Kufa Medical Journal | Vol. 20, No. 2, 2024

Original article | DOI: https://doi.org/10.36330/kmj.v20i2.16225

p-ISSN: 1993-517X

e-ISSN: 2709-4464

The Use of Arterial Blood Gases Analysis to Evaluate Lung Injury in Children with Congenital Heart Disease Disease who Undergo On-pump Cardiac Surgery

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ABSTRACT

Background: *Congenital heart disease is a defect in the heart or great vessel discovered during infancy or later in life. Congenital heart disease is divided into acyanotic and cyanotic. Surgery is the primary therapeutic option for any congenital heart disease. The cardiopulmonary bypass has advancements in on-pump cardiac surgery. It provides circulatory and respiratory support. An aortic cross-clamp is necessary in most on-pump cardiac surgeries to isolate the heart from Circulation. Patients undergoing cardiac surgery on cardiopulmonary bypass often have disturbances in arterial blood gases, including partial pressure of oxygen, partial pressure of carbon dioxide, PH value, and bicarbonate.* ***Materials and Methods:*** *This study was a cross-sectional study performed at Al-Najaf Center For Open Heart Surgery and Trans Catheter Therapy in Al-Najaf City, Iraq, along a period that extends from November 2023 to March 2024. The study involved (50) pediatric patients: (27) male and (23) female who suffered from congenital heart disease and submitted to surgical repair. The 20 cases are cyanotic, and 30 cases are acyanotic. The blood samples were taken from each patient via an arterial line to assay blood PH, bicarbonate level, partial pressure of oxygen, and partial pressure of carbon dioxide.*

Result: *The study showed significant differences in arterial blood gases between preoperative and postoperative (P value $\leq$ 0.05). Also, there was a correlation between changes in arterial blood gases and aortic cross-clamp time.*

Conclusion*: This study finds the partial pressure of carbon dioxide is more predictive of lung injury after on-pump cardiac surgery than the P/F ratio in cyanotic cases. In acyanotic cases, the P/F ratio and partial pressure of carbon dioxide are essential in determining lung injury. Also, this study finds that the prolonged cross-clamp time increases lung injury after on-pump cardiac surgery.*

Keywords: Congenital Heart Disease, Cardiopulmonary Bypass, Aortic Cross-Clamp, And Arterial Blood Gases.

Article Information

Received: May 17, 2024; Revised: August 20, 2024; Online December, 2024

INTRODUCTION

A congenital heart disease (CHD) is a heart or great vessel defect discovered during infancy or later in life [1]. The most prevalent inborn problem is congenital cardiac disease, which affects 5–11 out of every 1000 live newborns. It is divided into acyanotic and cyanotic congenital heart disease [2]. Treatment options for congenital heart disease fall into two categories: surgical management and non-surgical management. For any congenital cardiac condition, surgery remains the primary therapeutic option [3]

Cardiopulmonary bypass is an extracorporeal circuit that allows advances in cardiothoracic surgery in terms of technique and procedure by giving surgeons access to a bloodless, immobile field. Its mechanism permits systemic circulation and perfusion, active temperature control, oxygenation, and carbon dioxide removal [4]. Applying a cross-clamp to stop the blood flow through the aorta during on-pump cardiac surgery is frequently a crucial step to enable surgical repair. Parts of the body distant from the clamp location undergo ischemia. Hemodynamic alterations are virtually often linked to this significant variation in blood flow.

When the cross-clamp is released, blood flow restarts, and an ischemia-reperfusion response appears, which can result in various pathological processes, including humoral changes, inflammation, and metabolite circulation, which can cause harm to multiple organ systems and have a substantial impact on the prognosis following surgery [5].

Arterial blood gases (ABG):

Maintaining an appropriate acid-base balance is essential for the optimal functioning of nearly all physiological mechanisms within the body. Deviations from the standard pH range can cause abnormalities in the functioning of membrane transport proteins, pH-dependent enzymes, and metabolic processes [6].

Arterial blood gases analysis measures the amounts of bicarbonate, oxygen, carbon dioxide, and pH in arterial blood to evaluate the body's acid-base condition, ventilation, and oxygenation [7].

The following are normal ABG values:

• $PaCO_2$: 35 to 45 mmHg

• pH: 7.35 to 7.45

• HCO_3^-: 22 to 26 mEq/L

• PaO_2: 80 to 100 mmHg

Metabolic problems are indicated by abnormalities in the HCO_3^- level, while abnormalities in the PaCO2 level indicate respiratory problems [7]. In CPB, metabolic acidosis is a common occurrence. Arrhythmias and a decreased sensitivity to catecholamines are symptoms of acidosis. These two elements cause hypotension and further impair the heart muscle's ability to contract [8].

Primary reductions in blood pH and serum HCO_3^- concentrations are characteristics of metabolic acidosis. In many cases, metabolic acidosis is a component of mixed acid-base disorder, particularly in very ill patients. Acute metabolic acidosis is a common occurrence in critically sick individuals, with duration ranging from minutes to several days. Acute metabolic acidosis occurs due to increased nonvolatile acid (lactic acid) production [9].

