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Peritoneal Dialysis After Congenital Heart Surgery: Literature Review

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ABSTRACT

Background: Acute kidney injury (AKI) is a common complication in pediatric patients following open heart surgery.
Aim: This review investigates the contributing factors to AKI development and assesses the effectiveness of peritoneal dialysis (PD) as a kidney replacement therapy.
Material and Methods: This literature review was conducted to examine factors contributing to the development of acute kidney injury (AKI) in pediatric patients after open heart surgery and to evaluate the effectiveness of peritoneal dialysis (PD) as a kidney replacement therapy method.
Results: Key factors in AKI development include CPB usage, ischemia-reperfusion, and postoperative fluid excess. PD offers significant advantages such as ease of application, no need for anticoagulants, and large vein access. Timely PD implementation is crucial in reducing postoperative mortality rates. Complications of PD catheter placement include peritonitis, hydrothorax, and hemoperitoneum.
Conclusion: Effective prevention and management of AKI in pediatric congenital heart defect patients are critical. Proper management of postoperative fluid excess and timely PD can improve clinical outcomes. Related studies on chronic kidney disease, fluid management post-surgery, and inflammatory response offer further insights into improving treatment and diagnosis in this patient population.

Keywords: Peritoneal Dialysis, Congenital Heart Surgery, Acute Kidney Injury

1. Introduction

Excessive postoperative fluid in congenital heart surgery is a postoperative issue that can lead to morbidity and mortality. As a natural mechanism of the body in the healing process post-surgery, excess fluid should be excreted by the body itself, however, this can result in lower output in patients with critical illness.

Due to acute kidney injury and fluid overload can affect patient output, fluid removal performed in the early postoperative period is the focus of intervention in children following heart surgery. One method that can be used to achieve this is ultrafiltration, which can be done using a peritoneal dialysis catheter. This method offers several advantages compared to other methods, especially in infants and neonates because: (1) Peritoneal dialysis can be easily performed and is available in developing countries where forms of kidney replacement therapy such as intermittent hemodialysis and continuous kidney replacement therapy are not available; (2) no anticoagulant administration is required; and (3) no large vein access is needed, limiting the potential for thrombosis of blood vessels (Barhight et al., 2018).

Peritoneal dialysis (PD) is essential in the postoperative management of patients with congenital heart disease. Research has demonstrated that PD can effectively manage fluid overload in pediatric postoperative cardiac surgery patients, resulting in enhanced outcomes and survival rates (Aslan Kutsal et al., 2022). Furthermore, Peritoneal Dialysis has been proven to significantly reduce the New York Heart Association functional class, hospitalization rates, and mortality in refractory heart failure patients, indicating its potential as a viable treatment option for end-stage heart failure patients (Forcey et al., 2023; Sahu et al., 2019). Furthermore, peritoneal dialysis has been successfully employed in managing end-stage kidney disease in patients with left ventricular assist devices, offering advantages such as improved hemodynamic stability and lower infection rates compared to hemodialysis, highlighting its versatility and effectiveness in complex cardiac cases (Grossekettler et al., 2019). In general, Peritoneal dialysis has emerged as a valuable tool in the management of postoperative congenital heart disease, assisting in fluid balance, functional improvement, and overall patient outcomes.

2. Methodology

This literature review was conducted to examine factors contributing to the development of acute kidney injury (AKI) in pediatric patients after open heart surgery and to evaluate the effectiveness of peritoneal dialysis (PD) as a kidney replacement therapy method.

