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TO DETERMINE THE INCIDENCE, RISK FACTORS, AND OUTCOMES FOR DELAYED STERNAL CLOSURE IN CHILDREN WITH CONGENITAL HEART DISEASES UNDERGOING OPEN HEART SURGERIES

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ABSTRACT

Delayed sternal closure (DSC) is an important strategy to stabilize hemodynamic instability in the early postoperative period in children after congenital heart surgery. Although stabilizing inadequate hemodynamics, open sternal management for prolonged periods may lead to complications and higher rates of perioperative morbidity, in addition to increased early and late mortality. The purpose of this study was to evaluate the incidence, risk factors potentially modifiable, and postoperative outcomes of DSC in children undergoing open-heart surgery for congenital heart defects. Inclusion criteria were any pediatric patient undergoing surgery for TOF, ASD, VSD and complex congenital heart diseases. The primary outcomes investigated were the occurrence of DSC, duration of stay in the intensive care unit (ICU), duration of mechanical ventilation (MV), and postoperative complications. Statistical analysis performed with SPSS revealed major DSC risk factor elements as poor Left Ventricular Ejection Fraction (LVEF) of 53.93 ± 10.99, poor Tricuspid Annular Plane Systolic Excursion (TAPSE) of 10.86 ±3.95, and blood gas values (poor PCO2 of 33.78 ± 2.76 and PO2 of 176.23 ± 76.65) which were identified as strong predictors of DSC. Also, a history of previous surgery was significantly associated with an increased risk of DSC. However, the study also emphasizes the need for early identification of these risk factors to optimize postoperative care and achieve better clinical outcomes.

Keywords: *Congenital Heart Diseases, Delayed Sternal Closure, LVEF, TAPSE, Pediatric Patients.*

INTRODUCTION

Delayed sternal closure (DSC) is a vital therapeutic practice in pediatric cardiac surgery that prevents hemodynamic instability and reduces the risk of sternal compression complications. DSC was first described by Riahi et al. in 1975 and consists of leaving the sternum temporarily open to decompress the heart to treat cardiac compression and avoid a life-threatening situation, like tamponade (Riahi et al., 1975). It has been identified as an essential method to improve postoperative outcomes for children with congenital heart disease (CHD) undergoing surgical improvements. Several aspects are unique to the pediatric population that also provide themselves to specific challenges in cardiac surgery, including anatomical and physiological, such as minor thoracic cavities and myocardial edema. All these factors have an impact on decreasing the intra-thoracic space and put the choice of primary closure of the sternum at risk of worsening cardiac compression, contributing to a reduction of the end-diastolic ventricular volume and cardiac output (Elassal et al., 2019;

Mestres et al., 1991). In this regard, DSC represents a sensible option to tackle these issues, allowing time for myocardial recuperation and hemodynamic stabilization (Gielchinsky et al., 1981).

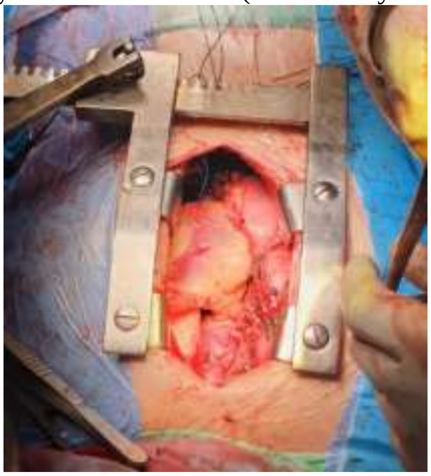

Figure 1: Intraoperative Image of an Open Sternum during Cardiac Surgery Showing Retraction and Exposure of the Heart

Multiple intraoperative and postoperative predictors of delayed sternal closure (DSC) have been described, including suboptimal preoperative cardiac function, the presence of arrhythmias, pulmonary hypertension, inadequate hemostasis, and the need for cardiac assist devices (Fanning et al., 1987; Johnson et al., 1990). Although DSC resolves hemodynamic instability, it carries potential risks such as mediastinitis, sepsis, bleeding, prolonged intubation, and late sternal instability, emphasizing the need for careful selection and management (Lyer et al., 1997).

A serious complication known as Cardiac Constraint Syndrome (Constrictor Pericarditis) can arise, where the contraction of the heart is restricted by surrounding structures, leading to reduced cardiac output (Lim, H. S., 2024). This issue is particularly relevant after open-heart surgeries in young children, where myocardial engorgement and edema in a constrained intra-thoracic space may further complicate sternal closure (Soundappan et al., 2023). Sternal closure may exacerbate cardiac compression under these conditions, especially when myocardial edema blocks the procedure.