Also, CPB causes the majority of postoperative respiratory dysfunction, which typically results in severe interstitial lung edema and aberrant gas exchange [10]; one indicator of pulmonary dysfunction is the P/F ratio [11]. The P/F ratio is the partial pressure of oxygen (PaO2) to the fraction of inspired oxygen(Fio2); when the P/F ratio is equal to or less than 200, it is referred to as acute respiratory distress syndrome, whereas acute lung injury describes individuals whose P/F ratio is equal to or less than 300. Acute lung injury and acute respiratory distress syndrome are known to be correlated with cardiac surgery [12]. The standard value of P/F ratios is ranging between 400 and 500 mm Hg [13].

The study aimed to investigate the serial changes in arterial blood gases before, and after on-pump cardiac surgery and to find the correlation between these changes and aortic cross-clamp time.

METHODS

Patient collection and study design

This study was a cross-sectional study carried out at the Al-Najaf Center For Open Heart Surgery and Trans Catheter Therapy in Al-Najaf City, Iraq, through a period that extends from November 2023 to March 2024. The study included(50) pediatric patients, 27 male and 23 female, who suffered from CHD and needed surgical repair. The 20 cases are cyanotic, and 30 cases are acyanotic. All cases will be subjected to complete history taking and subsequent laboratory investigations. Basic information, such as age, gender, and weight, is recorded for patients.

Blood samples were taken from each patient included in this study via arterial line before CPB, post aortic cross-clamp, immediately when the patient reached the ICU (ICU day 0), and after 12-24 hr from reaching the patient to ICU (ICU day1) for assay blood PH, PaO2, PaCO2 and HCO3- values.

Materials

The Pa O2 assay kit and PaCO2 assay kit (RADIOMETER/ Denmark). The Pa CO2 and PaO2 values were obtained by a blood gases machine (ABL 800 Flex Plus) using special kits, while the PH and HCO3- values were obtained through a chemical reaction in the blood gases machine (ABL 800 Flex Plus) without using kits. The P/F ratio obtained from partial pressure of oxygen(PaO2)/ fraction of inspired oxygen(FiO2)

Statistical analysis

All data of the 50 patients were analyzed by using the statistical package for social sciences software (SPSS) (version 25 IBM SPSS, Inc., Chicago, Illinois, USA) and Microsoft Excel 2019. All data is expressed as (mean ± SD) standard deviation. Correlation coefficient analysis was completed with Pearson's Eta square. The significance of differences was detected at ($P \leq 0.05$).

Ethical considerations

The study was conducted under the ethical principles of the Declaration of Helsinki. It was done with patients' verbal and analytical approval before taking the sample. The study protocol, the subject information, and the consent form were reviewed and approved by a local ethics committee according to document number 99 on November 2023 to get this approval.

RESULTS

Evaluation of pre and postoperative arterial blood gases in pediatric acyanotic congenital heart disease who submit to cardiac surgery:

This study showed a significant difference in the P/F ratio between preoperative and postoperative day 1 (decrease) and between postoperative day 0 and postoperative day 1 (decrease), as shown in Table 1.

Table 1: Distribution of P/F ratio among acyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.Deviation	P value
P/F ratio	Preoperative	450.5517±95.15198	**0.20**
	postoperative day 0	383.9500±139.57079	
	preoperative	450.5517±95.15198	<0.001*
	postoperative day 1	284.9759±129.77245	
	postoperative day 0	383.9500±139.57079	**0.02***
	postoperative day 1	284.9759±129.77245	

Also, there was a significant difference in PaCO2 value between postoperative day 0 and postoperative day 1 (decrease), as shown in Table 2

Table 2: Distribution of PaCO2 among acyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.Deviation	P value
PaCO2 mmHg	Preoperative	40.6211±9.18650	**0.60**
	postoperative day 0	43.9050±12.44611	
	preoperative	40.6211±9.18650	**0.40**
	postoperative day 1	36.2421±4.64032	
	postoperative day 0	43.9050±12.44611	**0.03***
	postoperative day 1	36.2421±4.64032	

Also, there was a significant difference in PH values between preoperative and postoperative day 1 (increase) and between postoperative day 0 and postoperatively day 1 (increase), as shown in Table 3.

Table 3: Distribution of PH among acyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.deviation	P value
PH	Preoperative	7.3164±.08178	**0.8**
	postoperative day 0	7.3294±.06549	
	preoperative	7.3164±.08178	**< 0.001***
	postoperative day 1	7.4127±.03794	
	postoperative day 0	7.3294±.06549	< 0.001*
	postoperative day 1	7.4127±.03794	

Finally, there was a significant difference in HCO3- values between preoperative and postoperative day 1 and (increase), as shown in Table 4

Table 4: HCO3 distribution among acyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.deviation	P value
HCO3- Mmol/L	Preoperative	20.5433±2.80599	**0.08**
	postoperative day 0	22.0367±2.12465	
	preoperative	20.5433±2.80599	**<0.001***
	postoperative day 1	23.6517±1.99349	
	postoperative day 0	22.0367±2.12465	**0.058**
	postoperative day 1	23.6517±1.99349	

Evaluation of pre and postoperative arterial blood gases in pediatric cyanotic congenital heart diseases (TOF) undergoing surgery repair:

The study showed there were no significant differences in the P/F ratio between preoperation and postoperation, as shown in Table 5

Table 5: Distribution of P/F ratio among cyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.Deviation	P value
P/F ratio	Preoperative	271.9412±97.98053	**0.90**
	postoperative day 0	290.5950±150.64541	
	preoperative	271.9412±97.98053	**0.30**
	postoperative day 1	199.5842±94.64329	
	postoperative day 0	290.5950±150.64541	**0.10**
	postoperative day 1	199.5842±94.64329	

Also, this study has shown a significant difference in PaCO2 values between postoperative day 0 and postoperative day 1 (decrease), as shown in Table 6.