3. Results and Discussion

Congenital Heart Defects

Congenital heart defects are defined as birth defects that may not necessarily be clinically apparent at birth. For example, a moderate-sized atrial septal defect (ASD) or non-obstructive subaortic stenosis may not be immediately noticeable (Micheletti, 2019). These defects can originate from various structures involved in the development of the heart itself or from the major blood vessels directly connected to the heart. Congenital heart defects can be classified in different ways. Broadly speaking, they can be categorized based on the anatomy and underlying pathophysiology, including: (a) congenital heart defects with shunting between the systemic and pulmonary circulations, (b) left-sided congenital heart defects, (c) right-sided congenital heart defects, (d) congenital heart defects involving anomalies of the major arteries, and (e) other congenital heart defects (Micheletti, 2019). The pathophysiology

of various congenital heart defects can be explained through key points such as the presence of shunting, cyanosis, and alterations in blood circulation at birth.

Shunting can be defined as an abnormal connection between the chambers of the heart or blood vessels that can cause blood flow between the two connected chambers. Typically, there will be blood flow from the high-pressure chamber of the heart, which is the left side of the heart, to the low-pressure chamber of the heart, which is the right side of the heart (left-to-right shunt). This causes blood to fill the right side of the heart and can result in changes in pulmonary blood flow. Increased pulmonary blood flow leads to increased pulmonary artery pressure, which, if left untreated, can cause structural changes in the arteries and result in pulmonary hypertension and increased pulmonary vascular resistance (PVR). If PVR increases to a level higher than systemic vascular resistance (SVR), the pressure gradient changes cause blood to flow in the opposite direction, from right to left, resulting in a right-to-left shunt, a condition known as Eisenmenger syndrome. In this condition, the blood that is pumped to the entire body is a mixture of oxygen-rich blood from the left side of the heart and oxygen-poor blood from the right side of the heart, leading to clinical signs of cyanosis. Cyanosis is a bluish coloration of the skin and mucous membranes that originates from deoxyhemoglobin with a concentration of 5.0 g/dl or higher in the blood (Micheletti, 2019).

During fetal circulation, shunting is crucial as at this point, only the placenta serves as the source of gas exchange and nutrients needed by the fetus. Immediately after birth, the cessation of placental flow leads to an increase in SVR and closure of the ductus venosus, one of the four shunt sites in fetal circulation. The expanding lungs filled with air decrease PVR and enhance pulmonary blood flow, resulting in the closure of the foramen ovale. As arterial oxygen saturation increases, the patent ductus arteriosus closes.

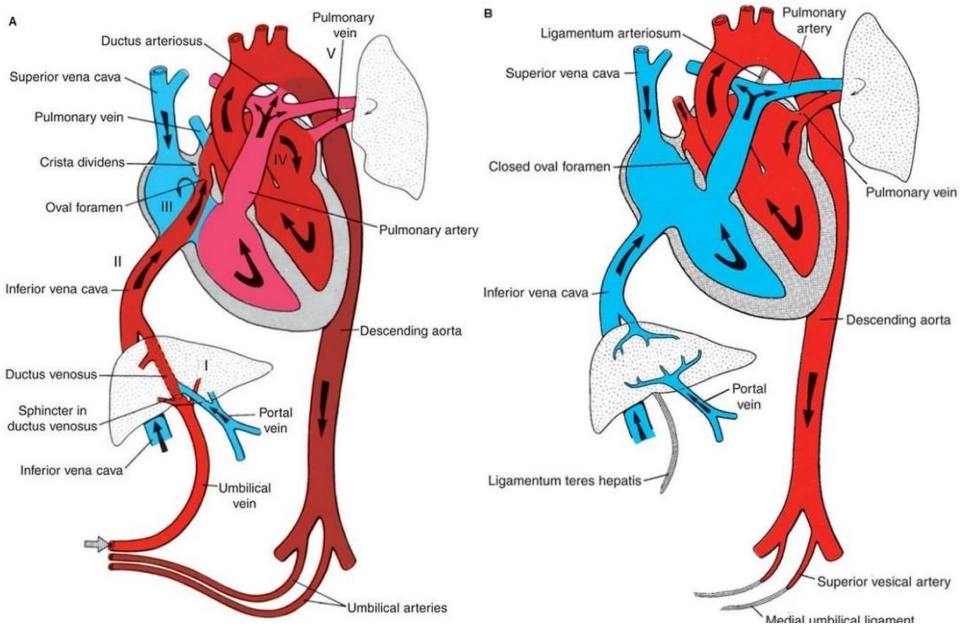

Figure 1: Comparison between blood circulation in fetuses and newborns
Source: (Micheletti, 2019)

