



Investigation of Serum Electrolyte Imbalances in Neonates Undergoing Cardiac Surgery

Serife Ozalp  ^{1,*}, Zinet Aslancı  ¹, Senay Coban  ², Selin Saglam  ¹, Ezgi Direnc Yucel  ¹, Incila Ali Kahraman  ¹, Hatice Dilek Ozcanoglu  ¹, Erkut Öztürk  ^{2,1}, Funda Gümüş Ozcan  ¹, Alican Hatemi  ^{3,1}

¹ Department of Anesthesiology and Reanimation, Basaksehir Cam and Sakura City Hospital, Istanbul, Turkey

² Department of Pediatric Cardiology, Basaksehir Cam and Sakura City Hospital, Istanbul, Turkey

³ Department of Pediatric Cardiac Surgery, Basaksehir Cam and Sakura City Hospital, Istanbul, Turkey

*Corresponding Author: Department of Anesthesiology and Reanimation, Basaksehir Cam and Sakura City Hospital, Istanbul, Turkey. Email: serife.kaplan@hotmail.com

Received: 18 November, 2024; Revised: 1 February, 2025; Accepted: 18 February, 2025

Abstract

Background: Neonatal cardiac surgery is crucial for addressing congenital heart anomalies yet poses a risk of notable perioperative electrolyte disturbances. Imbalances resulting from blood loss, fluid shifts, and surgical effects can negatively impact patients, leading to issues such as acute kidney injury (AKI), arrhythmias, and elevated mortality rates.

Objectives: The objective of this research is to assess the prevalence and outcomes of electrolyte imbalances during the perioperative, intraoperative, and postoperative phases on morbidity and mortality in neonates undergoing cardiac surgery.

Methods: This study, conducted as a retrospective, single-center analysis, encompassed 355 neonatal patients who underwent cardiac surgery at a tertiary city hospital from January 2021 to January 2024. The study involved neonates under one month old diagnosed with congenital heart disease who underwent cardiac surgery within this timeframe. Electrolyte levels (sodium, potassium, calcium, chloride) were documented preoperatively, intraoperatively, and postoperatively, along with clinical outcomes such as AKI, arrhythmias, seizures, intensive care unit (ICU) length of stay, and mortality. Statistical analyses, both descriptive and inferential, were conducted to examine the connections between electrolyte imbalances and clinical outcomes, using logistic regression.

Results: Notable correlations were identified between preoperative hyponatremia, hypocalcemia, hypochloremia, and the onset of AKI. The presence of arrhythmias was connected to preoperative hypocalcemia and postoperative hypernatremia and hyperchloremia. No significant relationship was found between any electrolyte imbalance and seizures. Mortality showed a significant association with preoperative hyponatremia, hypocalcemia, and hypochloremia, as well as postoperative hypernatremia and hyperchloremia.

Conclusions: Perioperative electrolyte imbalances are commonly observed in neonates undergoing cardiac surgery and have a strong association with negative outcomes. Managing these imbalances proactively may result in a decrease in complications, notably AKI and arrhythmias, and an enhancement in survival rates.

Keywords: Neonatal, Cardiac Surgery, Electrolyte Imbalance, ICU, Mortality

1. Background

Cardiac surgery and the use of cardiopulmonary bypass (CPB) during the neonatal period are intricate procedures designed to rectify congenital heart anomalies. Despite significant improvements in survival

rates resulting from these interventions, it is imperative to consider the potential risks they bring. Significant fluid and electrolyte imbalances can occur in neonatal patients undergoing cardiac surgery due to blood loss and the utilization of CPB (1). Patient outcomes may be negatively affected by these perioperative electrolyte

disturbances. Electrolyte imbalances cause changes in essential ion levels, leading to acute and chronic complications. Maintaining the precise balance of electrolytes is essential for cellular homeostasis, optimal neuromuscular function, and overall organ health. Imbalances in these levels can have harmful impacts, especially for critically ill neonates. Electrolyte imbalances can directly affect the functions of neonatal kidneys. The occurrence of acute kidney injury (AKI) poses a significant concern, as it is associated with increased morbidity and prolonged hospitalization in neonatal cardiac patients following surgery. Limited research has been conducted on the association between imbalances in sodium or chloride levels and AKI following pediatric cardiac surgery (1). Using various cardioplegia options during CPB can effectively address abnormal myocardial sodium depletion and minimize the incidence of hypochloremia in neonates (2).

One of the most common electrolyte disturbances seen in hospitalized patients is dysnatremia, characterized by sodium imbalances. While the impact of dysnatremia has been associated with increased infection complications, coronary events, and hospital mortality in adults following cardiac surgery, its effect on pediatric patients with heart disease remains understudied (3, 4). It is important to note that arrhythmias occurring in neonates shortly after surgery are primarily caused by direct injury to the cardiac conduction system, or edema and inflammation in the myocardial tissue surrounding the conduction pathways. Factors such as electrolyte imbalances, acidosis or alkalosis, patient age during surgery, CPB duration, and hemodynamic status can also affect the occurrence and frequency of arrhythmias (5, 6). Recent studies have revealed a higher prevalence of postoperative hypernatremia compared to hyponatremia in infants, which is linked to increased mortality rates, adverse neurological outcomes, and prolonged hospitalizations (7, 8). Acute hypernatremia can affect synaptic structure and function in the central nervous system (9). The careful selection of intravenous fluid therapy during surgery and CPB is imperative in avoiding dysnatremia (10). Proper recognition and management of electrolyte imbalances are vital for perioperative care, particularly in pediatric cardiac patients, as it has a direct impact on patient outcomes. By gaining a deeper understanding of these imbalances in a clinical setting, we can enhance the quality of care

and make a positive difference in patient outcomes. Additional research is required to enhance the management of electrolytes in this vulnerable population.