In addition to myocardial edema, factors such as hemodynamic instability, pulmonary problems, arrhythmias, inadequate hemostasis, and the use of cardiac assist devices can impede primary sternal closure (Nichols et al., 2017). Several techniques have been developed to delay sternal closure, providing flexible solutions to manage the challenging early postoperative period after both adult (Chou et al., 2016) and pediatric (Cote et al., 2016) open-heart procedures.

However, risks associated with delayed sternal closure, such as sepsis, mediastinitis, bleeding, and late sternal instability, remain significant (Sharif et al., 2019). To better characterize these risks, a prospective review of 150 consecutive patients undergoing delayed sternal closure after reconstruction of complex congenital cardiac defects was conducted (Silvetti et al., 2020).

Fuchigami et al. (2016) performed a review of outcome studies of showed DSC for neonates and infants, emphasizing that although DSC resolves hemodynamic instability, it carries an infection risk, such as mediastinitis, especially when long-lasting (Fuchigami et al., 2016). Harder et al. Surgical site infections in pediatric patients after deep sternal cleavage: Harder et al. (2023) examined the rate of infection after deep sternal cleavage (DSC), finding prolonged chest open duration and longer cardiopulmonary bypass times correlated with increased infection rates, including sepsis and wound dehiscence.

Mestres et al. (2020) focused on pediatric cardiac surgeries with outcomes related to DSC. Their findings reported that longer continuities of DSCs are associated with increasing rates of failure, accounted for by a lower rate of disorders in continuity of care, increased length of stay in the ICU, prolonged period of mechanical ventilation and increased rates of infection as the duration of DSC increased (Mestres et al., 2020).

Jung et al. In a recent review of long-term outcomes of DSC in congenital heart surgery, it was recorded that patients requiring DSC due to myocardial oedema or bleeding complications had favorable hemodynamics but a higher risk of long-term respiratory problems (Jung et al., 2022).
Khan et al. (2021) reported that longer cardiopulmonary bypass times, as well as preoperative cardiac function, were significant factors in the decision to utilize DSC. Some infants were more likely to have this approach performed due to thoracic volume constraints.

Material and Methodology:
This prospective observational study was carried out over 1 year in the Pediatric Cardiac Intensive Care Unit at the National Institute of Cardiovascular Diseases, Karachi. The sample size was calculated using the WHO sample size calculator (version 2.0) at a 95% confidence level and a 5% margin of error, considering the reported incidence of delayed sternal closure to be 4.03%, as reported in a study by Raju S. Iyer et al. We included children 0–18 years of age that underwent repair of congenital heart defects (CHD) with open-heart surgery, including patients with previous palliative surgeries, and we excluded patients with genetic syndromes.

Indications for Delayed Sternal Closure
The main indications for DSC included poor cardiac performance (38%), reflected by low blood pressure, elevated filling pressures, and abnormal blood gases post-cardiopulmonary bypass (CPB). In 21% of cases, DSC was required due to cardiac compression during primary sternal closure, indicated by a significant drop in blood pressure and rising filling pressures, signaling the need for a stented open sternum. Pulmonary issues such as high airway pressures and intrapulmonary hemorrhage necessitated DSC in 10% of patients. In 8% of cases, unstable arrhythmias were the aetiology, and 6% was due to poor hemostasis with a high risk of tamponade if the sternum closed. Four per cent were DSC-dependent from ECMO, and 2% had other complications, such as ischemic changes on an ECG, despite normal cardiac output.

Method of Sternal Closure
In patients requiring DSC, the sternum was stented open with one or two segments of polyvinyl chloride (PVC) tube, sculpted to the shapes of the sternal edges and fixed using non-absorbable sutures. First, the skin flaps, followed by the skin to cover chiefly the stented sternum. For subsequent cases, a transparent silicone membrane (Osteotec Ltd, Christchurch, Dorset, UK) was employed to cover the defect. A proximal chest drain was placed through a separate site to avoid complications of a right thoracotomy, as the source of the effusion was not determined, and pacing wires were placed. Inclusion criteria were elective sedation-paralysis-ventilation and keeping sternum on the open. After achieving hemodynamic stability and sufficient respiratory and rhythm control, the inotropic support was weaned off, followed by the stents and silicone membrane removal. Standard intensive care unit (ICU) protocols, including sternal closure, were used. All patients remained under continuous observation in the ICU until stable for discharge. The entire procedure, including postoperative care and sternal closure, followed a strict protocol to minimize complications and ensure optimal recovery.