Acute Kidney Injury

Based on KDIGO 2012, acute kidney injury (AKI) is defined as a sudden decrease in kidney function that includes, but is not limited to, acute kidney failure. AKI is a broad clinical spectrum syndrome that encompasses various etiologies, including specific kidney diseases (acute interstitial nephritis, acute glomerular and vascular kidney diseases); non-specific conditions (ischemia, toxins); and extrarenal pathologies (prerenal azotemia and

acute postrenal obstructive nephropathy) (KDIGO, 2012).

In pediatric patients, different physiology and pathophysiology compared to adult patients necessitate the use of specific AKI criteria for this patient group. Consequently, a study was conducted to establish new criteria for defining AKI in children. The pediatric version of the RIFLE criteria (pRIFLE) was introduced to (1) outline the epidemiology and course of AKI in critically ill children and (2) investigate the potential relationship between AKI and renal as well as non-renal morbidity (Akcan-Arikan et al., 2007). This modification categorizes each RIFLE criterion based on estimated creatinine clearance, rather than serum creatinine levels, with urine output monitored for a minimum of eight hours.

Table 1: RIFLE criteria in pediatric patients (pRIFLE)

	Estimated creatinine clearance	**Urine production**
Risk	25% reduction	<0,5 ml/kg/hour for 8 hours
Injury	50% reduction	<0,5 ml/kg/hour for 16 hours
Failure	75% reduction or <35 ml/min/1.73 m^2	<0,3 ml/kg/hour for 24 hours or anuria for 12 hours
Loss	Failure that occurs > 4 weeks	
End stage	Chronic Kidney Failure (> 3 months)	

Source: (Soler et al., 2013)

The emergence of acute kidney injury in critically ill patients is an independent risk factor for patient mortality (Christin et al., 2023). The body's homeostasis mechanism, which relies on the kidney's function as an excretory organ, becomes disrupted when there is damage to this organ to varying degrees. Generally, there are two perspectives regarding the effects of acute kidney injury, namely the conventional view and a new perspective in terms of the interaction between acute kidney injury and the body's immune system.

The conventional view of the consequences of AKI is divided into electrolyte disturbances, acidosis, uremia, and fluid overload as the problems that occur in its pathophysiology. The main electrolyte disturbance that occurs in AKI is hyperkalemia, which occurs due to the disruption of potassium homeostasis primarily carried out by the kidneys, intracellular potassium shift due to acidosis, and relative insulin resistance. The damage to the kidneys also disrupts acid-base regulation, leading to acidosis that is exacerbated by tissue hypoperfusion and increased lactic acid production, further worsening the acidosis. Uremia, which occurs due to the accumulation of uremic toxins, increases microvascular permeability, decreases cardiac contractility, and causes coagulation disorders through platelet functional impairment. As a result of the disturbances that cause salt and water retention, fluid overload due to sodium retention, decreased water clearance, and fluid resuscitation used to manage hemodynamic instability in critically ill patients appear to be independent factors that exacerbate AKI in patients (Singbartl & Joannidis, 2015).

Through various studies and data on patients with AKI, it has been found that AKI is a systemic disease involving the body's immune system, as evidenced by higher rates of infections such as bacteremia, post-cardiac surgery infections, and infections in patients with hematological malignancies. This is further supported by the host's dysregulation towards these infections, which can contribute to the pathophysiology of sepsis in AKI. These changes can be observed in various organs within the body, such as the lungs, heart, brain, and gastrointestinal tract, as well as disturbances in cytokine homeostasis. All of these factors

can increase the levels of pro-inflammatory mediators in the organ system and enhance vascular permeability, leading to apoptosis and exacerbating fluid overload in the body. This, in turn, worsens the morbidity and mortality associated with AKI.