2. Objectives

The present study aimed to assess the occurrence of electrolyte imbalances during the perioperative, intraoperative, and postoperative phases in neonates undergoing congenital cardiac surgery and their effects on morbidity (e.g., renal failure and seizures) and mortality. Based on these findings, the study seeks to offer valuable insights into preventive measures and clinical enhancements that can improve long-term health outcomes and contribute to the current evidence. Additionally, this study intends to assess electrolyte imbalances in pediatric patients with AKI and arrhythmia comorbidities.

3. Methods

3.1. Participants

The present retrospective study was conducted at a single center between January 2021 and January 2024 within a tertiary city hospital. The study involved neonates under one month old diagnosed with congenital heart disease who underwent cardiac surgery within this timeframe. Patients presenting with syndromic conditions, preoperative neurological comorbidities, renal failure, or arrhythmias were omitted from the analysis to establish a more standardized preoperative health status within the study sample. Patients with missing data were also excluded from the study. Following the application of the inclusion and exclusion criteria, 355 cases (both male and female) were examined (Figure 1).

3.2. Research Design

This study was a retrospective cohort analysis aimed at investigating the influence of perioperative electrolyte disturbances on postoperative outcomes, such as AKI, arrhythmia, seizure, and mortality, in neonates undergoing cardiac surgery. Data were obtained from patient medical records during the preoperative, intraoperative, and postoperative phases. The primary variables of interest were sodium, potassium, chloride, and calcium levels, which were

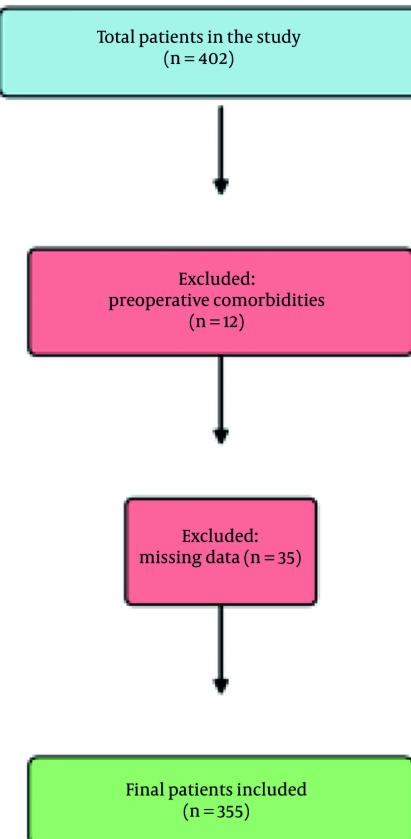


Figure 1. Consort diagram

assessed at designated time points: Preoperatively (blood gas sample taken in the operating room before surgery initiation), intraoperatively (blood gas sample taken in the operating room at the end of surgery), and postoperatively (blood gas sample taken at the 6th hour of postoperative intensive care admission). The assessed outcomes included the duration of postoperative intensive care unit (ICU) stay, seizures, AKI, arrhythmias, requirement for extracorporeal membrane oxygenation (ECMO), and mortality.

3.3. Measures

Electrolyte levels served as the key metrics in this research, utilizing predetermined thresholds to classify abnormal levels. Abnormal sodium levels were defined as less than 135 mmol/L or greater than 145 mmol/L potassium imbalances were described as levels less than

3.5 mmol/L or greater than 5.5 mmol/L chloride imbalances were defined when levels were below 98 mmol/L or above 107 mmol/L hypocalcemia was characterized by serum calcium levels below 8.5 mg/dL, while hypercalcemia was defined as levels exceeding 10.5 mg/dL. Age-specific thresholds were used to detect phosphorus irregularities. Data on electrolyte values were collected from medical records at the specified time points.

Secondary measures such as AKI were ascertained using the Kidney Disease: Improving global outcomes (KDIGO) criteria, while arrhythmias were identified through electrocardiographic findings observed during the patient's stay in the ICU (11). Seizures were identified during the ICU stay by motor symptoms typically seen in epileptic seizures and a clear and detailed clinical description by the treating intensivists, including

Table 1. Comparison of Electrolyte Imbalances in Neonates with and Without Acute Kidney Injury ^a

