; Cardioaccess local database with data extracted for the Pediatric Cardiac Critical Care Consortium, and the Etiometry™ platform.

Demographics, clinical predictor, and covariate data

Hourly central venous pressure and hourly renal near-infrared spectrometry values, as well as daily fluid balance, quantified by the difference between total input and all measured output, as well as peak daily serum creatinine were manually extracted from the electronic medical record. At our institution, central venous pressure is only accurately measured once per hour. Similarly, near-infrared spectrometry values are only recorded once per hour. Central venous pressure > 30 mmHg was considered to be erroneous and excluded. Demographic, surgical, and post-operative clinical data were extracted from the Cardioaccess database. Vasoactive doses were extracted, and the vasoactive inotrope score was calculated as previously described by Gais et al. every 6 hours post-operatively.[13] Patient haemodynamic data, including mean arterial pressure and oxygen saturations, were obtained from Etiometry™ every 5 s for the first 48 post-operative hours beginning on admission to the cardiac ICU. From the continuous data, an average mean arterial pressure and systemic oxygen saturation were calculated for each ten-minute interval for the analysis. Central venous pressure was recorded hourly in the electronic medical record. To calculate renal perfusion pressure, the hourly central venous pressure was subtracted from the average mean arterial pressure for each ten-minute interval. A measure for oxygen extraction was calculated as the mean systemic oxygen saturation for each ten-minute interval minus the hourly renal near-infrared spectrometry. Average mean arterial pressure measurements < 20 mmHg and oxygen saturations < 50% over ten minutes were considered erroneous and excluded. All venous saturations, regardless of sampling location, and lactate values in the first 48 hours were obtained from Etiometry™.

Outcome data

The primary outcome was the development of serum creatinine-defined acute kidney injury using the Kidney Disease: Improving Global Outcomes criteria during the first 7 post-operative days.[5] Severe acute kidney injury was defined as at least Stage 2. Baseline serum creatinine was the value most proximate to, and preceding cardiac surgery. Secondary outcomes included fluid balance for the first three post-operative days, duration of mechanical ventilation, need for renal replacement therapy due to acute kidney injury, cardiac ICU and hospital length of stay, and mortality.

Statistical analysis

Descriptive statistics were generated for all variables of interest, where frequency (%) was calculated for categorical variables, and mean, standard deviation, median, interquartile range, and range were calculated for continuous variables. Comparisons of non-repeated variables of interest between acute kidney injury groups were conducted using Student's t-test and Wilcoxon rank sum test as appropriate. Comparisons of repeated measurements were conducted using the univariate linear mixed effects model. Multiple linear regression models were fit to find whether a greater exposure to low renal perfusion pressure below a threshold was associated with acute kidney injury adjusted for the number of hours recorded. Three thresholds were tested centred around the lower interquartile range of renal perfusion pressure for the entire cohort (38, 40, and 42 mmHg). For each threshold, the number of minutes the renal perfusion pressure was below the threshold was multiplied by the depth below the threshold to calculate the mmHg*minutes of exposure to low renal perfusion pressure. Exposure to low renal perfusion pressure showed a skewed distribution, so the exposure to low renal perfusion pressure in mmHg*minutes was log-transformed for the analysis. Exposure to periods of low mean arterial pressure below a threshold (in mmHg*minutes) and oxygen saturation minus renal near-infrared spectrometry greater than a threshold were tested in the same manner. To determine if the primary predictor and confounders of interest were predictive of acute kidney injury, multiple logistic regression models were fit using a bidirectional stepwise process. Random forest plot was applied to determine the rank of the importance of variables, where the variables in the final model along with mean arterial pressure and central venous pressure were used. All analyses were conducted using R version 4.2.2.

https://doi.org/10.1017/S1047951124025149 Published online by Cambridge University Press