Acute Kidney Injury Following Congenital Heart Surgery

In a study, it was found that acute kidney injury is a common complication in patients undergoing heart surgery due to congenital abnormalities, with a prevalence ranging from 20% to 64.6% (Toda & Sugimoto, 2017). These patients are at a higher risk of developing acute kidney injury due to the use of cardiopulmonary bypass (CPB) machine, ischemia-reperfusion injury, and postoperative fluid overload. Acute kidney injury and postoperative fluid overload are closely related, and the presence of one factor may exacerbate the condition of the other factor.

Various methods have been employed to prevent the occurrence of both of these. CPB machines are known to induce acute inflammatory responses triggered by a combination of various factors suspected to be related to the patient's blood interaction with the CPB circuit, which is a foreign body, hypothermia, and reperfusion injury. This acute inflammation will lead to the activation of pro-inflammatory cytokines, increase cytokine production, and decrease the clearance of formed cytokines. Acute kidney injury itself can also modulate the immune response during inflammation, leading to further kidney damage (Bonavia & Singbartl, 2018).

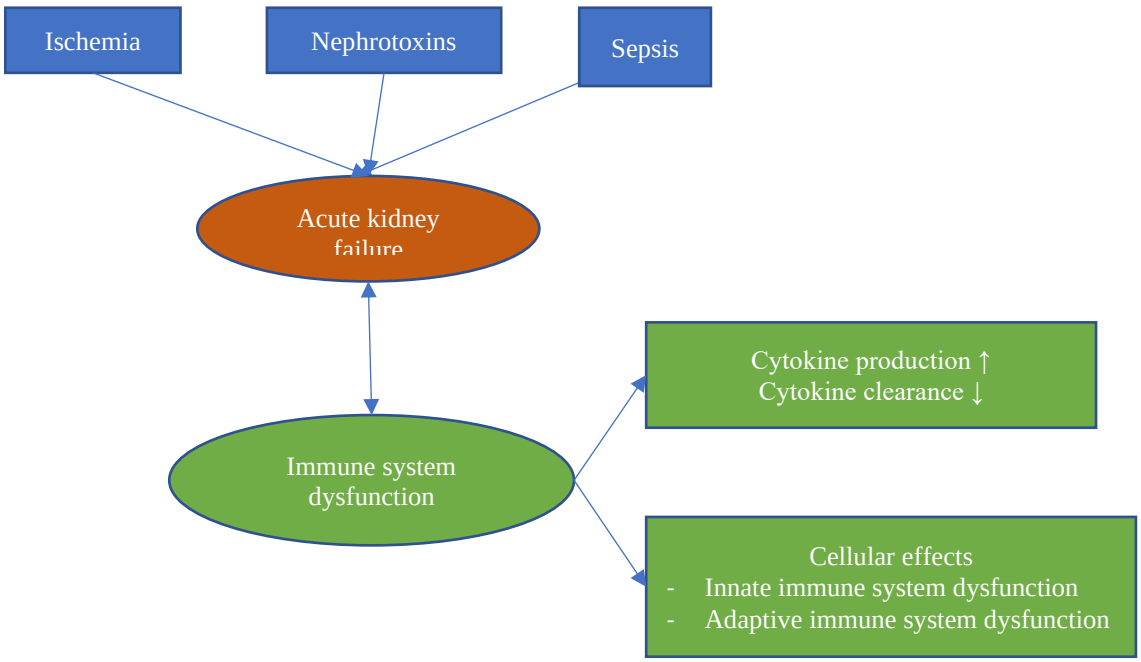

Figure 2: Etiological Circle of Acute Kidney Failure, Which Can Be Exacerbated by Immune System Dysfunction
Source: (Bonavia & Singbartl, 2018)