Variables	Overall (N = 355)	Non-AKI Group (N = 271)	AKI Group (N = 84)	P-Value
Preoperative				
Hyponatremia	114 (32.11)	75 (27.68)	39 (46.43)	0.002
Hypernatremia	7 (1.97)	4 (1.48)	3 (3.57)	0.363
Hypokalemia	116 (32.68)	83 (30.63)	33 (39.29)	0.179
Hyperkalemia	32 (9.01)	26 (9.59)	6 (7.14)	0.640
Hypocalcemia	133 (37.46)	88 (32.47)	45 (53.57)	< 0.001
Hypercalcemia	5 (1.41)	4 (1.48)	1 (1.19)	> 0.999
Hypochloremia	51 (14.37)	32 (11.81)	19 (22.62)	0.022
Hyperchloremia	58 (16.34)	40 (14.76)	18 (21.43)	0.202
Intraoperative				
Hyponatremia	10 (2.82)	7 (2.58)	3 (3.57)	0.706
Hypernatremia	103 (29.01)	67 (24.72)	36 (42.86)	0.002
Hypokalemia	176 (49.58)	144 (53.14)	32 (38.10)	0.022
Hyperkalemia	22 (6.20)	14 (5.17)	8 (9.52)	0.235
Postoperative				
Hypernatremia	89 (25.07)	39 (14.39)	50 (59.52)	< 0.001
Hypokalemia	201 (56.62)	159 (58.67)	42 (50.00)	0.202
Hyperkalemia	12 (3.38)	7 (2.58)	5 (5.95)	0.251
Hypocalcemia	226 (63.66)	178 (65.68)	48 (57.14)	0.196
Hyperchloremia	147 (41.41)	95 (35.06)	52 (61.90)	< 0.001

Abbreviation: AKI, acute kidney injury.

^aValues are expressed as No. (%).

postictal cessation of symptoms and recovery of consciousness and/or neurological status. Mortality rates and the requirement for ECMO assistance were documented from patient medical files.

3.4. Statistical Analysis

Descriptive statistics were employed to summarize the baseline characteristics of the study population, encompassing demographic variables and the occurrence of perioperative electrolyte imbalances. Continuous variables, such as electrolyte levels and CPB duration, were documented as either means \pm standard deviations or medians with interquartile ranges, depending on the distribution of the data. Categorical variables, such as arrhythmia occurrences or mortality rates, were presented as frequencies and percentages. Categorical variables between groups with and without electrolyte abnormalities were compared using the chi-square test or Fisher's exact test. Continuous variables were examined using t-tests or Mann-Whitney U tests following assessments of normality. Logistic regression models were employed to examine the links between perioperative electrolyte imbalances and outcomes, such as AKI, arrhythmia, and mortality. A P-value lower

than 0.05 was regarded as statistically significant. Statistical analyses were carried out utilizing R version 4.3.3 provided by the R Foundation for Statistical Computing in Vienna, Austria. The study was conducted in accordance with the Declaration of Helsinki and was approved by the University of Health Sciences Turkiye, Basaksehir Cam and Sakura city Hospital Local Ethics Committee (28.02.2024.130).

4. Results

Among the 355 patients, ages ranged from 0 to 1 month, with a median age of 0.3 months and an average age of 0.406 ± 0.30 months. Patient heights varied from 39 to 62 cm, with a median height of 50 cm and a mean of 50.175 ± 3.30 cm, suggesting a homogeneous distribution. Similarly, the weight range was from 1.6 to 5.8 kg, with a median weight of 3.1 kg (IQR: 0.70) and an average weight of 3.2 ± 0.64 kg, indicating a consistent neonatal weight distribution within this group of patients.

The length of anesthesia showed considerable variation, spanning from 95 to 810 minutes, with a median duration of 340 minutes. The CPB duration also exhibited significant variability, ranging from 0 to 545

minutes, with a median duration of 110 minutes. Postoperative ICU stays ranged from 1 to 180 days, with a median stay of 12 days and a mean stay of 16.70 ± 18.62 days. Hospital stays followed a comparable pattern, lasting from 1 to 180 days, with a median stay of 17 days and an average stay of 21.59 ± 18.62 days, demonstrating differences in recovery times and postoperative outcomes in the group.

4.1. Acute Kidney Injury

The research revealed significant distinctions between patients with AKI and those without. Hyponatremia was more prevalent in the AKI group (46.43%) compared to the non-AKI group (27.68%) before the operation ($P = 0.002$). Similarly, hypocalcemia was significantly more prevalent in patients with AKI (53.57% vs. 32.47%, $P < 0.001$), while hypochloremia also displayed a notable difference, occurring more frequently in the AKI population (22.62% vs. 11.81%, $P = 0.022$). No significant differences were found in other preoperative electrolyte disturbances between the groups.

Intraoperatively, a significantly higher proportion of patients in the AKI group exhibited persistent hypernatremia (42.86%) compared to the control group (24.72%) ($P = 0.002$), and there was also a greater prevalence of hypokalemia (61.90% vs. 46.86%, $P = 0.022$).

Post-surgery, AKI patients demonstrated notably higher rates of hypernatremia (59.52% vs. 14.39%, $P < 0.001$) and hyperchloremia (61.90% vs. 35.06%, $P < 0.001$). There were no significant differences between the two groups in terms of other post-surgery electrolyte imbalances, including hypokalemia, hyperkalemia, hypocalcemia, and hypochloremia (Table 1).

4.2. Arrhythmia

We examined variations in laboratory results in patients with and without arrhythmia, focusing on electrolyte imbalances before, during, and after surgery. Significant variations were evident preoperatively, with hypocalcemia being notably more prevalent in the arrhythmia group (50.65% vs. 33.81%, $P = 0.010$). Despite the higher occurrence of hyponatremia and hypokalemia in the arrhythmia group (40.26% for both) compared to the non-arrhythmia group (29.86% and 30.58%, respectively), these disparities did not show

statistical significance ($P = 0.111$ for hyponatremia, $P = 0.143$ for hypokalemia).

