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Optimization of perfusion parameters and Comorbidities during cardiac surgery: Analysis of post-operative complications

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Abstract

Cardiopulmonary bypass (CPB) has made open heart surgery possible, but is also associated with complications of systemic inflammation and hemoglobin dilution. It is important to take care of the parameters of the perfusion (flow rate, pressure, temperature, hemoglobin level), to avoid postoperative complications such as acute kidney injury (AKI) and neurologic dysfunction. The purpose of this study is to assess the impact of IOPM on the postoperative recovery and to determine the target range for optimal perfusion to ensure patient safety and recovery.A retrospective observational study was conducted in 289 patients who underwent OHS. Data obtained from the perfusion records were analyzed using SPSS 27 with descriptive statistics, t-test and chi-square test. The morbidity after surgery in the studied population was 27.3% for mortality, 26.3% for neurological dysfunction and 22.8% for AKI. Preoperative chronic conditions, like kidney disease and diabetes, as well as intra-operative factors, such as long CPB time, high pCO_2 and low venous oxygen saturation, were associated with complications. Strict control of comorbidities and

optimization of the key perfusion parameters: pCO_2, pump time and oxygen delivery should minimize life-threatening complications. This is one of the most important methods of improving the chances of recovery and survival for patients undergoing cardiac surgery.

Introduction

Background

In a "non-beating" heart state, surgeons can perform open heart surgery. Cardiopulmonary bypass (CPB) uses a machine to take over the job of both lungs and heart to keep the blood and oxygen flowing while the surgery is performed. Even with the development of CPB technology, the surgeon still struggles during the heart and lungs disconnect because of the patient's clinical status and specific surgical requirements (Barbu et al., 2017; Gaudino et al., 2018; Kertai et al., 2016; Tsai & Pan, 2015). CPB may cause systemic inflammatory reactions and hemodilution, which may cause micro-circulation disorders, endothelial injury, and post-surgical organ dysfunction. Therefore, the management of perfusion parameters during the surgical procedure is of critical importance in order to avoid unnecessary complications (Apostolakis et al., 2005; Zhang et al., 2023; Meersch et al., 2017).

The main problem is the patient's survival and minimising the effects of the procedure. The success of perfusion depends on the control of a series of interdependent variables, called perfusion parameters, which must be monitored and carefully regulated by the circulation staff in order to keep the system stable and in balance (Warltier et al., 2009). Several parameters affect oxygen delivery during CPB, and they include pump flow rate, MAP, oxygen-carrying capacity of blood and the influence of temperature on oxygen production (Garg et al., 2017). The undesirable values of the parameters may result in tissue hypoxia, inflammation, and in the postoperative period, in AKI, long stay in the intensive care unit, and mortality (Hoste et al., 2024). High rates of flow, on the other hand, can cause the destruction of blood cells and cause blood to leak from the capillaries, resulting in swelling in the tissues, especially in the lungs (Raja & Dreyfus, 2018).

MAP is a significant pressure that propels blood to organs and is closely related to pump flow. MAP depends on pump flow and systemic vascular resistance (SVR), which can change as a result of anesthetic medications, medications that affect blood vessels, and inflammation. There is debate about the best MAP level during surgery. Some have suggested using higher MAP levels (80-90 mmHg) to protect organs such as the brain and kidneys, whereas others have advocated for lower MAP levels (50-60 mmHg) which could minimize embolic risks (Li, Zhang, & Wang, 2023; Monaco & Landoni, 2021). Flow and pressure are important to maintain balance; high flow and low MAP would indicate low SVR and may require the use of vasoconstrictors, while low flow and high MAP would indicate high SVR and may require vasodilators and/or deeper anesthesia (Wang & Bellomo, 2017).

Today, CPB is used in practice and cooling the patient's body can help to decrease metabolism and oxygen consumption, which can spare the organs when the blood supply is low or stopped during certain procedures (McIlroy & Murphy, 2015). There are, however, some side effects of hypothermia such as the production of more urine, hemoglobin affinity for oxygen, and the risk of infection following surgery (Murphy & Hessel, 2014). Therefore, progressive rewarming is important to avoid temperature differences and minimise the risk of secondary neurological injuries (Roach et al., 1996). Now it is preferred to use mild to moderate cooling (32 to 34°C), which provides an adequate metabolic reduction without the negative effects of deeper cooling (Zheng & Xu, 2023).

