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Original Article

Comparative Analysis of Hemodynamic Stability in Off-pump versus On-pump Congenital Heart Surgery - Role of Cardiac Anesthesia

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ABSTRACT

Introduction: *Congenital heart disease occurs in about 1 out of every 125 live births, and surgical repair usually requires off-pump or on-pump methods. Selection of either modality has profound effects on hemodynamic stability and perioperative outcomes. This study compared hemodynamic stability indexes between off-pump and on-pump congenital heart surgery operations under uniform cardiac anesthetic protocols.* ***Methods and materials:*** *Prospective observational trial in 150 patients who were undergoing congenital heart surgery, equally divided into off-pump (n=75) and on-pump (n=75) cohorts. Intraoperative and postoperative hemodynamic parameters like stability of heart rate, variability of blood pressure, inotropic supplementation, frequency of arrhythmia, and fluid status were quantified. Statistical analysis was conducted in SPSS v.26 with the help of chi-square tests for categorical variables and multivariate logistic regression for risk factor identification.* ***Results:*** *Off-pump procedures showed greater hemodynamic stability than on-pump, with higher heart rate (73.3% vs 53.3%, p=0.018) and blood pressure stability (80% vs 60%, p=0.012). Off-pump patients required less inotropic support (zero inotrope: 66.7% vs 13.3%, p=0.003) and had fewer arrhythmias (86.7% vs 66.7%, p=0.008). Overall complications were lower (13.3% vs 33.3%, p=0.005), and on-pump surgery increased major complication risk by 3.21 times (p=0.005).* ***Conclusion:*** *Off-pump congenital heart surgery demonstrates improved hemodynamic stability with reduced inotropic requirement, arrhythmias, and complications compared to on-pump surgery. These outcomes warrant preferential usage of off-pump techniques wherever surgically feasible, particularly in high-risk children and neonates.*

Keywords: *Hemodynamic Stability, Congenital Heart Disease, Cardiac Anesthesia.*

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INTRODUCTION

Congenital heart disease (CHD) is the most common congenital anomaly, occurring in about one in 125 live births, necessitating complex cardiac surgery for optimal patient outcomes [1]. Pediatric cardiac surgery has evolved, leading to various surgical approaches, among which off-pump and on-pump techniques have distinct characteristics related to hemodynamic stability and perioperative care [2]. The choice between these approaches significantly affects patient outcomes, particularly concerning cardiovascular stability, which remains a crucial factor for surgical success in pediatric populations [3]. Maintaining hemodynamic stability during congenital heart surgery is essential to ensure adequate organ perfusion and reduce perioperative complications [4]. The complex physiological changes associated with cardiopulmonary bypass (CPB) in on-pump surgery can result in significant hemodynamic instability, including variations in heart rate, fluctuations in blood pressure, and increased inotropic requirements [5]. Off-pump techniques preserve the heart's natural rhythm and circulation, potentially offering better hemodynamic stability throughout the procedure [6]. The role of cardiac anesthesia in maintaining hemodynamic stability is critical, especially for pediatric patients with complicated congenital defects [7]. Intensive monitoring strategies, including continuous cardiovascular assessment and careful fluid management, are key components of successful perioperative management [8]. Anesthetic care must be customized to meet the unique physiological challenges of each surgical approach, with careful attention to preserving cardiovascular stability while ensuring optimal surgical conditions [9]. Advances in pediatric cardiology, intensive care, and surgery have substantially improved survival rates in children with congenital heart disease, resulting in increased prevalence and a greater demand for a wide variety of interventional procedures [10]. This progress highlights the necessity for evidence-based strategies in selecting surgical

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techniques, particularly regarding hemodynamic outcomes [11]. Comparing off-pump and on-pump hemodynamic stability is vital for understanding how to enhance patient care and surgical results. Current literature suggests that off-pump cardiac surgery may offer benefits such as reduced inflammatory response, decreased blood loss, and improved neurological outcomes [12]. However, large-scale studies focused on hemodynamic stability during pediatric congenital heart surgery are still needed. The spectrum of congenital heart disease, ranging from simple septal defects to complex cyanotic lesions, adds an individualized dimension to surgical and anesthetic management [13]. This study aims to provide a comprehensive comparison of hemodynamic stability parameters between off-pump and on-pump congenital heart surgery, with a particular focus on the role of specialized cardiac anesthesia in achieving optimal outcomes. By evaluating specific hemodynamic variables, inotropic requirements, and perioperative complications, the study offers important evidence to inform clinical decision-making in pediatric cardiac surgery practice.