Table 6: Distribution of PaCO2 among cyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.deviation	P value
PaCO2 mmHg	preoperative	42.3200±11.23214	**0.90**
	postoperative day 0	43.4267±7.65997	
	preoperative	42.3200±11.23214	**0.10**
	postoperative day 1	37.9448±4.71522	
	postoperative day 0	43.4267±7.65997	**.04*0**
	postoperative day 1	37.9448±4.71522	

Also, the study has shown a significant difference in PH values between preoperative and postoperative day 1 (increase) and between postoperative day 0 and postoperative day 1 (increase), as shown in Table 7.

Table 7: Distribution of PH among cyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.Deviation	P value
PH	Preoperative	7.2911±.09078	**0.60**
	postoperative day 0	7.3183±.07301	
	preoperative	7.2911±.09078	**0.001*0**
	postoperative day 1	7.3902±.06363	
	postoperative day 0	7.3183±.07301	**0.02*0**
	postoperative day 1	7.3902±.06363	

Finally, there was a significant difference in HCO3- value between preoperative and postoperative day 1 (increase), as shown in Table 8

Table 8: Distribution of HCO3 among cyanotic patients before and after surgery.

Parameters	Groups	Mean ±S.Deviation	P value
HCO3- Mmol/L	Preoperative	18.9474±3.86126	**0.0540**
	postoperative day 0	21.4250±2.32104	
	preoperative	18.9474±3.86126	**.05*0**
	postoperative day 1	21.4895 ±2.70758	
	postoperative day 0	21.4250±2.32104	**1.00**
	postoperative day 1	21.4895 ±2.70758	

Correlation in arterial blood gases between postoperative ICU day 0 and cross-clamp time (CCT) of open heart surgery:

The study showed negative correlations in P/F ratio, HCO3- and PaCO2 between postoperative ICU day 0 and CCT of acyanotic cases of congenital heart disease, as shown in Figures 1,2 and 3

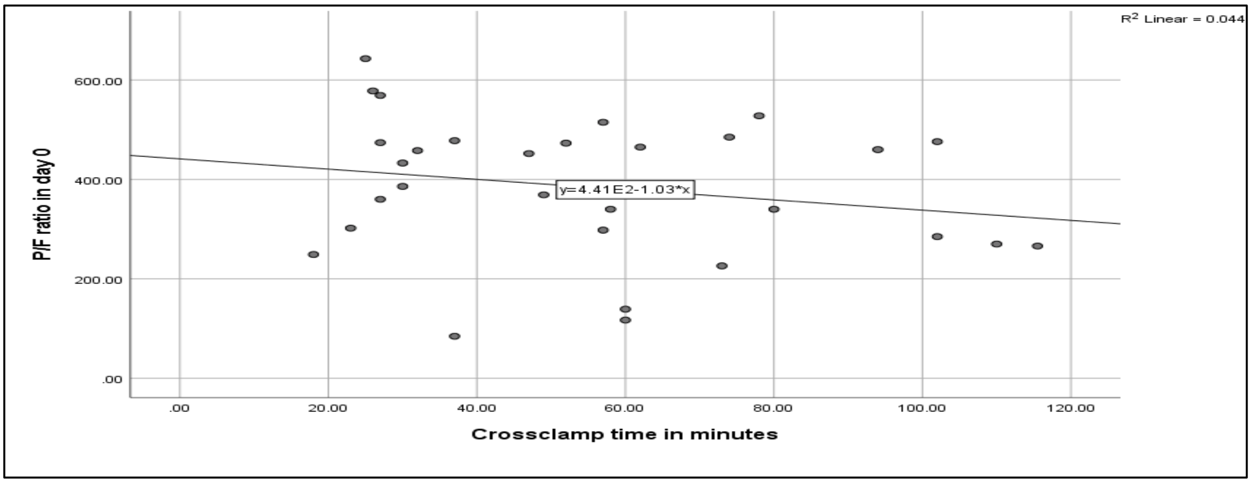

Figure 1: Correlation in P/F ratio between ICU day 0 and cross-clamp time.