The oxygenator is an artificial lung in the CPB circuit and careful monitoring of venous and arterial blood gases is essential. Mixed venous oxygen saturation (SvO_2) gives instant information on the utilization of oxygen by the body. Reduced SvO_2

levels are associated with reduced oxygen delivery, either caused by low flow rates or decreased hemoglobin mass, inadequate levels of arterial oxygen or increased metabolic demand for the tissue (Parolari et al., 2004). Arterial blood gas analysis helps to keep the acid-base status within predetermined limits and measures the levels of carbon dioxide ($PaCO_2$) and oxygen (PaO_2). There are two options of $PaCO_2$ control: pH-state and alpha-state, which affect cerebral blood flow, especially in the case of surgery at subnormal body temperature in patients (Smith & Muhlbaier, 2016).

Hematocrit is decreased during CPB, usually due to crystalloid dilution, which directly impacts oxygen carrying capacity. Low haematocrit is associated with reduced oxygen delivery, higher risk of AKI and neurological dysfunction, although the timing of blood transfusion is a matter of debate, because of the potential risks of fluid overload, infections and reactions (Küllmar & Zarbock, 2021; Li & Wang, 2023). The perfusionist must ensure an adequate amount of oxygen and blood viscosity to obtain proper flow.

Exposure to non-physiological circulation states during CPB and aortic cross clamping, two independent factors associated with postoperative morbidity which are closely related to the quality of perfusion during surgery, are exacerbated by longer duration of CPB and aortic cross clamping (Rossi & Lorusso, 2023). CPB management is complex because of the interaction between flow, pressure, temperature, oxygen levels, hematocrit, and time. If a factor changes, then other factors must change to maintain a stable and adequate perfusion.

Pre-existing patient conditions such as diabetes and hypertension are prevalent in Pakistan and may enhance sensitivity to perfusion-related injuries, underscoring the necessity of setting appropriate perfusion parameters during surgery (Nadim et al., 2018; Meng & Gelb, 2022). Such conditions can indicate a patient's physiological reserve, aiding in risk assessment and determination of optimal perfusion targets for safer treatment. Poor management of perfusion manifests clearly in prevalent postoperative problems, including AKI and prolonged ICU stays, affecting up to 30% of cardiac surgery patients with CPB. Such complications necessitate longer hospital stays, incur higher costs, and elevate both short-term and long-term mortality rates (Gu & Wang, 2021).

The development of AKI is attributable to various interconnected factors, including insufficient blood flow to the kidneys caused by low MAP, inflammatory damage to kidney tissues, or obstruction due to small clots in renal blood vessels. This tripartite influence collectively contributes to renal impairment (Wang & Bellomo, 2017). Inadequate intraoperative perfusion has a well-established correlation with postoperative AKI, neurological dysfunction, pulmonary complications, and extended ICU admissions, where AKI remains particularly common among CPB patients (Raja & Dreyfus, 2018; Zarifoglu et al., 2023).

Despite pharmacological support often utilized during CPB, modifiable perfusion parameters predominantly determine tissue oxygenation and organ protection (Ranucci et al., 2013; Warltier et al., 2009). Current trends emphasize abandoning fixed universal perfusion targets in favor of individualizing targets based on actual physiological metrics, with implementation varying across facilities based on resource availability (Nadim et al., 2018).

Advancements in technology, such as Near Infrared Spectroscopy, facilitate real-time monitoring of cerebral oxygenation, and viscoelastic testing aids in assessing blood clotting efficacy instantaneously. Such innovations empower clinicians to make timely and precise decisions regarding patient care (Rossi & Lorusso, 2023; Zakhary & Shehata, 2022). Given the high prevalence of cardiovascular disease in Pakistan, characterized by varied resource availability across hospitals, appropriate CPB management is crucial. Many patients present with diabetes or hypertension, differing

significantly from the Western patient population. Hence, attentively optimizing CPB parameters is vital for improved outcomes (Meng & Gelb, 2022).
Utilizing local research to discern the optimal perfusion settings essential for patient safety during cardiac operations is critical to realizing better patient outcomes.