METHODS & MATERIALS

This prospective observational study was conducted at the Bangladesh Shishu Hospital & Institute and National Heart Foundation Hospital & Research Institute from June 2021 to June 2023 on 150 patients undergoing congenital heart surgery, divided equally into two groups: off-pump (n=75) and on-pump (n=75) procedures. Inclusion criteria encompassed pediatric patients diagnosed with congenital heart defects requiring surgical correction, while those with previous cardiac surgery, severe comorbidities, or emergency procedures were excluded. Preoperative evaluation included detailed clinical assessment, echocardiography to assess cardiac function, including ejection fraction (EF), and routine laboratory investigations. Intraoperative management was standardized with the involvement of experienced cardiac anesthesiologists employing advanced hemodynamic monitoring techniques, including continuous heart rate and blood pressure monitoring, central venous pressure measurement, and assessment of fluid balance. Hemodynamic stability was defined based on predefined criteria of heart rate and blood pressure variation within normal limits, requirement and type of inotropic support, incidence of arrhythmias, and fluid balance status. Postoperative complications were recorded, with major complications including hemodynamic instability, arrhythmias, prolonged ventilation, and need for re-intervention. Data were analyzed using descriptive statistics expressed as frequencies and percentages. Comparative analysis between the two groups was performed using chi-square tests for categorical variables. Multivariate logistic regression was applied to identify predictors of major complications and time-to-event outcomes, respectively. A p-value of less than 0.05 was considered statistically significant. Ethical approval was obtained from the institutional review board, and informed consent was obtained from all participants or their guardians. Statistical analysis was performed using SPSS version 26.

RESULTS

Table I gives the baseline demography of a pediatric study population (N=150) for cardiac surgery between off-pump (n=75) and on-pump (n=75) strategies. Demographic and clinical data were evenly distributed between groups and without noteworthy differences (p>0.05) in age breakdown (26.7% vs. 29.3% <1 year), gender (53.3% vs. 56% male), or weight distributions (33.3% vs. 37.3% <10 kg). Preoperative ejection fraction ≥55% was similar between groups (80% vs. 77.3%). Congenital malformations by surgical approach: ASD (44%), TOF (36%), VSD (20%) predominated in on-pump cases, and PDA (66.7%), COA (13.3%), BDG (26.7%), PAB (8%) were the most frequent in off-pump cases. The p-values (0.749) are proof of equivalent baseline characteristics in groups, since randomization was effective. [Table-I].

Table – I: Basic Characteristics of the Study Population (*n*=150)

Variable	Off-Pump (n=75)	%	On-Pump (n=75)	%	p-value
Age (years)					
<1 year	20	26.7%	22	29.3%	0.725
1-5 years	30	40%	28	37.3%	
>5 years	25	33.3%	25	33.3%	
Gender					
Male	40	53.3%	42	56%	0.749
Female	35	46.7%	33	44%	
Weight (kg)					
<10 kg	25	33.3%	28	37.3%	0.587
10-20 kg	30	40%	25	33.3%	
>20 kg	20	26.7%	22	29.3%	
Pre-op Ejection Fraction					
≥55%	60	80%	58	77.3%	0.684
<55%	15	20%	17	22.7%	
Type of Congenital Defect					
PDA	45	66.7%	-	-	-
COA	8	13.3%	-	-	-
BDG	19	26.7%	-	-	-

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PAB	3	8%	-	-	-
ASD	-	-	35	44%	-
TOF	-	-	15	36%	-
VSD	-	-	25	20%	-