Hypernatremia was detected in a larger proportion of patients with arrhythmia (37.66%) based on blood tests performed during surgery, but this variation was not statistically significant ($P = 0.081$). Similarly, the arrhythmia group had a lower rate of hypokalemia (40.26%) compared to the non-arrhythmia group (52.16%), indicating a potential significance ($P = 0.086$).

After surgery, distinct disparities were identified in the blood test results across the groups, particularly in hypernatremia and hyperchloremia. Patients diagnosed with arrhythmia exhibited a marked increase in hypernatremia (50.65% vs. 17.99%, $P < 0.001$), alongside an elevated prevalence of hyperchloremia (62.34% vs. 35.61%, $P < 0.001$). Although hypocalcemia was significantly more frequent in subjects with arrhythmia before the operation, there was a slight decrease postoperatively, and the controls had a higher hypocalcemia rate (66.91% vs. 51.95%, $P = 0.023$) (Table 2).

4.3. Seizure

Seizures were documented in 17 (4.7%) of the 355 patients in our study group during postoperative intensive care monitoring. When all electrolyte imbalances in blood gas analyses at three time points were compared, none showed a statistically significant association with seizure occurrence ($P > 0.05$) (Table 3).

4.4. Mortality

Finally, we examined the discrepancies in electrolyte imbalances prior to, during, and following surgery among patients who survived and those who did not. Before the surgery, there were notable differences in the occurrence of hyponatremia, which was more prevalent in the group that passed away (45.98%, $P = 0.002$). The occurrence of hypocalcemia was markedly higher in non-survivors (50.57% vs. 32.84%, $P = 0.004$), as was hypochloremia (24.14% vs. 11.19%, $P = 0.005$).

Hypernatremia demonstrated a notable rise among the deceased during or shortly after the procedure (41.38% vs. 25.00%, $P = 0.005$). Similarly, hypokalemia was found to be more prevalent in the group experiencing mortality (63.22% vs. 46.64%, $P = 0.010$). Post-surgery, in patients who deceased, hypernatremia (56.32% vs. 14.93%, $P < 0.001$) and hyperchloremia (59.77% vs. 35.07%, $P < 0.001$) were notably more prevalent. Moreover, there

Table 2. Comparison of Electrolyte Imbalances in Neonates with and without Arrhythmia ^a

Variables	Overall (N = 355)	Non-arrhythmia Group (N = 278)	Arrhythmia Group (N = 77)	P-Value
Preoperative				
Hyponatremia	114 (32.11)	83 (29.86)	31 (40.26)	0.111
Hypernatremia	7 (1.97)	6 (2.16)	1 (1.30)	> 0.999
Hypokalemia	116 (32.68)	85 (30.58)	31 (40.26)	0.143
Hyperkalemia	32 (9.01)	25 (8.99)	7 (9.09)	> 0.999
Hypocalcemia	133 (37.46)	94 (33.81)	39 (50.65)	0.010
Hypercalcemia	5 (1.41)	4 (1.44)	1 (1.30)	> 0.999
Hypochloremia	51 (14.37)	37 (13.31)	14 (18.18)	0.371
Hyperchloremia	58 (16.34)	42 (15.11)	16 (20.78)	0.309
Intraoperative				
Hyponatremia	10 (2.82)	8 (2.88)	2 (2.60)	> 0.999
Hypernatremia	103 (29.01)	74 (26.62)	29 (37.66)	0.081
Hypokalemia	176 (49.58)	145 (52.16)	31 (40.26)	0.086
Hyperkalemia	22 (6.20)	15 (5.40)	7 (9.09)	0.356
Hypocalcemia	53 (14.93)	42 (15.11)	11 (14.29)	> 0.999
Hypercalcemia	145 (40.85)	113 (40.65)	32 (41.56)	0.990
Postoperative				
Hypernatremia	89 (25.07)	50 (17.99)	39 (50.65)	< 0.001
Hypokalemia	201 (56.62)	161 (57.91)	40 (51.95)	0.421
Hyperkalemia	12 (3.38)	10 (3.60)	2 (2.60)	> 0.999
Hypocalcemia	226 (63.66)	186 (66.91)	40 (51.95)	0.023
Hyperchloremia	147 (41.41)	99 (35.61)	48 (62.34)	< 0.001

^a Values are expressed as No. (%).

was a higher incidence of hypocalcemia in the group that experienced mortality (47.13% compared to 32.84%, $P = 0.023$). The mortality subgroups did not show notable differences in other electrolyte imbalances in potassium (Table 4).

Further investigation through regression analysis was conducted to understand the connection between electrolyte imbalances and the risk of mortality. An association between preoperative hyponatremia and mortality was observed in the univariable analysis, with an odds ratio (OR) of 0.80 (95% CI, 0.30 - 1.3; $P = 0.002$). After adjusting for other factors in the multivariable analysis, hyponatremia was still identified as a significant indicator of mortality (OR, 0.77; 95% CI, 0.22-1.3; $P = 0.006$).