Rationale of the Study

The success of open-heart surgeries hinges on effective cardiopulmonary bypass management, as even minor changes in perfusion can inflict significant harm on critical organs such as the brain and kidneys. In Pakistan, factors such as perfusionist practices, available technologies, and the high frequency of comorbid conditions like hypertension and diabetes influence patient outcomes. However, a lack of dedicated research has obstructed the investigation of how the management of perfusion parameters directly affects postoperative outcomes in this demographic. This study aims to determine whether optimizing these perfusion parameters can lower complication risks, improve recovery, and enhance survival rates for cardiac surgery patients in Pakistan.

Aim of the Study

To investigate the impact of perioperative perfusion parameter optimization and pre-existing comorbidities on the development of major postoperative complications in adult patients undergoing on-pump cardiac surgery

Objectives of the Study

To identify the most critical perfusion parameters leading to major postoperative complications, including mortality, neurological dysfunction, kidney injury, and extended ICU stays. This involves assessing the importance of a patient’s preoperative health alongside vital management factors during surgery.
To measure the interactions between specific patient health conditions and surgical management factors in exacerbating risks, resulting in poorer surgical outcomes and prolonged hospital admissions.
To develop a practical and effective clinical risk score to assist healthcare providers in estimating a patient’s complication risk by integrating critical elements from their preoperative health and surgical care plans.

Literature Review

The literature notes CPB time as a pivotal modifiable risk factor, which, along with complications such as renal failure and neurological injury, has been previously shown to correlate (Murphy et al., 2009). Research underscores that CPB time not only correlates with surgical complexity but also contributes to systemic inflammation, validating the significance of surgical technique and perfusion management in achieving optimal outcomes.
An important gap still exists regarding optimal MAP during CPB, with traditional guidelines advocating for higher MAP (>70 mmHg), while recent studies suggest comparable outcomes with lower MAP (50-60 mmHg) and potentially reduced embolic incidents (Siepe et al., 2011). Existing literature highlights the necessity for institution-level protocols tailored to individualized patient risk assessments.
Recent studies have shifted towards evaluating oxygen delivery adequacy, with the cumulative oxygen debt introduced by Ranucci (2013) serving as a stronger predictor of complications than static measures of flow or pressure. The focus has transformed from merely managing blood loss to actively preventing excessive hemodilution.
Literature documents the systemic inflammatory response associated with CPB, where pharmacological agents (steroids) have shown inconsistent clinical benefits (Whitlock et al., 2011). Investigations into new materials and technologies to mitigate inflammation post-CPB have pinpointed promising alternatives to traditional circuit

materials, thereby paving the way for advancements in materials science within this field.
Recent trends advocate for a paradigm shift from standardized perfusion to personalized, goal-directed therapy, where real-time data (e.g., lactate, SvO_2) facilitate clinical decision-making through preventative and corrective strategies (Jones et al., 2010). Determining how this clinical approach is applied routinely and its cost-effectiveness remains a pertinent question.
Meta-analyses highlight advantages of minimal invasive extracorporeal circulation over traditional methods, especially in reducing transfusion requirements and inflammation (Anastasiadis et al., 2013). The inconsistency of MECC technology adoption, often hindered by costs and requisite additional training, points to a gap in robust evidence from large clinical trials proving mortality benefits (Nicolini et al., 2019).
Revisiting the historical use of deep hypothermia (<25 °C) has yielded new insights; larger trials have shown that mild hypothermia (>34 °C) provides equivalent neuroprotection during complex aortic procedures without the associated coagulopathy risks (Nicolini et al., 2019). Identifying intraoperative metrics, such as low DO_2 levels and elevated lactate values, as strong outcome predictors is increasingly emphasized (Garg et al., 2017).
The literature also underscores the gap between existing evidence and individualized patient responses (Riley et al., 2007). Recent research utilizing machine learning to integrate real-time data aims to construct models that predict complications based on patient profiles, representing a future path for personalized medicine, although its integration into clinical practice remains nascent.

Materials and Methods

Study Design

This research utilized a retrospective observational study design to investigate the relationship between intraoperative perfusion parameters and postoperative outcomes.

Study Setting and Duration

This study was conducted at Hayatabad Medical Complex (HMC) and Peshawar Institute of Cardiology (PIC). Data collection spanned from September 2025 to January 2026 to ensure sufficient sample size.

Study Population and Sampling

The study population consisted of adult patients aged 18 years or older who underwent on-pump cardiac surgery within the specified period. Convenience sampling was employed to select patients with complete perfusion documentation.