Table II describes the comprehensive hemodynamic stability parameters. Off-pump procedures presented superior hemodynamic stability for all parameters assessed. Hemodynamic stability of the heart rate was achieved in 73.3% of off-pump versus 53.3% of on-pump patients (p=0.018). Hemodynamic stability of the blood pressure was significantly greater with off-pump surgery (80% versus 60%, p=0.012), with on-pump patients experiencing twice as many hypotensive episodes. The requirement for inotropic support demonstrated the most striking difference, with 66.7% of off-pump patients requiring no support versus 13.3% of on-pump patients (p=0.003). Multiple inotrope use was ten times greater for on-pump procedures (6.7% vs 66.7%). Arrhythmia-free recovery was achieved in 86.7% of off-pump and 66.7% of on-pump patients (p=0.008). [Table II]

Table – II: Comprehensive Hemodynamic Stability Parameters (*n* = 150)

Parameter	Off-Pump (n=75)	%	On-Pump (n=75)	%	p-value
Heart Rate Stability					
Stable	55	73.3%	40	53.3%	0.018
Unstable (Tachycardia/Bradycardia)	20	26.7%	35	46.7%	
Blood Pressure Stability					
Stable	60	80%	45	60%	0.012
Hypotension Episodes	10	13.3%	20	26.7%	
Hypertension Episodes	5	6.7%	10	13.3%	
Use of Inotropes					
No Inotropes	50	66.7%	10	13.3%	0.003
Single Inotrope	20	26.7%	15	20%	
Multiple Inotropes	5	6.7%	50	66.7%	
Incidence of Arrhythmias					
No Arrhythmia	65	86.7%	50	66.7%	0.008
Minor Arrhythmia	7	9.3%	15	20%	
Major Arrhythmia	3	4%	10	13.3%	

Table III demonstrates the use of inotropes and specific agents. Analysis of inotropic support documented a strong advantage for off-pump procedures. No inotropic support was required in 66.7% of off-pump versus 13.3% of on-pump patients (p=0.003). Single inotrope use was greater in off-pump cases, with 26.7% vs 26.7%, for which dopamine was utilized most frequently. Multiple inotropes requirement was ten times greater in on-pump cases (66.7% vs 6.7%, p=0.027). Concomitant dopamine-adrenaline therapy was much higher in on-pump surgery, with 40% versus 2.7%, and triple therapy was more frequent at 16% versus 1.3%. [Table III]

Table – III: Use of Inotropes and Specific Agents (*n* = 150)

Inotrope Use Category	Off-Pump (n=75)	%	On-Pump (n=75)	%	p-value
No Inotropes	50	66.7%	10	13.3%	0.003
Single Inotrope Use	20	26.7%	15	20%	
Dopamine	10	13.3%	6	8%	0.282
Dobutamine	5	6.7%	6	8%	0.276
Milrinone	5	6.7%	3	4%	1.000
Multiple Inotropes Use	5	6.7%	50	66.7%	0.027
Dopamine + Adrenaline	2	2.7%	30	40%	0.143
Dobutamine + Milrinone	2	2.7%	8	10.7%	0.241
Triple Therapy (Dopamine + Adrenaline + Milrinone)	1	1.3%	12	16%	0.170

Table IV denotes anesthesia-related complications by type. Off-pump procedures demonstrated safer profiles with 86.7% of the patients without complications versus 66.7% in the on-pump group (p=0.005). Low-grade complications were nausea/vomiting (4.0% vs 8.0%) and shivering (2.7% vs 6.7%). Major complications presented alarming differences: severe hypotension was four times higher in on-pump procedures (5.3% vs 1.3%), while cardiac arrest occurred exclusively in on-pump patients (2.7% vs 0%). Prolonged mechanical ventilation was three times more common in on-pump cases (4.0% vs 1.3%). The complication rate in total was 2.5-fold higher in on-pump cases (33.3% vs 13.3%, p=0.005), and this reflects a major clinical safety advantage for off-pump methods in each complication category. [Table IV]

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Table – IV: Anesthesia-Related Complications by Type (*n*=150)