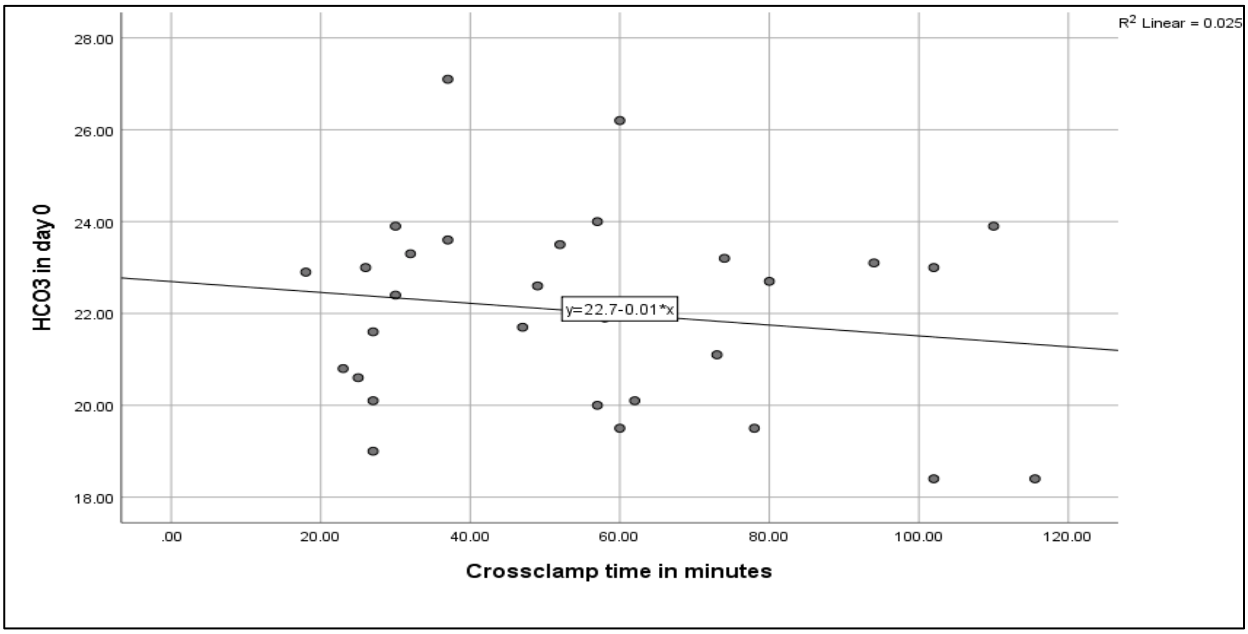

Figure 2: Correlation in HCO3- between ICU day 0 and cross-clamp time.

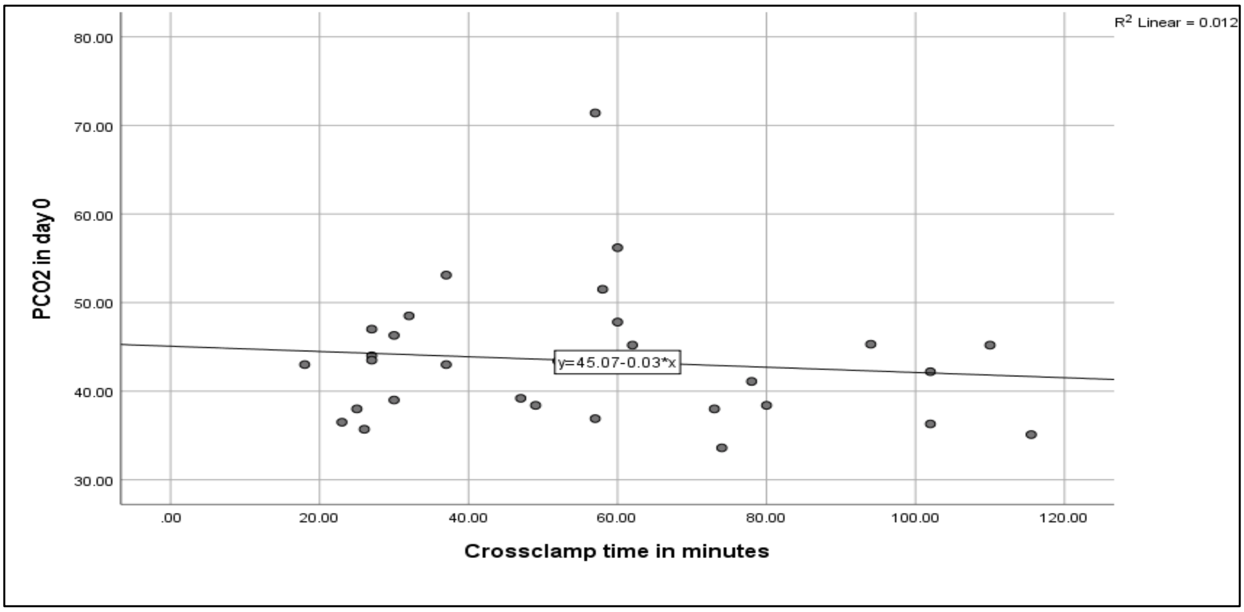

Figure 3: Correlation in PaCO2 between ICU day 0 and cross-clamp time.

However, there was no correlation between blood PH postoperation ICU day 0 and CCT in acyanotic cases of CHD. Also, the study showed positive correlations in HCO3- and PaCO2 between postoperative ICU day 0 and CCT of cyanotic cases of CHD, as shown in Figures 4 and 5.