Sample Size Calculation

A total of 289 patient records were included. Sample size was calculated using the single population proportion formula based on a 95% confidence level, a 5% margin of error, and an expected prevalence of postoperative complications of 30%, as cited in existing literature (de Somer et al., 2011). The calculation yielded an initial requirement of approximately 243 patient records. In light of preliminary data availability, the final sample included all 289 patient documents.

Data Collection

Data were collected from each patient's complete medical records through a standard questionnaire encompassing health information before, during, and after surgery. Additionally, technical data from operation logs maintained by the perfusionist at each surgical site were prospectively documented.

Data Analysis
Data were analysed using SPSS (Statistical Package for the Social Sciences) version 27. Descriptive statistics characterized the overall dataset, with normally distributed continuous variables, such as patient age and aortic cross-clamp time, reported as mean ± standard deviation, and non-normally distributed variables presented as median and interquartile range. Categorical variables, such as sex and occurrence of postoperative complications, were described as numbers and percentages. Comparisons were made between patients with and without complications, utilizing independent samples t-tests for continuous variables and chi-square tests for categorical distributions to assess statistical significance.

Data Presentation
Results were organized and conveyed through a combination of tables and figures for effective communication of findings.

Inclusion Criteria
Adult patients aged 18 years or older.
Patients undergoing elective or emergent on-pump cardiac surgery (e.g., coronary artery bypass grafting [CABG], valve surgery).

Exclusion Criteria
Patients undergoing off-pump cardiac surgery.
Cases with incomplete or missing perfusion data.
Patients with pre-existing end-stage renal disease (ESRD) on dialysis or other confounding medical conditions impacting postoperative assessments.

Ethical Considerations
Ethics Committee approval was secured prior to study initiation. As the research involved existing patient records and did not engage new treatments or direct patient contact, a waiver for individual consent forms was obtained.

Results and Discussion
Postoperative Complications
In studying 289 patients who underwent heart surgery, a considerable proportion faced serious recovery complications. Complications included significant adverse outcomes such as mortality (27.3%), neurological dysfunction (26.3%), and acute kidney injury (AKI) (22.8%). The relationships between these outcomes and patients' preoperative health conditions and intraoperative factors warrant a thorough examination.

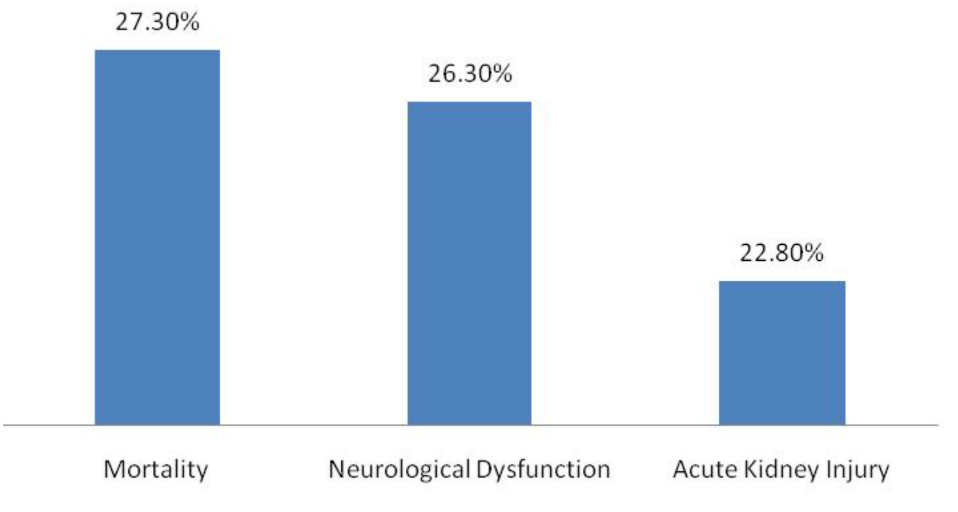

Figure 4.1: Percentage of Postoperative Complications

The categorical analysis identified high preoperative blood pressure ($p = 0.007$, 38.4% complication rate) and diabetes ($p = 0.013$, 33.3% complication rate) as significant predictors of neurological dysfunction.

Categorical Predictors of Neurological Dysfunction

The results indicated that hypertension was present in 38% of participants, making it the most common condition, followed by diabetes (33%) and chronic kidney disease (28%). Smoking was reported in 27% of patients, with gender distribution revealing 30% female and 24% male.