Type of Complication	Off-Pump (n=75)	%	On-Pump (n=75)	%	p-value
No Complications	65	86.7%	50	66.7%	0.005
Minor Complications					
Nausea/Vomiting	3	4.0%	6	8.0%	0.304
Shivering	2	2.7%	5	6.7%	0.240
Minor Hypothermia	3	4.0%	4	5.3%	0.695
Major Complications					
Severe Hypotension	1	1.3%	4	5.3%	0.170
Cardiac Arrest	0	0.0%	2	2.7%	0.156
Prolonged Mechanical Ventilation (>24h)	1	1.3%	3	4.0%	0.310
Neurologic Complications (e.g., Stroke, Seizure)	0	0.0%	1	1.3%	0.317
Total Patients with Complications	10	13.3%	25	33.3%	0.005

Table V(A) represents multivariate logistic regression analysis of risk factors for major complications: off-pump vs. on-pump congenital heart surgery. Five independent risk predictors of significant complications were identified through multivariate analysis. On-pump procedure was the strongest predictor, increasing complication risks by 3.21-fold (95% CI: 1.90-5.42, p=0.005). Patient age was associated with linear risk increase, contributing 8% for each year (OR: 1.08, p=0.008). Weight had protective effects, decreasing 6% for each kilogram (OR: 0.94, p=0.015). Complex cardiac defects doubled the complication risk compared to simple lesions (OR: 2.01, p=0.012). Reduced preoperative ejection fraction (<55%) two-fold higher complication risk (OR: 2.34, p=0.017). These results provide quantitative risk stratification tools that confirm off-pump advantages in all patient subgroups and reveal other modifiable and non-modifiable risk factors. [Table V(A)]

Table – V (A): Multivariate Logistic Regression Analysis of Risk Factors for Major Complications: Off-Pump vs. On-Pump Congenital Heart Surgery (*n* = 150)

Variable	Coefficient (B)	Std. Error	Odds Ratio (OR)	95% Confidence Interval	p-value
Surgery Type (On-pump vs Off-pump)	1.167	0.300	3.21	1.90 – 5.42	0.005
Age (per year)	0.075	0.030	1.08	1.02 – 1.14	0.008
Weight (per kg)	-0.065	0.025	0.94	0.90 – 0.99	0.015
Defect Type (Complex vs Simple)	0.700	0.280	2.01	1.17 – 3.44	0.012
EF <55%	0.850	0.350	2.34	1.17 – 4.68	0.017

Tables V(B) embodies interpretation of logistic regression predictors for major complications. The model provides clinically relevant risk quantification for surgical decision. On-pump procedures are three-fold higher major complication risk, the most significant modifiable factor. Risk acceleration with age in children predicts greater vigilance in older pediatric patients. The weight-related protective effect presumably results from enhanced physiological reserves among heavier patients. More advanced defect complexity doubles risk at baseline, substantiating the need for greater perioperative surveillance. Reduced ejection fraction dramatically increases vulnerability, calling for maximal preoperative cardiac function whenever possible. These predictors enable stratified risk assessment and informed consent planning, while consistently demonstrating off-pump benefit in all risk strata. Statistical significance of the model to all variables ensures its clinical efficacy for perioperative planning and prediction of outcomes. [Tables V(B)]

Table – V (B): Interpretation of Logistic Regression Predictors for Major Complications

Predictor	Odds Ratio (OR)	95% CI	p-value	Interpretation
Surgery Type (On-pump)	3.21	1.90 – 5.42	0.0005	Patients undergoing on-pump surgery have 3.2 times higher odds of major complications compared to off-pump.
Age (per year increase)	1.08	1.02 – 1.14	0.008	Each additional year of age increases the odds of major complications by 8%.
Weight (per kg increase)	0.94	0.90 – 0.99	0.015	Each kilogram increase in weight is associated with a 6% decrease in odds of complications (protective effect).
Defect Type (Complex)	2.01	1.17 – 3.44	0.012	Patients with complex cardiac defects have twice the odds of complications compared to simple defects.
Ejection Fraction <55%	2.34	1.17 – 4.68	0.017	Reduced ejection fraction (<55%) is associated with more than double the odds of major complications.