Table 1. Demographic data and peri-operative characteristics

Variable	Overall (n = 66)	No AKI (n = 42)	AKI (n = 24)	P-value
Age at surgery (days)	8 (5–36)	7.5 (5–33)	8 (5–38)	0.743
Sex (female)	32 (48)	21 (50)	11 (46)	0.745
Weight at surgery (kg)	3.3 (2.9–3.8)	3.3 (2.8–3.8)	3.3 (2.9–3.8)	0.984
Chromosome abnormality	31 (47)	20 (48)	11 (46)	0.889
Gestation age < 37 weeks	9 (14)	6 (14)	3 (12)	1.000
STAT Category				0.249
3	22 (33)	17 (40)	5 (21)	
4	37 (56)	21 (50)	16 (67)	
5	7 (11)	4 (9.5)	3 (12)	
Cross-clamp time (minutes)	81.5 (35.0–111.3)	84.5 (35.0–115.3)	72 (38.3–102.0)	0.841
CPB used	55 (83)	35 (83)	20 (83)	1.000
CPB duration (minutes)	123.0 (67.3–159.5)	126.0 (64.8–160.8)	119.5 (79.0–137.8)	0.733
VIS (n = 61)	7.0 (5.0–8.0)	7.4 (5.3–8.8)	6.0 (5.0–8.0)	0.179

Kg = kilograms; CPB = cardiopulmonary bypass; VIS = Vasoactive Inotrope Score calculated every 6 hours; RRT = renal replacement therapy; CICU = cardiac ICU; LOS = length of stay. Continuous variables presented as median with interquartile range. Categorical variables presented as frequency (%).

Results:

Seventy-four patients met inclusion criteria. Eight were excluded due to incomplete data, leaving 66 for analysis. The median age of this group was 8 days (interquartile range 5–36) and median weight was 3.3 kg (interquartile range 2.9–3.8). Six (9.1%) patients died. Demographics, operative variables, and outcomes are summarised in Table 1.

Acute kidney injury

Acute kidney injury occurred in 24 patients (36%) of which 7 (10.6%) were classified as severe. Of the patients with severe acute kidney injury, five required renal replacement therapy. A comparison of demographics and operative characteristics among those with and without acute kidney injury is summarised in Table 1.

Haemodynamic data and acute kidney injury

Table 2 summarises a comparison of haemodynamic data between patients with and without acute kidney injury. There was no significant difference between patients with and without acute kidney injury for median mean arterial pressure or central venous pressure. There was also no significant difference in median renal perfusion pressure between these groups at 24 and 48 hours.

The patients that developed acute kidney injury had greater exposure to renal perfusion pressure lower than two of the tested thresholds (40 and 42 mmHg) in mmHg*minutes (Table 2). The most significant difference was seen over the first 24 hours when a threshold of low renal perfusion pressure of 42 mmHg was used, resulting in a median of 94 versus 35 mmHg*minutes/hour for those with versus without acute kidney injury ($p = 0.008$). In the multivariable model, greater Society of Thoracic Surgery-European Association for Cardio-Thoracic Surgery Congenital Heart Surgery category, higher vasoactive inotrope score, and amount of renal perfusion pressure < 42mmHg*minutes was significantly associated with acute kidney injury development (aOR: 2.07, 95%CI: 1.25–3.82, $p = 0.009$).

In order to investigate the relative importance of mean arterial pressure and central venous pressure compared to low renal perfusion pressure, a random forest plot was used which included all the variables in the multivariate analysis described previously with the addition of central venous pressure and mean arterial pressure. A greater exposure to low renal perfusion pressure was the most influential variable in predicting acute kidney injury while mean arterial pressure and central venous pressure were the least (Fig. 1). Amount of exposure to low mean arterial pressure was tested in the same manner as renal perfusion pressure with three thresholds tested centred at the lower interquartile range of mean arterial pressure for the cohort. We found that exposure to mean arterial pressure below thresholds of 45 mmHg, 47 mmHg, and 49 mmHg was not associated with the development of acute kidney injury.

Correlations of renal perfusion pressure < 42 mmHg with outcomes

Greater exposure to renal perfusion pressure < 42 mmHg over the first 24 hours was positively correlated with several outcomes, though most did not reach statistical significance. These outcomes include longer post-operative ICU length of stay ($r = 0.21$, $p = 0.09$), longer hospital length of stay ($r = 0.19$, $p = 0.12$), mortality ($p = 0.18$), and use of renal replacement therapy ($p = 0.24$). A more positive fluid balance on post-operative day one only was associated with greater exposure to renal perfusion pressure below 42 mmHg though the correlation was weak ($p < 0.001$, $r = 0.41$).