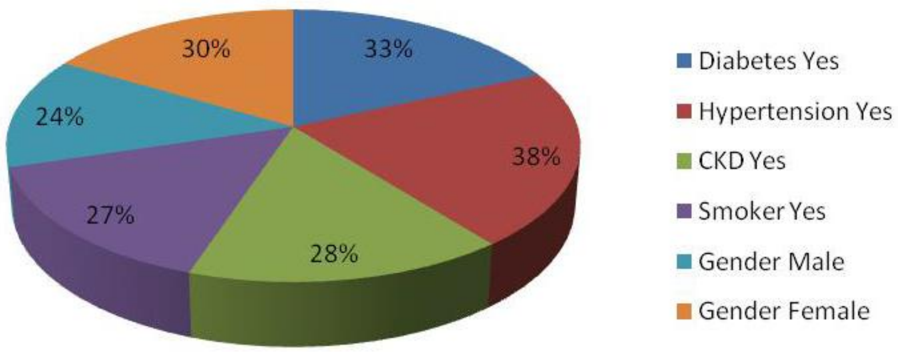

Figure 4.2: Categorical Predictors of Neurological Dysfunction

Analysis revealed hypertension (38.4%) and diabetes (33.3%) as major predictors of neurological dysfunction.

Continuous Predictors of Neurological Dysfunction

Key continuous parameters contributing to neurological dysfunction included elevated partial pressure of carbon dioxide (24%), older age (22%), lower mean arterial pressure (21%), and increased cardiopulmonary bypass time (18%).

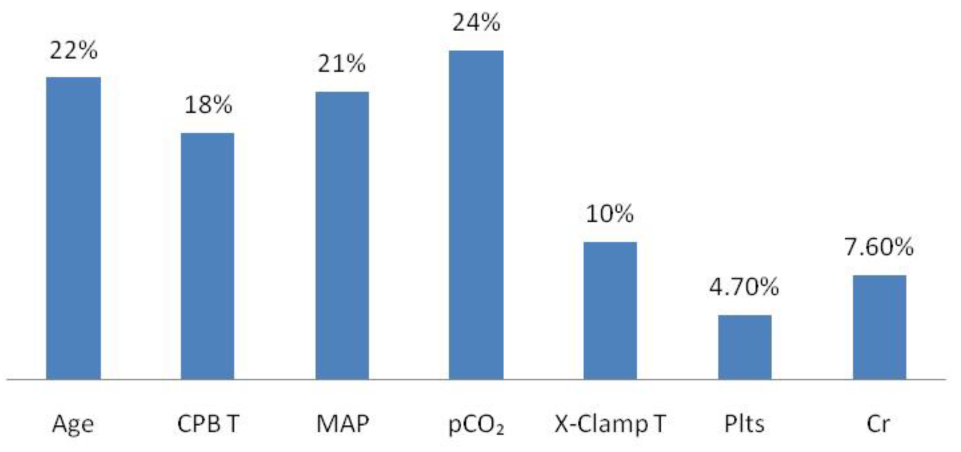

Figure 4.3: Continuous Predictors of Neurological Dysfunction

Parameters Associated with Mortality

Noteworthy predictors for mortality included chronic kidney disease (48.9%), diabetes (37.1%), smoking (31.9%), and hypertension (31.5%), with gender distribution reflecting 28% male and 25% female.