The presence of preoperative hypocalcemia was identified as a significant predictor of mortality in the univariable model (OR, 0.74; 95% CI, 0.25 - 1.2; $P = 0.003$); however, it only approached significance in the multivariable model ($P = 0.074$). Hypochloremia emerged as another crucial factor, demonstrating a notable correlation with mortality in both univariable

(OR, 0.93; 95% CI, 0.30 - 1.5; $P = 0.003$) and multivariable analysis (OR, 0.79; 95% CI, 0.09 - 1.5; $P = 0.025$).

No significant relationships with mortality were observed for other electrolyte imbalances, such as preoperative hypernatremia, hypokalemia, hyperkalemia, and hypercalcemia, in either univariable or multivariable analyses.

5. Discussion

Perioperative electrolyte imbalances were found to be closely connected to critical outcomes, such as AKI, arrhythmia, and mortality, as highlighted in this study. Our research aligns with existing data, emphasizing the crucial role of monitoring and correcting electrolyte levels, especially in at-risk groups, to enhance recovery after surgery.

Preoperative hyponatremia, hypocalcemia, and hypochloremia were notably more prevalent in patients who experienced AKI compared to those who did not. The findings presented are in line with the study by Formeck et al., which emphasized hyponatremia as a pivotal factor influencing the prognosis of AKI patients

Table 3. Comparison of Electrolyte Imbalances in Neonates with and Without Seizure

Variables	Overall (N=355)	Non-seizure Group (N=338)	Seizure Group (N=17)	P-Value
Preoperative				
Hyponatremia	114 (32.11)	109 (32.15)	5 (29.41)	> 0.999
Hypernatremia	7 (1.97)	6 (1.77)	1 (5.88)	0.292
Hypokalemia	116 (32.68)	110 (32.45)	6 (35.29)	> 0.999
Hyperkalemia	32 (9.01)	31 (9.14)	1 (5.88)	> 0.999
Hypocalcemia	133 (37.46)	127 (37.46)	6 (35.29)	> 0.999
Hypercalcemia	5 (1.41)	5 (1.47)	0 (0.00)	> 0.999
Hypocholeemia	51 (14.37)	47 (13.86)	4 (23.53)	0.282
Hypercholeemia	58 (16.34)	55 (16.22)	3 (17.65)	0.746
Intraoperative				
Hyponatremia	10 (2.82)	8 (2.36)	2 (11.76)	0.077
Hypernatremia	103 (29.01)	97 (28.61)	6 (35.29)	0.750
Hypokalemia	176 (49.58)	165 (48.67)	11 (64.71)	0.298
Hyperkalemia	22 (6.20)	21 (6.19)	1 (5.88)	> 0.999
Hypocalcemia	53 (14.89)	49 (14.45)	4 (23.53)	0.297
Hypercalcemia	145 (40.73)	139 (41.00)	6 (35.29)	0.830
Postoperative				
Hypernatremia	89 (25.07)	84 (24.78)	5 (29.41)	0.886
Hypokalemia	201 (56.62)	191 (56.34)	10 (58.82)	> 0.999
Hyperkalemia	12 (3.38)	11 (3.24)	1 (5.88)	0.449
Hypocalcemia	226 (63.66)	216 (63.72)	10 (58.82)	0.880
Hypercalcemia	2 (0.56)	2 (0.59)	0 (0.00)	> 0.999
Hypocholeemia	25 (7.02)	24 (7.08)	1 (5.88)	> 0.999
Hypercholeemia	147 (41.29)	136 (40.12)	11 (64.71)	0.079

^a Values are expressed as No. (%).

(12). Hyponatremia in AKI is often linked to impaired renal handling of sodium and water, exacerbating fluid imbalances and leading to poorer prognoses (8, 13, 14).

Reinforcing our results, Lin et al. illustrated the correlation between intraoperative and postoperative hypernatremia and increased mortality among cardiac patients, underscoring the importance of meticulous intraoperative fluid control (9). In our study, both intraoperative hypernatremia and hypokalemia were more prevalent in the AKI group, reinforcing the critical role of perioperative electrolyte control. CoŞKun et al. reported that hypernatremia and hypercholeemia in postoperative AKI patients are associated with poorer renal outcomes and increased mortality (15). While the administration of postoperative free water is a topic of debate, there is a consensus on the unfavorable outcome (10, 16, 17).

Our research on arrhythmia revealed important electrolyte disruptions, notably preoperative hypocalcemia, among patients with arrhythmia. Pillai et

al. established a link between hypocalcemia and critical morbidity and mortality, especially in patients undergoing major surgical interventions (18). Calcium is crucial for the proper functioning of the heart muscle, and a lack of it can cause disturbances in the heart's electrical activity, resulting in irregular heartbeats (5, 19). Although preoperative hyponatremia and hypokalemia did not show statistical significance in our research, their increased occurrence in the arrhythmia group corresponds to literature, which presents that imbalances in sodium and potassium can lead to arrhythmias by interfering with the electrolyte equilibrium for cardiac stability (6, 7, 20).