Additional haemodynamic parameters tested for association with acute kidney injury

A number of other haemodynamic parameters were tested to evaluate if they were associated with the development of acute kidney injury and these are described in Table 2. There was no difference in oxygen saturation minus renal near-infrared

https://doi.org/10.1017/S1047951124025149 Published online by Cambridge University Press

Table 2. Haemodynamic data

Variable	Overall (n = 66)	No AKI (n = 42)	AKI (n = 22)	P-value
Median RPP (mmHg)	44.6 (39.4–50.4)	45.1 (39.9–50.7)	43.6 (38.8–49.8)	0.263
Mean of lowest RPP (mmHg)	31.8 (5.8)	31.7 (4.2)	31.9 (7.9)	0.940
Median MAP (mmHg)	52.5 (46.9–59.1)	52.6 (47.0–59.4)	52.2 (46.6–58.7)	0.637
Median hourly MAP below 47 mmHg (mmHg*minutes)	24.6 (3.7–83.1)	16.3 (2.4–74.3)	26.3 (10.9–84.9)	0.354
Median CVP (mmHg)	8 (6–9)	8 (6–9)	8 (7–10)	0.182
Median renal NIRS (%)	75 (64–88)	76 (64–88)	74 (63–87)	0.745
Median of lowest Svo2 (%)	68.0 (58.8–76.0)	68.5 (61.0–76.0)	67.5 (54.5–75.3)	0.321
Median of highest lactate (mmol/L)	3.6 (2.4–5.2)	3.1 (2.3–5.1)	4.1 (3.4–5.7)	0.052
Median O2-NIRS (%)	15.3 (7.0–27.0)	14.7 (5.9–25.4)	17.0 (8.4–30.0)	0.461
Median (interquartile range) O2-NIRS > 27% (%*minutes)	7.3 (0–181.0)	1.4 (0–139)	39 (0–217)	0.137
RPP thresholds				
38 mmHg over 24 hours		9 (1.1–58.2)	32 (6.3–74.1)	0.172
38 mmHg over 48 hours		12 (4.0–37.2)	34 (9.8–66.9)	0.071
40 mmHg over 24 hours		20 (2.9–108.0)	56 (18.8–110.5)	**0.034**
40 mmHg over 48 hours		24 (10.9–69.7)	58 (19.9–105.6)	**0.039**
42 mmHg over 24 hours		35 (12.2–169.8)	94 (42.4–172.2)	**0.008**
42 mmHg over 48 hours		50 (27.2–121.4)	90 (39.4–158.3)	**0.030**

RPP = renal perfusion pressure; MAP = mean arterial pressure; CVP = central venous pressure; NIRS = near-infrared spectroscopy; Svo2 = venous saturation; O2-NIRS = arterial oxygen saturation minus renal NIRS.
For RPP thresholds, all data reported as mmHg*minutes as median with interquartile range. Multiple linear regression models were fit to log-transformed lower RPP with the adjustment of the number of hours recorded.
Data are presented as median with interquartile range for non-normally distributed variables and mean with standard deviation (SD) for normally distributed variables.

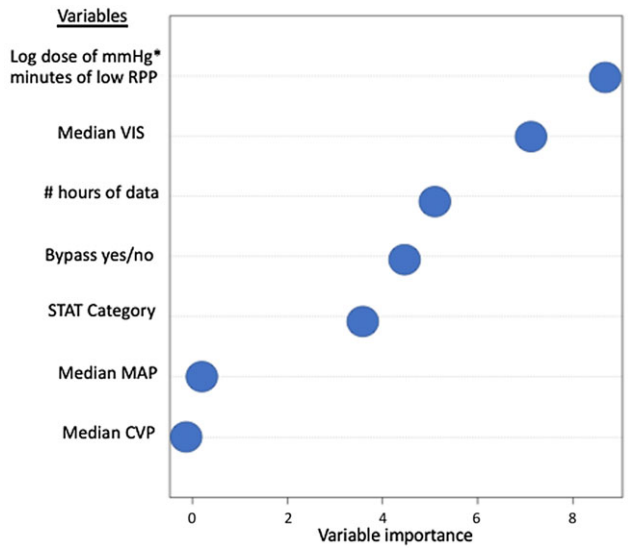

Figure 1. Random forest plot showing variables' relative influence on AKI. More rightward indicates higher relative importance.