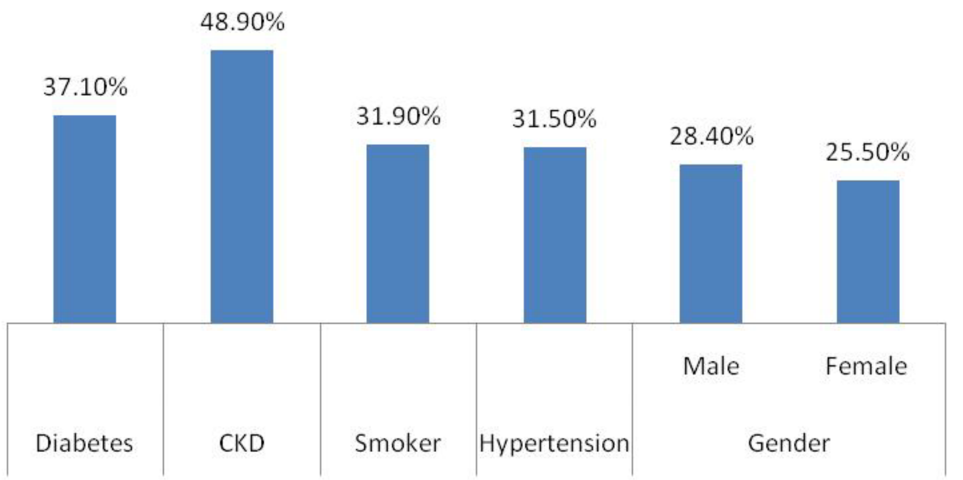

Figure 4.4: Categorical Predictor Associated with Mortality

Continuous Parameters Associated with Mortality

Table 4.5: Continuous Parameters Associated with Mortality

Parameter	**Dead (Mean)**	**p-value**	**Mortality Rate (%)**
Age	58.11	0.001	18
Creatinine	1.108	0.002	16
CPB Time	181.89	< 0.001	25
Cross Clamp Time	126.14	< 0.001	22
MAP	78.304	0.013	12
Pump Flow	6.3444	0.025	11
Temperature	29.887	0.005	14
SvO_2	67.519	< 0.001	20
pO_2	307.633	0.001	16
pCO_2	42.8890	< 0.001	22
pH	7.42704	0.076	8

Parameter	Dead (Mean)	p-value	Mortality Rate (%)
Platelets	290,886	0.002	1
Creatinine	1.108	0.076	16.1

Categorical Parameters Associated with Acute Kidney Injury

The categorical parameters significantly associated with AKI included smoking (31.9% risk) and chronic kidney disease (82.2% risk), along with being male as an important demographic factor (26.8% risk).

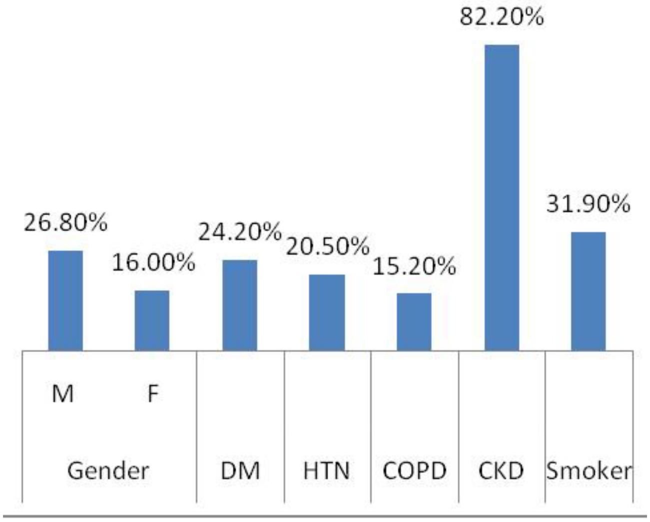

Figure 4.6: Categorical Parameters Associated with Acute Kidney Injury

Continuous Parameters Associated with Acute Kidney Injury

Table 4.7: Continuous Parameters Associated with Acute Kidney

Parameter	Acute Kidney Injury (Mean)	p-value	Risk Rate (%)
Age	58.52	0.001	12.3
eGFR	56.97	0.000	16.0
LVEF	49.23	0.102	4.3
Platelets	263.17	0.000	12.8
CPB Time	173.18	0.011	9.4
Cross Clamp Time	119.21	0.023	11.9
MAP	78.39	0.021	2.9
Pump Flow	6.72	0.132	50.4
Temperature	30.24	0.812	0.2
Hematocrit	24.97	0.297	3.4
SvO_2	68.31	0.180	1.4
pH	7.385	0.824	0.2
pO_2 (mmHg)	295.91	0.267	5.4
pCO_2 (mmHg)	42.82	0.002	4.8
Creatinine	1.183	0.000	25.9

Parameters Associated With ICU Stay Duration

Table 4.8: Parameters Associated With ICU Stay Duration

Parameter	Change Amount	ICU Stay Effect (Days)
pCO_2	+10 mmHg	+3.0

Parameter	Change Amount	ICU Stay Effect (Days)
SvO_2	-10%	+3.3
MAP	+10 mmHg	+2.4
Arterial pO_2	+100 mmHg	+2.1
eGFR	-20 mL/min/1.73m²	+2.2
Cross Clamp Time	+30 minutes	+1.6
pH	+0.3 units	+1.5
CPB Time	+30 minutes	+1.5
Platelets	+100,000/µL	+1.4
CKD Present	(vs. Absent)	+1.2
Creatinine	+0.5 mg/dL	+1.2
Age	+20 years	+1.1
Temperature	+1°C	-1.1
Pump Flow	+5 L/min	+1.0
Gender	Male (vs. Female)	+0.9
COPD Present	(vs. Absent)	+0.8
LVEF	+20%	+0.8
Hematocrit	+10%	-1.3
Smoker	Smoker (vs. Non-smoker)	+0.6
Diabetes	Yes (vs. No)	+0.4
Hypertension	Yes (vs. No)	+0.3