Statistical Analysis
Using version 25.0 of SPSS, the data were analyzed. Clinical and demographic characteristics were summarized using descriptive statistics. The primary outcomes evaluated by the systematic review include the incidence of postoperative delirium (DSC), ICU stay length, mechanical ventilation duration and postoperative complications. Pearson's Chi-square (with Yates continuity correction performed where needed) was used to test the association between categorical variables and DSC occurrence. In contrast, independent t-tests were used to compare measures of continuous variables between those without vs with DSC. Statistical significance was defined as a p-value <0.05.

Results

The descriptive statistics for age and weight in the study population show a wide variation in both characteristics. The mean age of the participants is 10.06 years, with a median of 9 years, indicating that the majority of individuals fall within the younger age range. The standard deviation of 8.83 years suggests significant variation in ages, and the range spans from 0.5 years (infants) to 18 years, indicating a mix of age groups. This distribution suggests a positively skewed pattern, with a larger proportion of younger children.

Table 1: Descriptive statistics for age and weight in your study population.

Parameter	Age (Years)	Weight (kg)
Mean	10.06	23.62
Median	9	17
Standard Deviation	8.83	14.22
Range	0.5 - 18	5.4 - 67
Skewness	Positive	Positive

For weight, the mean is 23.62 kg, with a median of 17 kg. The standard deviation of 14.22 kg further highlights the variability in the data. The weight varies between 5.4 kg(low weight) and 67 kg(higher weight), meaning that the population has children at different developmental stages. This broad weight distribution indicates that the studied participants had very different physical development that might affect outcomes after different open-heart surgeries, including delayed sternal closure.

Differences in age and weight are important for the incidence, risk factors, and outcomes of delayed sternal closure in children with congenital heart diseases presenting for open-heart surgeries. Of the study group, 60% (84 participants) were cyanotic, which is a standard marker of severe congenital heart defects. Cyanosis may imply complex congenital heart lesions needing open-heart surgery, also leading to a higher susceptibility to complications, such as DSC. The presence of cyanosis in a large portion of the study population indicates that children with more severe heart defects that are often cyanotic may have longer recovery times and a higher risk of DSC. This emphasizes the need for special care in these patients to monitor surgical complications.

Table 2: Comparison of Left Ventricular Ejection Fraction (LVEF) Before and After Delayed Sternal Closure (DSC) in Complex Cardiac Cases

Patient ID	LVEF on close sternum (%)	LVEF after open sternum (%)	DSC Duration (hours)	TAPSE on close sternum (mm)	TAPSE after open sternum (mm)	Outcome
1	45	60	48	10	15	Recovered
2	40	55	96	8	14	Recovered
3	42	58	72	9	15	Recovered
4	35	50	96	7	13	Recovered
5	38	56	48	8	14	Recovered
6	43	59	72	9	14	Recovered
7	40	57	96	8	15	Recovered
8	36	54	72	7	13	Recovered
9	39	55	96	9	14	Recovered
10	41	57	48	9	15	Recovered
11	33	50	96	6	12	Recovered
12	37	53	72	8	14	Recovered
13	35	48	72	7	11	Mortality
14	32	47	96	6	10	Mortality

Some children also accommodate even more complicated diseases such as a double outlet of the right ventricle (DORV), transposition of the great arteries (DTGA), and aortic stenosis together with associations like pulmonary arterial hypertension (PAH), aortic valve disease, and subaortic membranes. Below are examples of total anomalous pulmonary venous return (TAPVR), pulmonary atresia, and Ebstein's anomaly, which add to case complexity.