In general, the factors contributing to the development of AKI can be classified into five groups: preoperative, CPB, postoperative, inflammation, and neuroendocrine (Toda & Sugimoto, 2017). Several mechanisms are believed to underlie this phenomenon, including:

1. Exogenous and endogenous toxins
2. Metabolic factors
3. Ischemia-reperfusion
4. Neurohormonal activation

5. Inflammation
6. Oxidative stress (Bellomo et al., 2008)

The risk factors for the occurrence of acute kidney injury (AKI) after open heart surgery can be classified into renal and extrarenal factors. Table 2 outlines these risk factors, with younger age being a stronger predictor of postoperative AKI, longer ICU stays, and mortality. Prolonged duration of cardiopulmonary bypass (CPB) (more than 180 minutes) and deep hypothermic circulatory arrest are also risk factors for the development of AKI (Yuan, 2019).

Table 2: The risk factors for acute kidney injury following open heart surgery

Risk factors
Renal • Decreased renal perfusion • Decreased glomerular filtration • Malfunctioning renal tubules • Nephrotoxic drugs
Extrarenal *Constitutional* • Younger age and lower body weight at surgery • Hypothermia
Hemodynamics • Higher RACHS-1 (risk adjustment for congenital heart surgery) score • Presence of cyanotic lesions • Uncorrected or residual heart defects • Cardiopulmonary bypass (nonpulsatile flow; inflammatory cascade) • Longer CPB time • Hypothermic circulatory arrest • Need for inotropic drugs • Low cardiac output syndrome • Prolonged ventilator use • Requires ECMO (extracorporeal membrane oxygenation) • Fluid overload in the early phase
Inflammation • *Systemic inflammatory response syndrome* (SIRS) • Sepsis and sepsis shock

Source: (Yuan, 2019)

Failure to regulate the inflammatory response may lead to the development of low cardiac output syndrome (LCOS), characterized by excessive capillary leakage, tachycardia, hypotension, and reduced peripheral organ perfusion (Barhight et al., 2018). The therapy used to address LCOS broadly includes the administration of fluids and vasoactive medications, both of which can have negative effects on renal blood flow, decrease the rate of blood filtration by the kidneys, and exacerbate acute kidney injury that has already occurred. Excessive fluid administration and fluid volume overload increase central venous pressure, leading to right heart failure, decreased right cardiac output, decreased pulmonary venous flow, and decreased cardiac output with hypotension (Barhight et al., 2018). Therefore, alternative methods are required to prevent the occurrence of LCOS by avoiding fluid overload and post-CPB inflammatory response. One approach that is still utilized to achieve

both of these goals, especially in pediatric patients, is the use of peritoneal dialysis.

Peritoneal Dialysis

Renal replacement therapy (RRT) is a modality that can be employed in the treatment of children with AKI. The available modalities for RRT have expanded from peritoneal dialysis (PD) and intermittent hemodialysis (HD) to continuous renal replacement therapy (CRRT), slow low-efficiency dialysis, and slow continuous ultrafiltration (Cullis et al., 2014). In infant and pediatric patients, the use of PD is the primary choice due to several advantages offered by this modality.

Peritoneal dialysis is a more convenient technique for conducting intermittent irrigation of the peritoneal cavity through the use of a disposable single-lumen catheter and dialysate solution (Gokal & Mallick, 1999). The principle employed in this renal replacement therapy method revolves around the mechanism of solute transport through the diffusion of soluble materials and fluid osmosis within the peritoneal cavity, which is rich in blood flow and vascularization. By adhering to these principles, dialysis fluid is instilled into the peritoneal cavity, inducing the movement of soluble substances and intravascular fluid towards the peritoneum for eventual elimination from the body.