spectrometry between groups (p = non-significant). Similar to the analysis of renal perfusion pressure, we further tested if greater exposure to an oxygen saturation minus renal near-infrared spectrometry above a threshold was associated with acute kidney injury. Three thresholds were tested centred on the highest interquartile range, and we found that none of the 25, 27%, or 29% (p = non-significant) thresholds were associated with the development of acute kidney injury.

The median of the highest lactate recorded for each patient showed a trend towards higher lactate in the acute kidney injury group (4.1 versus 3.1 mmol/L, p = 0.052). There was no difference between groups in the single lowest ten-minute mean renal perfusion pressure for each patient (p = non-significant). There was also no difference in the median renal near-infrared spectrometry (p = non-significant) or lowest mixed venous saturation (p = non-significant).

Discussion

This study demonstrates that greater exposure to low renal perfusion pressure is independently associated with the development of acute kidney injury in infants after cardiac surgery. Median renal perfusion pressure was not associated with acute kidney injury. However, the time and depth below a threshold of renal perfusion pressure were closely associated with acute kidney injury suggesting periods of hypoperfusion could be a driving factor. Individually, mean arterial pressure and central venous pressure were not associated with acute kidney injury and were the least predictive variables in a random forest plot. Measures of inadequate oxygen delivery were not associated with acute kidney injury development in this cohort.

Patterson conducted a similar study of renal perfusion pressure in the cardiac ICU in paediatrics where 182 patients were analysed after Fontan completion surgery.[14] In this study, lower renal perfusion pressure was associated with acute kidney injury (50 versus 58 mmHg, p = 0.0001). A multivariate regression model

https://doi.org/10.1017/S1047951124025149 Published online by Cambridge University Press

found that mean arterial pressure and central venous pressure were significantly associated with acute kidney injury, though renal perfusion pressure was not included in the model. Esch completed a very similar study of 211 patients after Fontan surgery.[15] Lower renal perfusion pressure was again independently associated with the development of acute kidney injury, as was higher vasoactive inotrope score. Central venous pressure was not independently associated with acute kidney injury in their multivariate model when renal perfusion pressure was included.

This study in infants similarly finds that low renal perfusion pressure is predictive of acute kidney injury, though we only found a difference in periods below a threshold rather than overall median values. Our study devalues mean arterial pressure and central venous pressure individually compared to renal perfusion pressure similar to these previous two studies. The degree to which periods of low renal perfusion pressure are more important in this study could be due to the continuous mean arterial pressure data used rather than once per-hour values used in the previous two studies. The threshold minimum of 42 mmHg for renal perfusion pressure suggests injury may occur in infants at a mean arterial pressure many practitioners would find acceptable. Some practitioners may accept mean arterial pressure > 40 mmHg in infants after Norwood surgery for instance which would lead to a renal perfusion pressure that is associated with acute kidney injury in this cohort. A recent study by Primeaux compiled normal haemodynamic data in infants post Norwood from a number of published sources and found a median mean arterial pressure of 50.3 mmHg,[16] very similar to our study. When a normal central venous pressure of approximately 5–8 mmHg is present, this suggests that an adequate renal perfusion pressure could be maintained by targeting the median mean arterial pressure described for this cohort.

We did not demonstrate that low renal perfusion pressure was associated with worse outcomes, though most trended in that direction. This is likely secondary to small sample size. We suspect that this study was underpowered to detect the difference in outcomes that were shown with the larger numbers in the previous two studies. It is also possible that lower renal perfusion pressure does not affect outcomes as much in our infant population versus the Fontan population.