Furthermore, the occurrence of postoperative hypernatremia and hypercholeemia, which were notably higher in patients with arrhythmia in our study, aligns with the conclusions drawn by Ganea et al., who highlighted the impact of perioperative sodium and chloride imbalances on postoperative arrhythmias and cardiac issues (21). The results emphasize the necessity

Table 4. Comparison of Electrolyte Imbalances Based on Mortality Outcomes in Neonates ^a

Variables	Overall (N = 355)	No Mortality (N = 268)	Mortality (N = 87)	P-Value
Preoperative				
Hyponatremia	114 (32.11)	74 (27.61)	40 (45.98)	0.002
Hypernatremia	7 (1.97)	4 (1.49)	3 (3.45)	0.369
Hypokalemia	116 (32.68)	81 (30.22)	35 (40.23)	0.110
Hyperkalemia	32 (9.01)	27 (10.07)	5 (5.75)	0.313
Hypocalcemia	132 (37.18)	88 (32.84)	44 (50.57)	0.004
Hypercalcemia	5 (1.41)	4 (1.49)	1 (1.15)	> 0.999
Hypochloremia	51 (14.37)	30 (11.19)	21 (24.14)	0.005
Hyperchloremia	57 (16.06)	39 (14.55)	18 (20.69)	0.235
Intraoperative				
Hyponatremia	10 (2.82)	7 (2.61)	3 (3.45)	0.712
Hypernatremia	103 (29.01)	67 (25.00)	36 (41.38)	0.005
Hypokalemia	175 (49.30)	143 (53.36)	32 (36.78)	0.010
Hyperkalemia	22 (6.20)	14 (5.22)	8 (9.20)	0.281
Hypocalcemia	53 (14.93)	39 (14.55)	14 (16.09)	0.859
Hypercalcemia	145 (40.85)	110 (41.04)	35 (40.23)	0.993
Postoperative				
Hypernatremia	89 (25.07)	40 (14.93)	49 (56.32)	< 0.001
Hypokalemia	200 (56.34)	155 (57.84)	45 (51.72)	0.382
Hyperkalemia	12 (3.38)	7 (2.61)	5 (5.75)	0.287
Hypocalcemia	226 (63.66)	180 (67.16)	46 (52.87)	0.023
Hyperchloremia	146 (41.13)	94 (35.07)	52 (59.77)	< 0.001

^a Values are expressed as No. (%).

of perioperative electrolyte surveillance, especially in high-risk patients for arrhythmias, to avoid unfavorable cardiac consequences.

Strong links were noted between certain electrolyte imbalances and the likelihood of patient survival in terms of mortality. Preoperative hyponatremia, hypocalcemia, and hypochloremia were significant predictors of mortality, consistent with the literature that preoperative hyponatremia is associated with a significantly increased risk of in-hospital mortality (4, 22, 23). Studies have indicated that hyponatremia can exacerbate outcomes in critically ill individuals by interfering with cellular processes and leading to organ dysfunction (3, 24). Current evidence has demonstrated that hyperchloremia plays a role in exacerbating metabolic acidosis and deteriorating renal and cardiac function in critically ill patients (25-27). These results underscore the significance of managing sodium and chloride imbalances during the perioperative phase to enhance patient outcomes.

The present study shows that electrolyte imbalances, particularly disruptions in sodium, calcium, and

chloride levels, play a significant role in affecting postoperative results. Recent studies have affirmed the crucial impact of these disruptions on AKI, arrhythmia, and mortality. The strong associations we have recognized, particularly in hyponatremia, hypernatremia, and hypocalcemia, highlight the significance of precise electrolyte correction protocols, especially for neonates with congenital heart disease who have undergone cardiac surgery.

5.1. Conclusions

This study revealed a significant correlation between perioperative electrolyte imbalances and adverse outcomes, including AKI, arrhythmia, and mortality. The results of our study indicate that specific electrolyte abnormalities before and after surgery are important indicators of poor outcomes in high-risk surgical groups. The increasing frequency of electrolyte disruptions in patients with AKI and arrhythmia, as well as their strong link to mortality, underscores the vital need for proactive monitoring of electrolyte levels and timely interventions. Prompt correction of imbalances,

specifically those concerning sodium, calcium, and chloride, might mitigate postoperative complications and enhance survival rates among these at-risk cohorts.

Future research should focus on enhancing protocols and exploring targeted interventions to reduce the impact of electrolyte imbalances on postoperative outcomes, thereby improving patient prognosis and decreasing mortality rates.

5.2. Limitations

Despite its strengths, this study has several limitations. First, its retrospective and single-center design may limit the generalizability of our findings. The study population was derived from a single tertiary hospital, which may not fully represent variations in surgical and perioperative management across different institutions. Additionally, we were unable to account for all potential confounders, such as specific fluid management protocols, variations in electrolyte correction strategies, and the impact of different anesthetic techniques. However, in our study, anesthesia and fluid management protocols were standardized for all patients, and the same anesthesiologist was responsible for intraoperative management in all cases. This consistency minimizes variations related to anesthetic and fluid administration.

Future prospective studies with larger multicenter cohorts are needed to validate our findings and explore potential interventions aimed at mitigating electrolyte-related complications.

Footnotes

Authors' Contribution: S. O.: Conception or design of the work, drafting the work, final approval of the version to be published, and ensuring that any part of the work is appropriately investigated and resolved; Z. A., S. C., S. S., E. D. Y., I. A. K., and H. D. O.: Revising the work, final approval of the version to be published, and ensuring that any part of the work is appropriately investigated and resolved; E. O., F. G. O., and A. C. H.: Acquisition and analysis, final approval of the version to be published, and ensuring that any part of the work is appropriately investigated and resolved.

Conflict of Interests Statement: The authors declare no conflict of interest.