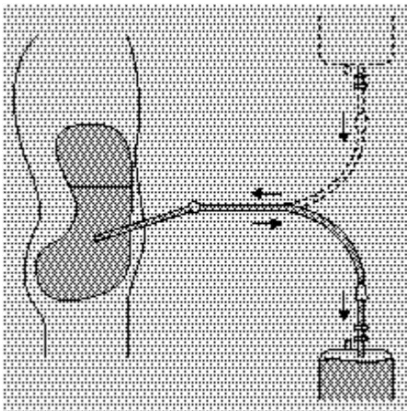

Figure 3: Representation diagram of PD filling and drainage phase
Source: (Gokal & Mallick, 1999)

One hypothesis suggests that the superiority of peritoneal dialysis (PD) in children compared to adults is attributed to the larger surface area of the peritoneum relative to body weight in children. This difference allows for more efficient dialysis in pediatric patients. Additionally, peritoneal dialysis offers several advantages over other kidney replacement therapies. Firstly, it can be easily performed and is readily available in developing countries where alternative treatments like intermittent hemodialysis and continuous kidney replacement therapy may not be accessible. Secondly, the administration of anticoagulants is unnecessary during peritoneal dialysis. Lastly, the absence of a requirement for a large venous access reduces the potential risk of thrombosis in blood vessels (Barhight et al., 2018). Another advantage gained from the selection of peritoneal dialysis as a modality for AKI therapy in pediatric patients is that PD is a dynamic dialysis process that is more physiological and less likely to trigger an inflammatory response compared to HD. This is because the peritoneal membrane, which has natural biocompatibility, is used as the dialysate. Cardiovascular tolerance is also well-maintained because fluid administration and removal are done gradually and continuously, allowing for a large volume of ultrafiltration to be delivered without causing hemodynamic instability (Vasudevan et al., 2017).

Peritoneal dialysis also presents benefits over HD in reducing inflammatory response; patients undergoing HD exhibit significantly higher levels of hs-CRP (high sensitivity C-

reactive protein) compared to patients undergoing PD for a period of three to six months (Yong et al., 2018). hs-CRP is a low-grade systemic inflammation marker that is currently known to act as a risk factor and at the same time a potential factor in the development and progression of AKI (Cosentino et al., 2019).

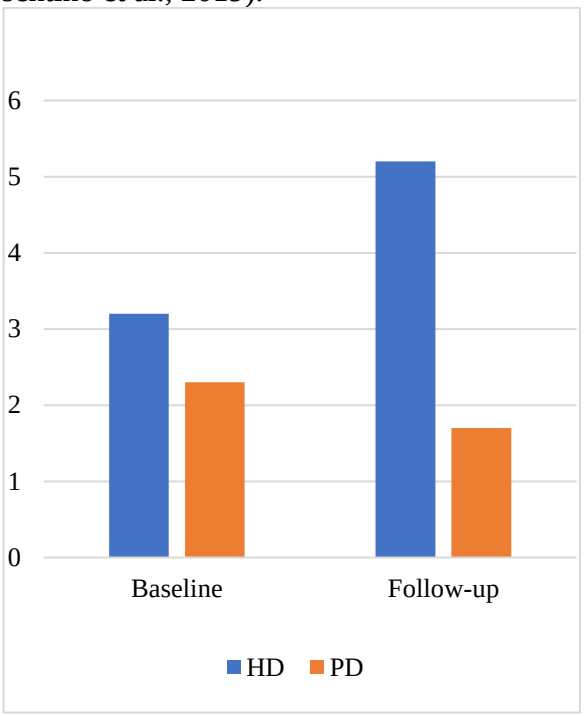

Figure 4: 1The hs-CRP levels in patients undergoing PD were compared to those undergoing conventional HD
Source : (Yong et al., 2018)

Other methods have been implemented as alternatives to PD to prevent both fluid overload and inflammatory responses in postoperative congenital heart surgery patients. Kwiatkowski et al. (2017) conducted a study comparing postoperative fluid output in pediatric heart surgery patients using PD with furosemide as a diuretic agent. The findings revealed that patients receiving furosemide therapy were more likely to require mechanical ventilation for a longer period, had higher electrolyte abnormalities, and had a longer duration of vasoactive infusion usage.