Given the importance of renal perfusion pressure in these three studies, targeting a higher renal perfusion pressure may be a modifiable factor to reduce acute kidney injury incidence and severity. Algaze et al demonstrated a 20% reduction in acute kidney injury in paediatric heart transplant patients after implementing a quality improvement project.[17] Maintenance of mean arterial pressure > 60 mmHg, central venous pressure < 12 mmHg, and achieving both to ensure an adequate renal perfusion pressure were all associated with a lower acute kidney injury rate. It is not clear what vasoactive strategy would be best to achieve the desired renal perfusion pressure, recognising that vasoconstriction may actually reduce blood flow to the kidney. Fluid administration may increase mean arterial pressure, but if central venous pressure increases as much as (or more than) mean arterial pressure, it may offer no advantage for renal perfusion pressure. Further, excessive fluid administration could lead to fluid overload which in itself is deleterious.[18] Higher renal perfusion pressure may be protective for acute kidney injury, but as clinicians try to prevent low renal perfusion pressure we must be mindful that the cure is not more harmful than the disease.

Given the pitfalls of treatment to increase renal perfusion pressure, it is likely that it would be beneficial to have just enough renal perfusion pressure, but not too much. A precision approach may be available by measuring cerebral autoregulation. Ono et al found in adults during cardiac surgery that duration and degree of mean arterial pressure below a patient's individually measured cerebral autoregulation threshold was associated with acute kidney injury.[19] The median mean arterial pressure was not different between groups. Patients may have varying levels of resistance in their vasculature requiring different pressure thresholds to adequately perfuse their organs. When bedside monitoring becomes available, cerebral autoregulation measurements may be a way to more precisely identify minimum pressure thresholds.

Our secondary aim was to study other haemodynamic variables for an association with acute kidney injury development. Measures of adequacy of oxygen delivery (oxygen saturation minus renal near-infrared spectrometry, renal near-infrared spectrometry, and lowest Svo2) were not different between groups. We find it unlikely that oxygen delivery is not important in avoiding renal injury. Our sample size may have not been large enough, or our methods in assessing oxygen delivery may not have been robust enough, to demonstrate a difference. Alternatively, practitioners trained to provide adequate oxygen delivery may have intervened so that few in the cohort experienced inadequate oxygen delivery.

The strength of this study is the frequency of available blood pressure measurements to calculate renal perfusion pressure, and we restricted the population to the highest risk for the outcome of interest using Society of Thoracic Surgery-European Association for Cardio-Thoracic Surgery Congenital Heart Surgery category ≥ 3. There are however several limitations, including small sample size and the retrospective design. The renal perfusion pressure thresholds under which kidney injury was more common in this particular sample may not be generalisable given the limited sample size. Despite having very granular measurements of mean arterial pressure, we only had accurate measures of central venous pressure and renal near-infrared spectrometry hourly whereas continuous measures of both would be ideal. We only considered renal perfusion pressure in the cardiac ICU, as haemodynamic parameters in the operating room were not captured. Acute kidney injury was defined using serum creatinine only, during any of the first post-operative days, which is known to be affected by factors unrelated to kidney disease, such as the use of modified ultrafiltration in the operating room.[20] Creatinine-only definitions of acute kidney injury can also underestimate incidence if the baseline is still reflective of maternal creatinine and has not fallen to a steady state in the newborn.

Conclusions

Increased exposure to low renal perfusion pressure in the post-operative period is associated with the development of acute kidney injury. This represents a modifiable risk factor that could be targeted in future prospective studies in children after cardiac surgery though the renal perfusion pressure thresholds require more study, preferably with continuous mean arterial and central venous pressures. Mean arterial pressure, central venous pressure, and measures of inadequate oxygen delivery as individual variables were not associated with acute kidney injury in this cohort.

Acknowledgements. The authors would like to acknowledge Conor Holland, Evan Butler, and the rest of the staff at Etiometry™ for help with retrieving and managing the very large dataset needed for this project.

Financial support. The division of cardiology at Lurie Children's Hospital provided statistical support.

https://doi.org/10.1017/S1047951124025149 Published online by Cambridge University Press

Competing interests. None.