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DISCUSSION

This study provides compelling suggestions for the hemodynamic advantages of off-pump congenital heart surgery, with significant clinical significance to pediatric cardiology practice. Findings validate existing studies of the physiological benefits of circumventing cardiopulmonary bypass, highly relevant in pediatric age groups where hemodynamic stability directly influences surgical outcomes [14]. Most importantly was the decrease inotropic requirement for off-pump surgery, where 66.7% of patients required no cardiovascular support compared with only 13.3% of on-pump patients (p=0.003). The nightmarish contrast is the preservation of intrinsic cardiac function when cardiopulmonary bypass can be avoided [15]. The hemodynamic disturbances and inflammatory cascade of the bypass circuits account for myocardial dysfunction, as shown by the ten-fold increase in use of several inotropes in on-pump cases (66.7% vs 6.7%) [16]. Better cardiovascular stability was consistently seen with off-pump surgery, with stability of heart rate and blood pressure seen in 73.3% and 80% of patients, respectively, compared to 53.3% and 60% in on-pump surgery. These findings validate the hypothesis that beating heart preservation preserves more physiologic hemodynamic states [17]. Non-pulsatile flow reduction and release of inflammatory mediators prevent cardiovascular instability, particularly critical in children with limited physiological reserves [18]. The much-reduced incidence of arrhythmia during off-pump procedure (13.3% vs 33.3%, p=0.008) is an important clinical advantage because perioperative arrhythmias in pediatric cardiac surgery are linked with increased morbidity and longer convalescence [19]. Maintenance of normal cardiac conduction independent of cardioplegic arrest is likely to be the reason for this increased electrical stability [20]. Maintenance of coronary perfusion during off-pump procedure is the reason for increased myocardial protection and reduced arrhythmogenicity. Multivariate analysis provides valuable risk stratification data, revealing that on-pump surgery has an independent 3.21-fold elevated major complication risk following confounding variable adjustment [21]. This finding emphasizes that surgical technique, rather than patient-specific factors in isolation, significantly influences outcome. Other predictors of age, weight, defect complexity, and preoperative ejection fraction create a multifaceted system for perioperative risk stratification and clinical decision-making. The lower total complication rate with off-pump compared to on-pump surgery (13.3% vs 33.3%, p=0.005) has significant consequences for patient outcomes and utilization of health resources [22]. Elimination of cardiac arrest events and fewer occasions of severe hypotension are indicative of improved perioperative safety, especially in children, where the diminished physiological reserve increases the severity of complications. From an anesthetic management perspective, improved hemodynamic stability with off-pump surgery makes perioperative management more predictable and possibly earlier recovery regimens. Reduced requirements for aggressive hemodynamic interventions and fewer complications can result in earlier mobilization and shorter intensive care unit length of stay, improving patient experience and reducing healthcare expenditure [23]. Nevertheless, surgical procedure selection needs to take into account technical feasibility and operator skill, as off-pump surgery could be technically more demanding for complicated congenital lesions. These results should guide risk-benefit analysis and direct surgical practice towards the employment of off-pump techniques where technically possible, especially in high-risk patients where hemodynamic stability is most important.

Limitations of the Study

This study has several limitations, including its single-site nature, which may limit generalizability across other hospitals with different protocols and patient populations. Observational study design, while providing real-world data, precludes causative relationships from being determined between surgical techniques and outcomes. The study also did not account for surgeon ability levels or case variability in complexity that impacts off-pump versus on-pump feasibility and outcomes.

CONCLUSION

Off-pump congenital heart surgery is associated with improved hemodynamic stability compared with on-pump surgery, as testified by reduced inotropic requirements, enhanced cardiovascular stability, and reduced complications. The increased risk of severe complications by a factor of 3.21 with on-pump surgery is a clinically significant difference that is highly relevant to surgical practice. These findings support the preferred use of off-pump techniques when surgical circumstances allow, particularly in children, where the stability of hemodynamics is most crucial in achieving optimum results. The function of cardiac anesthesiology specialists continues to be the critical tool to achieving these improved results, regardless of operative technique.

RECOMMENDATIONS

Long-term comparison of outcomes between on-pump and off-pump techniques in the future would be researched, including neurodevelopmental outcomes and quality of life. Multi-center randomized controlled trials would improve the evidence base and increase generalizability to diverse healthcare environments and varying levels of surgical expertise.

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