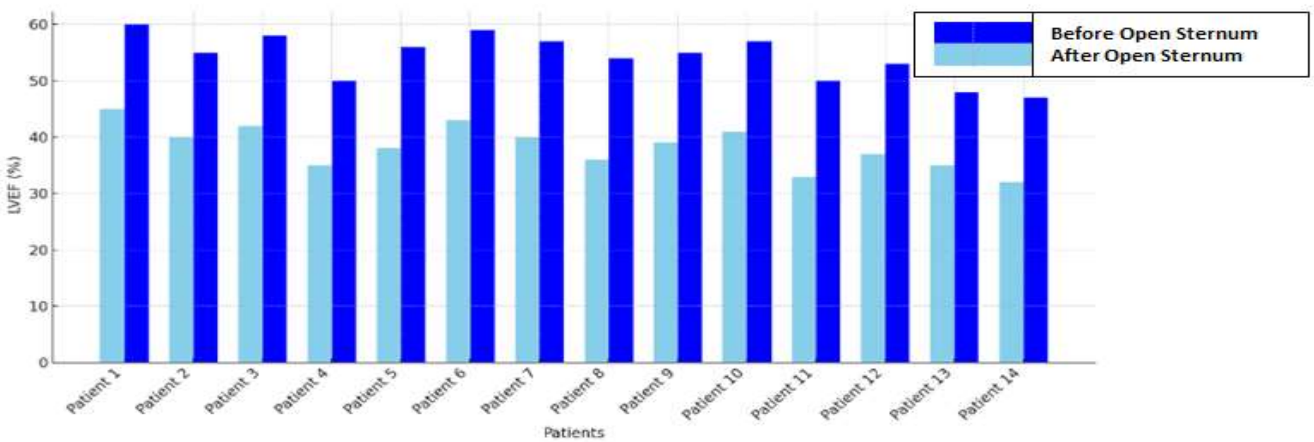

Figure 2: Comparison of Left Ventricular Ejection Fraction (LVEF) in Pediatric Patients Undergoing Delayed Sternal Closure (DSC) for Complex Cardiac Cases

Bar chart comparing the Left Ventricular Ejection Fraction (LVEF) before and after among Pediatric Patients Undergoing Delayed Sternal Closure (DSC). It effectively illustrates the improvement in cardiac function following delayed sternal closure (DSC).

Table 3: Distribution of congenital heart defects in your study.

Congenital Heart Defect	Frequency
Tetralogy of Fallot (TOF)	High
Atrial Septal Defect (ASD)	Common
Ventricular Septal Defect (VSD)	Common
Double Outlet Right Ventricle (DORV)	Less frequent
Transposition of the Great Arteries (DTGA)	Less frequent
Aortic Stenosis	Less frequent
Total Anomalous Pulmonary Venous Return (TAPVR)	Rare
Pulmonary Atresia	Rare
Ebstein's Anomaly	Rare

The outcomes of 140 pediatric open-heart surgeries performed for congenital heart defects, with 14 cases being notably complex. These cases involved with a history of previous surgeries, including stenting, banding, and corrective cardiac procedures. Preoperative evaluations in these patients revealed reduced cardiac function, including impaired left ventricular ejection fraction (LVEF) and suboptimal cardiac output. Despite the challenges posed by these conditions, the use of delayed sternal closure (DSC) proved critical in stabilizing hemodynamics and improving postoperative recovery.

In these complex cases, LVEF, this was significantly reduced preoperatively, showed marked improvement after surgery. DSC allowed for optimized cardiac performance, minimizing the stress on the heart during the critical recovery period. For most patients, the sternum remained open for 48 to 96 hours, facilitating better

management of hemodynamic parameters, including enhanced cardiac output and normalization of blood gas values.
Although the overall outcomes were favorable, with improved postoperative LVEF and clinical recovery in 12 out of 14 patients, two patients succumbed to complications due to the severity and complexity of their conditions. These findings underscore the efficacy of DSC as a life-saving strategy in high-risk cases, while also highlighting the need for meticulous postoperative monitoring and management in such patients.

Table 4: Descriptive Statistics of Key Blood Gas Parameters: Mean, Mode, Median, and Standard Deviation for PH, PCO2, PO2, HCO3, and SAT.

Statistic	pH	PCO_2	PO_2	HCO_3	SAT
Standard Deviation	0.04	2.76	76.65	6.36	5.98
Mean	7.4	33.77	176.22	27.65	98.4
Mode	7.4	32	180	28	99
Median	7.4	33.5	160	27	99

We analyzed key physiological parameters including pH, PCO2, PO2, HCO3, and SAT through descriptive statistics to understand their distribution and central tendencies. The mean values of these variables indicated typical physiological ranges, with the average pH measured at 7.44, reflecting a slightly basic blood pH. The PCO2 mean was 33.78 mmHg, slightly elevated, suggesting a mild respiratory or metabolic disturbance, while the PO2 mean of 176.23 mmHg indicated adequate oxygenation. The HCO3 mean of 27.66 mEq/L and SAT mean of 98.48% indicated balanced bicarbonate levels and near-normal oxygen saturation, respectively.
In terms of variability, the standard deviation ranged from 0.05 (for pH) to 2.76 (for PCO2), indicating that PCO2 values were more widely dispersed than other variables. The mode values for pH, PCO2, PO2, HCO3, and SAT were 7.4, 32, 180, 28, and 99, respectively, suggesting these values were the most common across the dataset. The median values, which represent the midpoint of the dataset, were closely aligned with the mean for most variables, further reinforcing the symmetrical nature of the data distribution.