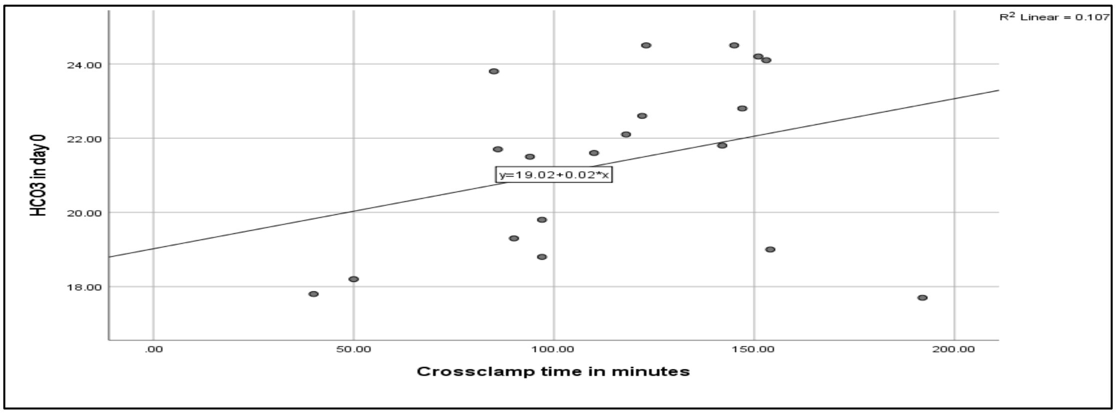

Figure 4: Correlation in HCO3- between ICU day 0 and cross-clamp time.

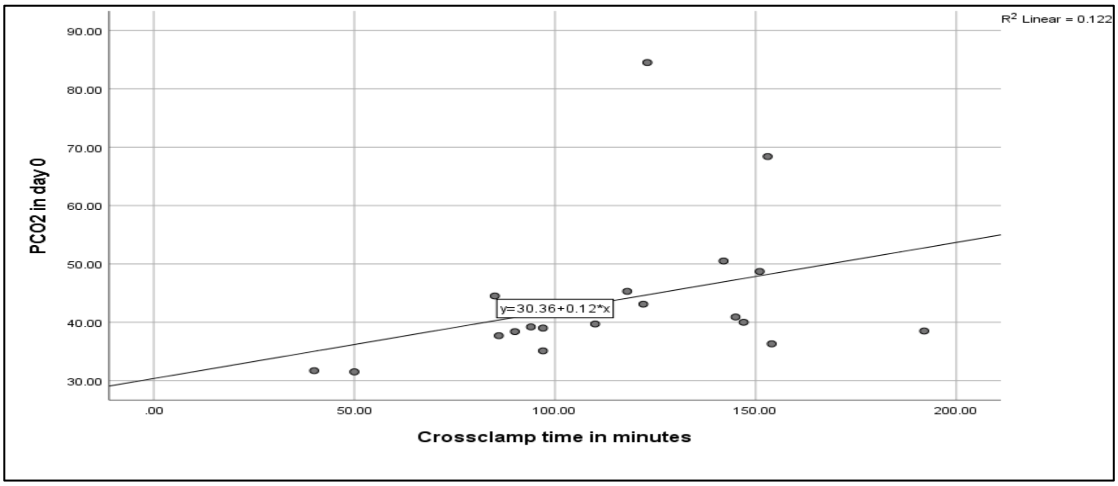

Figure 5: Correlation between PaCO2 of ICU day 0 and cross-clamp time

While a negative correlation between PH postoperation ICU day 0 and CCT, as shown in Figure 6

There was no correlation between the P/F ratio postoperation ICU day 0 and CCT in cyanotic cases of CHD.

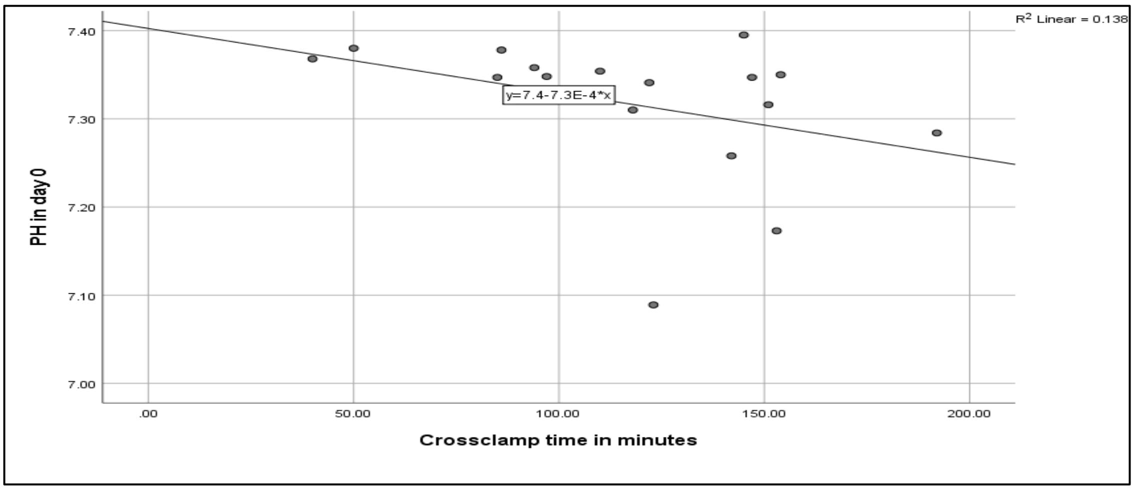

Figure 6: Correlation between blood PH of ICU day 0 and cross-clamp time.