Data Availability: The de-identified dataset generated and analyzed in the present study is available from the corresponding author upon reasonable request.

Ethical Approval: The study was conducted in accordance with the Declaration of Helsinki and was approved by the University of Health Sciences Turkiye, Basaksehir Cam and Sakura city Hospital Local Ethics Committee (28.02.2024.130).

Funding/Support: The present study received no funding/support.

Informed Consent: Informed consent was obtained from all participants.

References

1. Kimura S, Iwasaki T, Shimizu K, Kanazawa T, Kawase H, Shioji N, et al. Hyperchloremia Is Not an Independent Risk Factor for Postoperative Acute Kidney Injury in Pediatric Cardiac Patients. *J Cardiothorac Vasc Anesth.* 2019;33(7):1939-45. [PubMed ID: 30638924]. <https://doi.org/10.1053/j.jvca.2018.12.009>.
2. Taka H, Douguchi T, Miyamoto A, Shimizu K, Kimura S, Iwasaki T, et al. Modified del Nido cardioplegia is associated with low incidence of low main strong ion difference and hyperchloremia in pediatric patients after cardiac surgery. *J Anesth.* 2024;38(2):244-53. [PubMed ID: 3858399]. <https://doi.org/10.1007/s00540-023-03306-0>.
3. Ontaneda AM, Coss-Bu JA, Kennedy C, Akcan-Arikan A, Fernandez E, Laso JJ, et al. Post-operative dysnatremia is associated with adverse early outcomes after surgery for congenital heart disease. *Pediatr Res.* 2023;94(2):611-7. [PubMed ID: 36707662]. <https://doi.org/10.1038/s41390-023-02495-4>.
4. Kaufman J, Phadke D, Tong S, Eshelman J, Newman S, Ruzas C, et al. Clinical Associations of Early Dysnatremias in Critically Ill Neonates and Infants Undergoing Cardiac Surgery. *Pediatr Cardiol.* 2017;38(1):149-54. [PubMed ID: 27826706]. <https://doi.org/10.1007/s00246-016-1495-3>.
5. Ozturk E, Kafali HC, Tanidir IC, Tunca Sahin G, Onan IS, Haydin S, et al. Early postoperative arrhythmias in patients undergoing congenital heart surgery. *Turk Gogus Kalp Damar Cerrahisi Derg.* 2021;29(1):27-35. [PubMed ID: 33768978]. [PubMed Central ID: PMC7970075]. <https://doi.org/10.5606/tgkdc.dergisi.2021.20366>.
6. Alotaibi RK, Saleem AS, Alsharef FF, Alnemer ZA, Saber YM, Abdelmohsen GA, et al. Risk factors of early postoperative cardiac arrhythmia after pediatric cardiac surgery: A single-center experience. *Saudi Med J.* 2022;43(10):1111-9. [PubMed ID: 36261205]. [PubMed Central ID: PMC9994501]. <https://doi.org/10.1553/smj.2022.43.10.20220275>.
7. Kronborg JR, Lindhardt RB, Vejlstrup N, Holst LM, Juul K, Smerup MH, et al. Postoperative dysnatremia in infants after open-heart surgery occurs frequently and is associated with prolonged intensive care length of stay. *Acta Anaesthesiol Scand.* 2022;66(3):337-44. [PubMed ID: 34870843]. <https://doi.org/10.1111/aas.14009>.
8. Lee JJ, Kim YS, Jung HH. Acute serum sodium concentration changes in pediatric patients undergoing cardiopulmonary bypass and the association with postoperative outcomes. *Springerplus.* 2015;4:641.

[PubMed ID: 26543775]. [PubMed Central ID: PMC4628041]. <https://doi.org/10.1186/s40064-015-1436-2>.