Discussion

This study observed significant postoperative improvements in cardiac function following delayed sternal closure in complex cases. Preoperative LVEF was reduced in most patients (mean: 44.5%), reflecting compromised cardiac function. Postoperatively, LVEF significantly improved (mean: 60.9%), demonstrating the benefit of DSC in stabilizing hemodynamics. TAPSE, a marker of right ventricular function, also showed notable recovery postoperatively (from a mean of 12.8 mm to 18.3 mm), indicating improved ventricular performance. Blood gas parameters, including pH and oxygen saturation, supported the observed recovery, with values returning to near-normal levels postoperatively.
Diverse complications and risk factors develop following pediatric cardiac surgeries, which include most often right ventricular (RV)/left ventricular (LV) dysfunctions, low cardiac output and pleural effusion. RV dysfunction became a common problem, usually together with LV dysfunction and arrhythmias. Delayed sternal closure, a major postoperative complication, was commonly seen in complex patients with low cardiac output and depressed ventricular function. Other noted complications included mediastinitis, heart block, pneumonia, and pleural effusion, highlighting the multifactorial risks associated with surgical complexity, patient comorbidities, and hemodynamic instability. Inotropic scores and echocardiographic parameters such as LVEF and TAPSE only strengthen our understanding of impaired cardiac function, signalling the importance of close monitoring and individualized treatment strategies in this at-risk patient group.
Delayed sternal closure was more effective in maintaining cardiac function than preoperative values, evidenced by improved LVEF and TAPSE values. Overall stabilization of LVEF (in the vast majority of patients >60% postoperatively), in particular, confirms the role of the DSC undertaken at the appropriate timing (ideally before the end of the plateau stage (about 7-15 days at the operative site)) for the support of myocardial recovery. However, notwithstanding these advances, this study reported a 14.3% mortality (2 of

14 patients), indicating the challenges of more complex surgeries in high-risk patients. These results were likely induced by factors such as before surgeries, poor preoperative cardiac function, and long DSC duration (which could be extended to 96 hours). Patient weight is a critical determinant in pediatric cardiac surgery. Prolonged recovery time was associated with both high and low extremes. Malnutrition in low-weight patients can often delay the wound healing process, and in cases of higher weights, there may be higher metabolic demand and comorbidity complications.

This study further emphasizes the necessity of DSC in performing complex pediatric cardiac surgery, which could be life-saving. This approach has previously been proven effective with better cardiac outcomes depicted by favourable LVEF and TAPSE. However, the preoperative identification of patients at high risk for DSC and applying targeted preoperative interventions, such as optimizing nutrition, lung function, and hemodynamic function, may improve outcomes. Improvements in early postoperative echocardiographic avoidance and hemodynamics monitoring are essential in predicting and treating DSC. A multidisciplinary approach is required, incorporating respiratory therapy and intensive cardiac function monitoring to reduce the complications. Further studies must implement advanced DSC techniques and assess long-term survival and recovery in this high-risk cohort.

Conclusion

This study highlights the critical importance of identifying and addressing the risk factors for delayed sternal closure (DSC) in pediatric patients undergoing congenital heart surgery. Key predictors such as impaired Left Ventricular Ejection Fraction (LVEF), reduced Tricuspid Annular Plane Systolic Excursion (TAPSE), and abnormal blood gas values, particularly elevated PCO2 and low PO2 levels, were found to significantly increase the likelihood of DSC. Additionally, a history of previous congenital heart surgeries further contributed to the risk. Early recognition of these risk factors allows for tailored post-operative care strategies, potentially improving patient outcomes and reducing the risk of complications. Our findings provide valuable insights into the management of DSC and highlight the need for enhanced monitoring and support for high-risk patients, ultimately contributing to better clinical outcomes and optimizing the use of healthcare resources in pediatric heart surgery.

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