Discussion

The findings of this study reinforce existing literature on heart surgery outcomes while extending understanding of their relevance. The primary predictor of mortality and complications has been identified as prolonged CPB time, underscoring its correlation with systemic inflammation and organ injury (Murphy et al., 2009). This emphasizes the pivotal role of surgical technique and perfusion management in outcomes.

One notable addition to the literature is the understanding that intraoperative management of arterial CO_2 levels significantly impacts outcomes, comparable to the duration of CPB. The relationship between elevated pCO_2 and mortality, neurological dysfunction, and ICU stays signals that perfusion quality extends beyond MAP and pump flow discussions. Ongoing debates regarding optimal MAP levels reveal that careful gas exchange regulation may offer a more precise measure of adequate perfusion than isolated MAP rates (Siepe et al., 2011). The observed correlation between patient co-morbidities, particularly chronic kidney disease, and AKI substantiates the need for greater attention to modifiable risk factors, such as smoking, that double the risk of AKI (Gu & Wang, 2021).

Additionally, variations in patient physiological responses to intraoperative management necessitate that perfusion strategies be tailored individually rather than applying a singular MAP target across all patients. Elevated pCO_2 appears to correlate with neurological complications and delays in ICU discharge, furthering support for individualized perfusion management (Li et al., 2023).

The mixed outcomes regarding ICU stays reveal that numerous factors, with pCO_2 and SvO_2 being paramount, could indicate inadequate oxygen delivery. The positive correlation between increased MAP and extended ICU stays challenges traditional notions that higher perfusion pressure is always beneficial, advocating for patient-centered adjustments per metabolic needs rather than standardized cut-offs.

Overall, this study substantiates the necessity for vigilant CPB management, highlighting the critical influence of physiological regulation on patient outcomes, particularly concerning CO_2 levels. The findings stress the need for identifying preoperative modifiable risk factors and support the drive towards individualized goal-directed therapy, with an emphasis on real-time physiological indicators for formulating tailored strategies to prevent adverse outcomes and enhance recovery.

Conclusion and Recommendations

Our study identified that common complications following open heart surgeries include neurological dysfunction, AKI, and mortality, with chronic kidney disease, hypertension, and elevated pCO_2 levels being the most significant contributors. The study's principal aim is to pinpoint these risk factors leading to postoperative complications, enabling better management to enhance patient survival rates.

Recommendations

The focus of this research on parameters contributing to postoperative complications suggests a need for further investigations into preoperative conditions such as diabetes, COPD, hypertension, CKD, and smoking, along with intraoperative factors like CPB time, pCO_2 levels, MAP, temperature, and pH. These factors significantly influence patient mortality, neurological dysfunction, ALI, and ICU stay durations. Due to the substantial risks posed by elevated pCO_2 and chronic kidney disease, future research should encompass pre, intra, and post-operative factors across various centers in Pakistan, particularly those equipped with robust data recording systems and advanced laboratories, facilitating enhanced patient outcomes.

Limitations

While this study provides crucial insights, several limitations warrant acknowledgment. The observational design permits correlation assessments but not causal inferences. The findings also have limited generalizability as they derive from data at only two centers with distinct patient demographics and treatment protocols. Despite an adequate sample size, it might be insufficient to identify significant associations for rare outcomes or inter-variable complexities. Outcome measures, particularly neurological dysfunction and persistent renal dysfunction, lack detailed follow-up and standardization, potentially affecting diagnostic accuracy. Moreover, reliance on routinely collected clinical data may limit precise evaluation of the extent and duration of physiological disturbances. Long-term follow-up and biomarker analyses were not part of the study, restricting insight into clinical trajectories and underlying mechanisms. These limitations emphasize the necessity for future multi-center studies with standardized definitions of outcomes, structured follow-up, and advanced physiological assessments to validate and refine the findings presented herein.

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