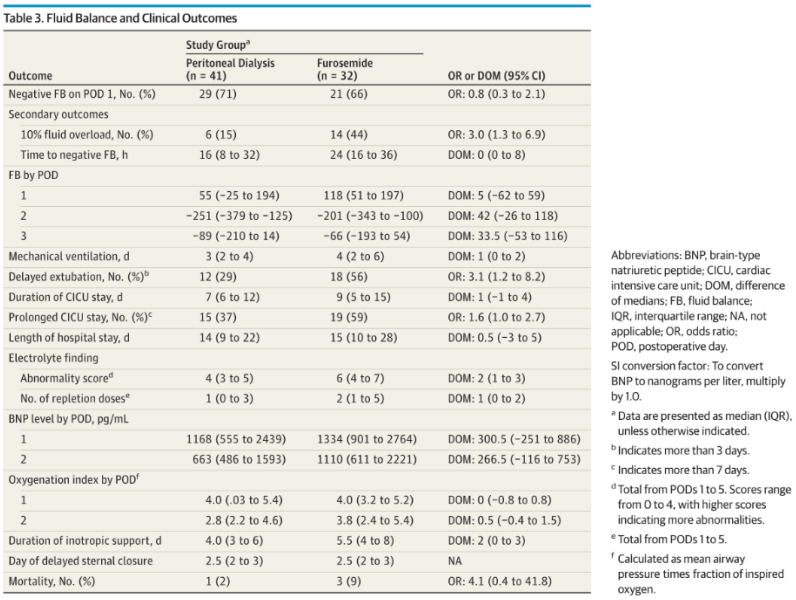

Table 3. Fluid Balance and Clinical Outcomes

Outcome	Study Group[a] Peritoneal Dialysis (n = 41)	Furosemide (n = 32)	OR or DOM (95% CI)
Negative FB on POD 1, No. (%)	29 (71)	21 (66)	OR: 0.8 (0.3 to 2.1)
Secondary outcomes			
10% fluid overload, No. (%)	6 (15)	14 (44)	OR: 3.0 (1.3 to 6.9)
Time to negative FB, h	16 (8 to 32)	24 (16 to 36)	DOM: 0 (0 to 8)
FB by POD			
1	55 (−25 to 194)	118 (51 to 197)	DOM: 5 (−62 to 59)
2	−251 (−379 to −125)	−201 (−343 to −100)	DOM: 42 (−26 to 118)
3	−89 (−210 to 14)	−66 (−193 to 54)	DOM: 33.5 (−53 to 116)
Mechanical ventilation, d	3 (2 to 4)	4 (2 to 6)	DOM: 1 (0 to 2)
Delayed extubation, No. (%)[b]	12 (29)	18 (56)	OR: 3.1 (1.2 to 8.2)
Duration of CICU stay, d	7 (6 to 12)	9 (5 to 15)	DOM: 1 (−1 to 4)
Prolonged CICU stay, No. (%)[c]	15 (37)	19 (59)	OR: 1.6 (1.0 to 2.7)
Length of hospital stay, d	14 (9 to 22)	15 (10 to 28)	DOM: 0.5 (−3 to 5)
Electrolyte finding			
Abnormality score[d]	4 (3 to 5)	6 (4 to 7)	DOM: 2 (1 to 3)
No. of repletion doses[e]	1 (0 to 3)	2 (1 to 5)	DOM: 1 (0 to 2)
BNP level by POD, pg/mL			
1	1168 (555 to 2439)	1334 (901 to 2764)	DOM: 300.5 (−251 to 886)
2	663 (486 to 1593)	1110 (611 to 2221)	DOM: 266.5 (−116 to 753)
Oxygenation index by POD[f]			
1	4.0 (.03 to 5.4)	4.0 (3.2 to 5.2)	DOM: 0 (−0.8 to 0.8)
2	2.8 (2.2 to 4.6)	3.8 (2.4 to 5.4)	DOM: 0.5 (−0.4 to 1.5)
Duration of inotropic support, d	4.0 (3 to 6)	5.5 (4 to 8)	DOM: 2 (0 to 3)
Day of delayed sternal closure	2.5 (2 to 3)	2.5 (2 to 3)	NA
Mortality, No. (%)	1 (2)	3 (9)	OR: 4.1 (0.4 to 41.8)