DISCUSSION

Evaluation of pre and postoperative arterial blood gases in pediatric patients who have congenital heart diseases undergoing surgical repair:

Blood gas analysis is essential for evaluating the acid-base balance and ventilation status of critically ill cases [14]. This study showed significant differences in PaCO2 values between postoperative day 0 and postoperative day 1 (decrease) in cyanotic and acyanotic cases. The reduction in PaCO2 value near the normal value (35-45) mmHg may be due to a cardiac surgical repair that decreases the CO2 level and corrects the respiratory acidosis.

Changes in the PaCO2 may significantly impact critically ill patients because it is one factor that determines blood PH. A study by (Pramanik *et al.*, 2017) showed that The PaCO2 value decreased on days 1st, 5th, 9 th after coronary artery bypass grafting [16].

Also, this study showed a significant difference in HCO3- values between preoperative and postoperative day 1 (increase) in acyanotic and cyanotic patients. However, the patients who have CHD have a slight decrease in PH value. During cardiac surgery on CPB, there was a decrease in tissue perfusion and an increase in lactate level that caused the acidosis. One day after surgery, the impact of CPB, cardioplegia, and surgical factors diminished; therefore, the HCO3- value was elevated and reached near the typical values, resulting in the correction of blood PH.

Congenital Heart Disease is one of the causes of metabolic acidosis observed in newborns [17]. A study by (Dubin *et al.*, 2007) showed that the most frequent acid-base disorder in ICU patients is metabolic acidosis, in which the plasma HCO3- value is less than 20 mM [18]. A study by (ERNEST, HERKES, and RAPER, 1992) showed that metabolic acidosis is common in patients after cardiac surgery requiring CPB. Metabolic acidosis is characterized by a reduced serum bicarbonate value that minimizes PH [9].

This study showed significant differences in PH values between preoperative and postoperative day 1 (increase) and significant differences between postoperative day 0 and postoperative day 1 (increase) in both cyanotic and acyanotic cases.

This result was most properly due to surgical repair, and after the diminished impact of the CPB, surgical factors, and cardioplegia, there was a decrease in the PaCO2 and an increase in HCO3- value that resulted in the return of the PH to the standard value(7.35-7.45)

A study by (Phypers and Pierce, 2006) showed that the patients after cardiac arrest present with a combination of respiratory and metabolic disturbances since increased lactate value is the primary cause of metabolic acidosis ($pH \leq 7.35$ and lactate > 2.0 mmol/L and a $PaCO2 \leq 42$ mmHg) [20]. A study by (Xiong *et al.*, 2004) showed that the anaerobic metabolism of glucose causes an increase in lactic acid levels and decreases pH, resulting in metabolic acidosis [21]. A study by (Pramanik *et al.*, no date) showed that following coronary artery bypass grafting, there were significant changes in PH values on day five and day nine but non-significant changes on day 1 compared to preoperative state [22].

Also, this study showed there were significant differences in the P/F ratio between preoperative and postoperative day1 (decrease) and significant differences between postoperative day 0 and postoperative day1 (decrease) in acyanotic cases in contrast to no significant differences in the P/F ratio among any reading in cyanotic cases.

The P/F ratio is used as an indicator of pulmonary function. When the P/F ratio is less than 300, this indicates post-CPB lung injury [11]. A study by (Murata *et al.*, 2021) demonstrated that postoperative cardiopulmonary bypass lung injury occurred frequently in valve surgeries. Two hours after CPB, the value of the P/F ratio was correlated with postoperative parameters, such as duration of mechanical ventilation, ICU stay, and hospitalization. The P/F ratio ≥ 354 predicted early extubation, and the P/F ratio < 213 predicted prolonged duration of mechanical ventilation [23]. A study by (Pramanik *et al.*, no date) showed a significant alteration in PaO2 values. The changes were most found on day 1 post coronary artery bypass grafting [22]. A study by (Zhou *et al.*, 2021) showed that the incidence of hypoxemia is prevalent after cardiac surgery since about 84% of cases have postoperative hypoxemia [24]

Correlation in arterial blood gases between postoperative ICU day 0 and cross-clamp time of open heart surgery:

The P/F ratio reflects lung injury, which is expected to be more lung injury with long CCT. In acyanotic CHD, there was a negative correlation between the P/F ratio postoperation ICU day 0 and CCT; this was due to lung injury after surgery.

However, in cyanotic CHD, there was lung injury due to long CCT, which gave a negative correlation. However, at the same time, there was a positive correlation between surgical correction and cyanotic CHD; therefore, the net result showed no correlation between the P/F ratio and CCT of cyanotic CHD (mean CCT =56 min in acyanotic versus 115 min in cyanotic).

Also, this study showed that in cyanotic CHD, there was a positive correlation between PaCO2 and CCT, which indicates more lung damage in cyanotic cases due to long CCT; this increase in PaCO2 causes a decrease in PH value (respiratory acidosis) that leads to increase HCO3- value as a compensatory mechanism.