9. Lin R, Du N, Feng J, Li J, Li X, Cui Y, et al. Postoperative hypernatremia is associated with worse brain injuries on EEG and MRI following pediatric cardiac surgery. *Front Cardiovasc Med.* 2023;10:1320231. [PubMed ID: 38188252]. [PubMed Central ID: PMC10768027]. <https://doi.org/10.3389/fcvm.2023.1320231>.
10. Kronborg JR, Lindhardt RB, Vejlstrup N, Holst LM, Juul K, Smerup MH, et al. Postoperative free water administration is associated with dysnatremia after congenital heart disease surgery in infants. *Acta Anaesthesiol Scand.* 2023;67(6):730-7. [PubMed ID: 36866603]. <https://doi.org/10.1111/aas.14223>.
11. Kidney Disease: Improving Global Outcomes C. K. D. Work Group. KDIGO 2024 Clinical Practice Guideline for the Evaluation and Management of Chronic Kidney Disease. *Kidney Int.* 2024;105(4S):S117-314. [PubMed ID: 38490803]. <https://doi.org/10.1016/j.kint.2023.10.018>.
12. Formeck CL, Siripong N, Joyce EL, Ayus JC, Kellum JA, Moritz ML. Association of early hyponatremia and the development of acute kidney injury in critically ill children. *Pediatr Nephrol.* 2022;37(11):2755-63. [PubMed ID: 35211792]. [PubMed Central ID: PMC9399308]. <https://doi.org/10.1007/s00467-022-05478-5>.
13. Lee SW, Baek SH, Ahn SY, Na KY, Chae DW, Chin HJ, et al. The Effects of Pre-Existing Hyponatremia and Subsequent-Developing Acute Kidney Injury on In-Hospital Mortality: A Retrospective Cohort Study. *PLoS One.* 2016;11(9). e0162990. [PubMed ID: 27622451]. [PubMed Central ID: PMC5021268]. <https://doi.org/10.1371/journal.pone.0162990>.
14. Itoh J, Aoki Y, Omoto M, Katsuragawa T, Mimuro S, Nakajima Y. Association Between Early Hyponatremia and Clinical Outcomes in Critically Ill Patients: A Retrospective Cohort Study. *Cureus.* 2024;16(3). <https://doi.org/10.7759/cureus.56138>.
15. CoŞKun Ç, Buyan N, TÜRKYILMAZ C, Atalay Y, Bakkaloğlu EzgÜ SA. Acute kidney injury in neonatal intensive care unit and the significance of nRIFLE criteria on diagnosis and prognosis. *Europ Res J.* 2024;10(1):51-8. <https://doi.org/10.18621/eurj.1319806>.
16. Jetton JG, Vidal E. Evaluation and Management of Acute Kidney Injury in Neonates. In: Emma F, Goldstein SL, Bagga A, Bates CM, Shroff R, editors. *Pediatric Nephrology*. Cham: Springer International Publishing; 2022. p. 1593-616. https://doi.org/10.1007/978-3-030-52719-8_125.
17. Nada A, Bonachea EM, Askenazi DJ. Acute kidney injury in the fetus and neonate. *Semin Fetal Neonatal Med.* 2017;22(2):90-7. [PubMed ID: 28034548]. [PubMed Central ID: PMC5373985]. <https://doi.org/10.1016/j.siny.2016.12.001>.
18. Pillai SS, Foster CA, Ashraf AP. Approach to Neonatal Hypocalcemia. *Newborn.* 2022;1(1):190-6. <https://doi.org/10.5005/jp-journals-11002-0017>.
19. Ban JE. Neonatal arrhythmias: diagnosis, treatment, and clinical outcome. *Korean J Pediatr.* 2017;60(11):344-52. [PubMed ID: 29234357]. [PubMed Central ID: PMC5725339]. <https://doi.org/10.3345/kjp.2017.60.11.344>.
20. Nasr VG, Markham LW, Clay M, DiNardo JA, Faraoni D, Gottlieb-Sen D, et al. Perioperative Considerations for Pediatric Patients With Congenital Heart Disease Presenting for Noncardiac Procedures: A Scientific Statement From the American Heart Association. *Circ Cardiovasc Qual Outcomes.* 2023;16(1). e000113. [PubMed ID: 36519439]. <https://doi.org/10.1161/HCQ.00000000000000113>.
21. Ganea G, Cintea EE, Filip C, Iancu MA, Balta MD, Vatasescu R, et al. Postoperative Cardiac Arrhythmias in Pediatric and Neonatal Patients with Congenital Heart Disease-A Narrative Review. *Life (Basel).* 2023;13(12). [PubMed ID: 38137879]. [PubMed Central ID: PMC10744555]. <https://doi.org/10.3390/life13122278>.
22. Teo CB, Gan MY, Tay RYK, Loh WJ, Loh NW. Association of Preoperative Hyponatremia With Surgical Outcomes: A Systematic Review and Meta-analysis of 32 Observational Studies. *J Clin Endocrinol Metab.* 2023;108(5):1254-71. [PubMed ID: 36472931]. [PubMed Central ID: PMC10099166]. <https://doi.org/10.1210/clinem/dgac685>.
23. Benzon HA, Bobrowski A, Suresh S, Wasson NR, Cheon EC. Impact of preoperative hyponatraemia on paediatric perioperative mortality. *Br J Anaesth.* 2019;123(5):618-26. [PubMed ID: 31540668]. <https://doi.org/10.1016/j.bja.2019.07.024>.
24. Chatterjee R, Garg AK. Sodium and Chloride Balance in Critically Ill Patients. In: Malbrain ML, Wong A, Nasa P, Ghosh S, editors. *Rational Use of Intravenous Fluids in Critically Ill Patients*. Cham: Springer International Publishing; 2024. p. 459-80. https://doi.org/10.1007/978-3-031-42205-8_23.
25. Khan AH, Gai J, Faruque F, Bost JE, Patel AK, Pollack MM. Pediatric Mortality and Acute Kidney Injury Are Associated with Chloride Abnormalities in Intensive Care Units in the United States: A Multicenter Observational Study. *J Pediatr Intensive Care.* 2022;11(2):91-9. [PubMed ID: 35734213]. [PubMed Central ID: PMC9208842]. <https://doi.org/10.1055/s-0040-1719172>.
26. Weyker PD, Webb C. 85C8Metabolic Acidosis in the Cardiothoracic Intensive Care Unit. In: Flynn B, Ivascu NS, Moitra VK, Flynn B, Gaffney A, editors. *Cardiothoracic Critical Care*. Oxford, England: Oxford University Press; 2020. 0 p. <https://doi.org/10.1093/med/9780190082482.003.0008>.
27. Iacobelli S, Guignard JP. Renal aspects of metabolic acid-base disorders in neonates. *Pediatr Nephrol.* 2020;35(2):221-8. [PubMed ID: 30456666]. <https://doi.org/10.1007/s00467-018-4142-9>.