Abbreviations: BNP, brain-type natriuretic peptide; CICU, cardiac intensive care unit; DOM, difference of medians; FB, fluid balance; IQR, interquartile range; NA, not applicable; OR, odds ratio; POD, postoperative day.

SI conversion factor: To convert BNP to nanograms per liter, multiply by 1.0.

[a] Data are presented as median (IQR), unless otherwise indicated.

[b] Indicates more than 3 days.

[c] Indicates more than 7 days.

[d] Total from PODs 1 to 5. Scores range from 0 to 4, with higher scores indicating more abnormalities.

[e] Total from PODs 1 to 5.

[f] Calculated as mean airway pressure times fraction of inspired oxygen.

Figure 5. Comparison of Fluid Output After Pediatric Heart Surgery Using Peritoneal Dialysis (PD) Versus Furosemide
Source : (Kwiatkowski et al., 2017)

The timing of the initiation of peritoneal dialysis is also considered a crucial factor in reducing mortality rates in pediatric patients following open-heart surgery. Bojan et al. (2012) discovered that in the neonatal and infant population under one year of age, commencing peritoneal dialysis earlier leads to a decrease in the 30-day and 90-day mortality rates post-operation compared to patients who underwent PD more than one day after open-heart surgery. Pediatric patients with MODS and AKI undergoing CRRT indicate that children with fluid overload exceeding 20% at the commencement of CRRT have higher mortality rates compared to patients who start RRT when fluid overload is less than 20% (Vasudevan et al., 2017)

Several complications that have been found in the installation of PD include: non-functioning PD catheter (leakage at the insertion site, displacement, or inadequate drainage), hydrothorax and hemoperitoneum during installation, as well as catheter dislodgement and perforation of hollow organs (Bojan et al., 2012). Peritonitis, omental evisceration, catheter entry into the pleural cavity (indicated by the appearance of dialysate fluid in the chest tube system in post-cardiac surgery patients), pulmonary insufficiency, and hemodynamic instability are also concerns that need to be monitored during catheter placement (Barhight et al., 2018).

4. Conclusion

This literature review concludes that acute kidney injury (AKI) in pediatric patients after open heart surgery is influenced by various factors, including preoperative conditions, the use of cardiopulmonary bypass (CPB) machine, postoperative conditions, inflammatory response, and neuroendocrine factors. Peritoneal dialysis has been proven to be an effective renal replacement therapy method in managing AKI in pediatric patients, with advantages such as ease of application, no need for anticoagulants, and no requirement for large venous access. The timing of peritoneal dialysis implementation is also a key factor in reducing postoperative mortality rates. However, the placement of peritoneal dialysis catheter can lead to several complications such as peritonitis, hydrothorax, and hemoperitoneum. Proper management of postoperative fluid overload is crucial, especially in patients with congenital

heart abnormalities, as it can exacerbate AKI. Factors such as CPB usage, ischemia-reperfusion injury, and postoperative fluid overload have been identified as major contributors to AKI. Adequate prevention and management efforts are necessary to reduce the risk of AKI in patients with congenital heart abnormalities. Studies related to chronic kidney disease, peritoneal dialysis, fluid overload in infants after heart surgery, congenital heart disease, AKI, and inflammatory response in patients with end-stage kidney disease provide additional insights into the diagnosis, treatment, and clinical outcomes in pediatric patients.

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