While in acyanotic CHD, there was a negative correlation between PaCO2 of ICU day 0 and CCT, because acyanotic cases are less complex cases and surgical correction results in an improvement in the acid-base status of patients and this slight decrease in PaCO2 did not increase the PH value; this result was due to shorter CCT in acyanotic compared with cyanotic CHD.

A study by (Alisher *et al.*, 2023) found that increased CCT was associated with postoperative morbidity and complication in patients who have CHD and submitted to open heart surgery [25].

A study by (Al-Sarraf *et al.*, 2011) showed that the CCT times equal to or greater than 90 minutes increase the risk of pulmonary complications than patients with a shorter CCT [26].

A study by (Zammert and Gelman, 2016b) showed that pulmonary dysfunction is a common postoperative complication due to humoral changes that occur during aortic cross-clamping and after unclamping the aorta [27].

A study by (He *et al.*, 2022) showed that complications of severe lung injury occur after surgical repair for TOF that result in longer ventilation times and increased rate of mortality [28].

Another study (Gelman, 1995) suggested that accumulation of the anaerobic metabolic products in the blood flowing declamping and a postoperative increase in the cell membrane permeability, which results in pulmonary edema, cause more complications [29].

A study by (Bernard *et al.*, 1994) found that PF ratio ≤300 was one diagnostic criterion for acute lung injury [30].

A study (Cooper, 2007) found that the increase in PaCO2 was due to inadequate ventilation because patients cannot breathe normally (pump failure) [31].

A study (Arieff, 1998) found that cardiopulmonary arrest during open heart surgery increases PaCO2, which causes hypercapnic acidosis [32].

CONCLUSION

This study finds the partial pressure of carbon dioxide is more predictive of lung injury after open heart surgery than the P/F ratio in cyanotic cases. In acyanotic cases, the P/F ratio and partial pressure of carbon dioxide are essential in determining lung injury. Also, this study finds that the prolonged cross-clamp time increases lung injury after open heart surgery.

RECOMMENDATION

According to a result of this study, a study recommends the following:

1) Additional parameters such as blood parameters and serum electrolytes must be evaluated besides arterial blood gases before and after open heart surgery.

2) Evaluation of these changes for other cardiac surgery, such as coronary artery bypass grafting and valve surgery.

3) molecular studies such as nitric oxide and tissue necrotic factors are needed to assess these changes.

4) The evaluation must have a large sample size and be multi-center.

REFERENCES

[1] s. M. Gilboa, j. L. Salemi, w. N. Nembhard, d. E. Fixler, and a. Correa, "mortality resulting from congenital heart disease among children and adults in the united states, 1999 to 2006," *circulation*, vol. 122, no. 22, pp. 2254–2263, 2010.

[2] j. I. E. Hoffman and s. Kaplan, "the incidence of congenital heart disease," *j. Am. Coll. Cardiol.*, vol. 39, no. 12, pp. 1890–1900, 2002.

[3] n. K. Wenger, w. E. Boden, b. A. Carabello, r. Carney, m. Cerqueira, and m. Criqul, "cardiovascular disability: updating the social security listings," *natl. Acad. Sci.*, vol. 16, 2010.

[4] a. E. Barry, m. A. Chaney, and m. J. London, "anesthetic management during cardiopulmonary bypass: a systematic review," *anesth. Analg.*, vol. 120, no. 4, pp. 749–769, 2015.

[5] g. S. Cox, p. J. O'hara, n. R. Hertzer, m. R. Piedmonte, l. P. Krajewski, and e. G. Beven, "thoracoabdominal aneurysm repair: a representative experience," *j. Vasc. Surg.*, vol. 15, no. 5, pp. 780–788, 1992.

[6] p. Astrup and j. W. Severinghaus, "the history of blood gases, acids and bases," *(no title)*, 1986.

[7] t. K. Brock, "trends in blood gases analysis-portable blood gas analyzers, poc testing, and venous blood gas values," *am. Lab.*, vol. 44, no. 4, pp. 14-+, 2012.

[8] c. H. Orchard and j. C. Kentish, "effects of changes of ph on the contractile function of cardiac muscle," *am. J. Physiol. Physiol.*, vol. 258, no. 6, pp. C967–c981, 1990.

[9] k. J. Gunnerson, m. Saul, s. He, and j. A. Kellum, "lactate versus non-lactate metabolic acidosis: a retrospective outcome evaluation of critically ill patients," *crit. Care*, vol. 10, pp. 1–9, 2006.

[10] r. G. H. Speekenbrink, w. Van oeveren, c. R. H. Wildevuur, and l. Eijsman, "pathophysiology of cardiopulmonary bypass," in *minimally invasive cardiac surgery*, springer, 2004, pp. 3–26.

[11] k.-y. Rhee, t.-y. Sung, j. D. Kim, h. Kang, n. Mohamad, and t.-y. Kim, "high-dose ulinastatin improves postoperative oxygenation in patients undergoing aortic valve surgery with cardiopulmonary bypass: a retrospective study," *j. Int. Med. Res.*, vol. 46, no. 3, pp. 1238–1248, 2018.