References

1. Kimura S, Shimizu K, Iwasaki T, et al. Outcomes associated with unrecognized acute kidney injury in postoperative pediatric cardiac patients. Pediatr Nephrol 2023; 38: 2861–2871.
2. Kourelis G, Kanakis M, Samanidis G, et al. Acute kidney injury predictors and outcomes after cardiac surgery in children with congenital heart disease: an observational cohort study. Diagnostics (Basel) 2022; 12: 2397.
3. Van den Eynde J, Rotbi H, Schuermans A, et al. Long-term consequences of acute kidney injury after pediatric cardiac surgery: a systematic review. J Pediatr 2023; 252: 83–92.
4. Meersch M, Schmidt C, Hoffmeier A, et al. Prevention of cardiac surgery-associated AKI by implementing the KDIGO guidelines in high risk patients identified by biomarkers: the prevAKI randomized controlled trial. Intensive Care Med 2017; 43: 1551–1561.
5. Group KDIGOKAKIW. KDIGO clinical practice guidelines for acute kidney injury. Kidney Int Suppl 2012; 2: 1–138.
6. Hu R, Kalam Y, Broad J, et al. Decreased mean perfusion pressure as an independent predictor of acute kidney injury after cardiac surgery. Heart Vessels 2020; 35: 1154–1163.
7. Bojan M, Bastro Duarte M, Lopez V, et al. Low perfusion pressure is associated with renal tubular injury in infants undergoing cardiac surgery with cardiopulmonary bypass: a secondary analysis of an observational study. Eur J Anesthesiol 2018; 35: 581–587.
8. Ruf B, Bonelli V, Balling G, et al. Intraoperative renal near-infrared spectroscopy indicates developing acute kidney injury in infants undergoing cardiac surgery with cardiopulmonary bypass: a case-control study. Crit Care 2015; 19: 27.
9. Gist K, Kaufman J, da Cruz E, et al. A decline in intraoperative renal near infrared spectroscopy is associated with adverse outcomes in children following cardiac surgery. Pediatr Crit Care Med 2016; 17: 342–349.
10. Wakamatsu Y, Nakanishi K, Satoh T, et al. Use of renal near-infrared spectroscopy and urinary neutrophil gelatinase-associated lipocalin monitoring as indicators of acute kidney injury in pediatric cardiac surgery. J Clin Med 2023; 12: 2085.
11. Saito S, Uchino S, Takinami M, et al. Postoperative blood pressure deficit and acute kidney injury progression in vasopressor-dependent cardiovascular surgery patients. Crit Care 2016; 20: 74.
12. Jacobs J, Jacobs M, Maruszewski B, et al. Initial application in the EACTS and STS congenital heart surgery databases of an empirically derived methodology of complexity adjustment to evaluate surgical case mix and results. Eur J Cardiothorac Surg 2012; 42: 775–779.
13. Gaies M, Gurney J, Yen A, et al. Vasoactive-inotropic score as a predictor of morbidity and mortality in infants after cardiopulmonary bypass. Pediatr Crit Care Med 2010; 11: 234–238.
14. Patterson T, Hehir D, Buelow M, et al. Hemodynamic profile of acute kidney injury following the fontan procedure: impact of renal perfusion pressure. World J Pediatr Congenit Heart Surg 2017; 8: 367–375.
15. Esch J, Salvin J, Thiagarajan R, et al. Acute kidney injury after fontan completion: risk factors and outcomes. J Thorac Cardiovasc Surg 2015; 150: 190–197.
16. Primeaux J, Salavitabar A, Lu J, et al. Characterization of post-operative hemodynamics following the norwood procedure using population data and multi-scale modeling. Front Physiol 2021; 12: 603040.
17. Algaze C, Margetson T, Sutherland S, et al. Impact of a clinical pathway on acute kidney injury in patients undergoing heart transplant. Pediatr Transplant 2022; 26: e14166.
18. Lex D, Toth R, Czobor N, et al. Fluid overload is associated with higher mortality and morbidity in pediatric patients undergoing cardiac surgery. Pediatr Crit Care Med 2016; 17: 307–314.
19. Ono M, Arnaoutakis G, Fine D, et al. Blood pressure excursions below the cerebral autoregulation threshold during cardiac surgery are associated with acute kidney injury. Crit Care Med 2013; 41: 464–471.
20. Kaddourah A, Basu R, Bagshaw S, et al. Epidemiology of acute kidney injury in critically ill children and young adults. N Engl J Med 2017; 376: 11–20.

https://doi.org/10.1017/S1047951124025149 Published online by Cambridge University Press