[12] o. Gajic *et al.*, "early identification of patients at risk of acute lung injury: evaluation of lung injury prediction score in a multicenter cohort study," *am. J. Respir. Crit. Care med.*, vol. 183, no. 4, pp. 462–470, 2011.

[13] o. Abou-arab, p. Huette, m. Guilbart, h. Dupont, and p.-g. Guinot, "hyperoxia during cardiopulmonary bypass does not increase respiratory or neurological complications: a post hoc analysis of the cardiox study," *br. J. Anaesth.*, vol. 125, no. 5, pp. E400–e401, 2020.

[14] b. L. Lim and a.-m. Kelly, "a meta-analysis on the utility of peripheral venous blood gas analyses in exacerbations of chronic obstructive pulmonary disease in the emergency department," *eur. J. Emerg. Med.*, vol. 17, no. 5, pp. 246–248, 2010.

[15] s. T. Selby, t. Abramo, and n. Hobart-porter, "an update on end-tidal co2 monitoring," *pediatr. Emerg. Care*, vol. 34, no. 12, pp. 888–892, 2018.

[16] s. S. Pramanik, k. N. Harley, r. K. Jambhulkar, r. K. Das, and j. S. Sathe, "investigating pre and postoperative blood gases and serum electrolyte in patients undergoing coronary artery bypass surgery (cabg)," *int. J. Clin. Biochem. Res.*, vol. 4, no. 2, pp. 149–153, 2017, doi: 10.18231/2394-6377.2017.0035.

[17] n. Demir, i. Ece, k. Demirören, n. Ceylan, e. Peker, and o. Tuncer, "a rare cause of metabolic acidosis; hypoplastic left heart syndrome," *east. J. Med.*, vol. 20, no. 4, pp. 235–237, 2015.

[18] a. Dubin *et al.*, "comparison of three different methods of evaluation of metabolic acid-base disorders," *crit. Care med.*, vol. 35, no. 5, pp. 1264–1270, 2007.

[19] d. Ernest, r. G. Herkes, and r. F. Raper, "alterations in anion gap following cardiopulmonary bypass," *crit. Care med.*, vol. 20, no. 1, pp. 52–56, 1992.

[20] b. Phypers and j. M. T. Pierce, "lactate physiology in health and disease," *contin. Educ. Anaesthesia, crit. Care pain*, vol. 6, no. 3, pp. 128–132, 2006.

[21] z.-g. Xiong *et al.*, "neuroprotection in ischemia: blocking calcium-permeable acid-sensing ion channels," *cell*, vol.

118, no. 6, pp. 687–698, 2004.

[22] s. S. Pramanik, k. N. Harley, r. K. Jambhulkar, r. K. Das, and j. S. Sathe, "investigating pre and postoperative blood gases and serum electrolyte in patients undergoing coronary artery bypass surgery (cabg)".

[23] t. Murata *et al.*, "postoperative changes in pulmonary function after valve surgery: oxygenation index early after cardiopulmonary is a predictor of postoperative course," *j. Clin. Med.*, vol. 10, no. 15, 2021, doi: 10.3390/jcm10153262.

[24] j. Zhou *et al.*, "independent risk factors of hypoxemia in patients after surgery with acute type a aortic dissection," *ann. Palliat. Med.*, vol. 10, no. 7, pp. 7387397–7388397, 2021.

[25] n. Alisher, r. A. Khokhar, m. U. Rehman, a. S. Shaikh, h. B. Korejo, and r. Sangi, "impact of cardiopulmonary by pass time and aortic cross-clamp time on immediate post-operative outcomes patients with congenital heart disease ," vol. 73, no. December 2021, pp. 443–447, 2023.

[26] N. Al-Sarraf *et al.*, "Cross-clamp time is an independent predictor of mortality and morbidity in low-and high-risk cardiac patients," *Int. J. Surg.*, vol. 9, no. 1, pp. 104–109, 2011.

[27] M. Zammert and S. Gelman, "The pathophysiology of aortic cross-clamping," *Best Pract. Res. Clin. Anaesthesiol.*, vol. 30, no. 3, pp. 257–269, 2016.

[28] Y. He, H. S. Zhang, T. Z. Zhang, Y. Feng, Y. Zhu, and X. Fan, "Analysis of the risk factors for severe lung injury after radical surgery for tetralogy of fallot," *Front. Surg.*, vol. 9, no. August, pp. 1–9, 2022, doi: 10.3389/fsurg.2022.892562.

[29] S. Gelman, "The pathophysiology of aortic cross-clamping and unclamping," *Anesthesiol. THEN HAGERSTOWN-*, vol. 82, p. 1026, 1995.

[30] G. R. Bernard *et al.*, "The American-European Consensus Conference on ARDS. Definitions, mechanisms, relevant outcomes, and clinical trial coordination.," *Am. J. Respir. Crit. Care Med.*, vol. 149, no. 3, pp. 818–824, 1994.

[31] B. G. Cooper, "Review Series: Lung function made easy - Introduction," *Chron. Respir. Dis.*, vol. 4, no. 3, p. 149, 2007, doi: 10.1177/1479972307079023.

[32] A. I. Arieff, "Efficacy of buffers in the management of cardiac arrest," *Crit. Care Med.*, vol. 26, no. 8, pp. 1311–1313, 1998.