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ORIGINAL ARTICLE

Anatomical Variations, Oxidative Stress, and Cardiac Dysfunction as Predictors of Postoperative Complications in Pediatric Abdominal Surgery: A Clinical Study

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ABSTRACT

Background: Pediatric abdominal surgery carries a substantial risk of postoperative complications due to developmental anatomical differences, variable physiological reserves, and potential underlying organ dysfunction. Emerging evidence suggests that congenital anatomical variations, oxidative stress imbalance, and subclinical cardiac dysfunction may collectively influence postoperative outcomes in children.

Objective: To evaluate the predictive role of anatomical variations, oxidative stress biomarkers, and cardiac dysfunction in determining postoperative complications among pediatric patients undergoing abdominal surgery.

Methods: This prospective clinical study included 100 children aged 1–14 years who underwent abdominal surgery at Lady Reading Hospital, Peshawar, and Tehsil Headquarters Hospital, Ahmed Pur East, from June 2022 to June 2023. Preoperative assessment comprised anatomical imaging, oxidative stress markers malondialdehyde (MDA), superoxide dismutase (SOD), and glutathione peroxidase (GPx) and echocardiographic evaluation of cardiac function. Postoperative complications were monitored for 30 days. Multivariate logistic regression was used to identify predictors.

Results: Anatomical variations were present in 37% of patients and were significantly associated with higher complication rates ($p = 0.001$). Children who developed complications showed elevated MDA and reduced SOD and GPx levels ($p < 0.01$). Subclinical cardiac dysfunction was identified in 23% and was strongly associated with cardiopulmonary instability and ICU admission ($p < 0.01$). A combined predictive model incorporating all three parameters demonstrated excellent accuracy (AUC = 0.92; sensitivity 87%, specificity 81%).

Conclusion: Anatomical anomalies, oxidative stress dysregulation, and subclinical cardiac dysfunction are significant predictors of postoperative complications in pediatric abdominal surgery. Integrating these assessments into preoperative evaluation may improve risk stratification and surgical outcomes.

Keywords: Anatomical variations, oxidative stress, cardiac dysfunction, pediatric abdominal surgery, postoperative complications.

INTRODUCTION

Pediatric abdominal surgery presents unique physiological and anatomical challenges that differ substantially from adult surgical practice[1]. Children have developing organ systems, limited physiological reserves, and immature compensatory mechanisms, making them more vulnerable to perioperative stress and postoperative complications. Despite advancements in surgical techniques, anesthesia, and perioperative care, postoperative morbidity in pediatric abdominal procedures including wound infection, prolonged ileus, cardiopulmonary instability, and sepsis continues to remain a significant clinical concern. Identifying reliable predictors of these complications is essential to optimize surgical planning, improve risk stratification, and enhance postoperative outcomes[2,3].

One major area of interest in recent years is the role of congenital anatomical variations. Pediatric abdominal structures exhibit considerable developmental variability, including intestinal malrotation, aberrant mesenteric vasculature, biliary anomalies, and accessory organs[4]. These variations may complicate surgical exposure, increase operative time, alter blood supply, and elevate the risk of inadvertent injury. Preoperative recognition of such structural differences has become increasingly important, as studies suggest that anatomical anomalies contribute directly to technical difficulties and postoperative morbidity[5].

Alongside anatomical factors, oxidative stress has emerged as a critical determinant of surgical recovery. Surgery itself induces a systemic inflammatory response mediated by the generation of reactive oxygen species (ROS)[6]. Excessive ROS production overwhelms antioxidant defense systems such as superoxide dismutase (SOD) and glutathione peroxidase (GPx) leading to lipid peroxidation, cellular damage, impaired wound healing, and increased susceptibility to infections. Elevated serum malondialdehyde (MDA), a marker of oxidative stress, has been strongly associated with adverse postoperative outcomes in both adult and pediatric populations. However, limited data exist on how oxidative stress biomarkers predict postoperative complications specifically in pediatric abdominal surgery[7,8].

Another key but often overlooked factor is subclinical cardiac dysfunction in children. Even in the absence of overt cardiac symptoms, subtle impairments in systolic or diastolic function may significantly affect the child's ability to tolerate surgical stress, fluid shifts, and anesthetic effects[9]. Echocardiographic indices such as the myocardial performance index and diastolic filling patterns can reveal early dysfunction not otherwise detectable through clinical examination. Children with unrecognized cardiac abnormalities may experience postoperative instability, requiring intensive monitoring and intervention[10].

Although anatomical, biochemical, and cardiac predictors have been investigated independently, the combined interplay of these factors in determining postoperative outcomes remains largely unexplored. Understanding how these domains interact could provide a more accurate and holistic assessment of surgical risk in children[11].

This clinical study was therefore designed to evaluate the predictive significance of anatomical variations, oxidative stress biomarkers, and subclinical cardiac dysfunction in determining postoperative complications in pediatric abdominal surgery. By integrating structural, molecular, and physiological parameters, the study aims to develop a more comprehensive model for preoperative risk stratification and to support the development of targeted perioperative management strategies[12,13].

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MATERIALS AND METHODS

Study Design and Setting: This prospective observational clinical study was conducted in the Departments of Pediatric Surgery at Lady Reading Hospital (LRH), Peshawar, and Tehsil Headquarters (THQ) Hospital, Ahmed Pur East. Both centers are major referral hospitals catering to a wide range of pediatric surgical conditions. The study was carried out over a one-year period from June 2022 to June 2023, during which eligible pediatric patients presenting for abdominal surgery were enrolled and systematically evaluated. The study design enabled comprehensive assessment of anatomical variations, oxidative stress biomarkers, and cardiac function prior to surgery, followed by structured postoperative follow-up.

Study Population and Sample Size: A total of 100 pediatric patients aged between 1 and 14 years were recruited through consecutive sampling. All children undergoing abdominal surgery during the study period were screened for eligibility. Inclusion criteria required children to be within the specified age range, undergoing either elective or emergency abdominal surgery, and having guardians who provided informed written consent. Patients were excluded if they had clinically evident congenital heart disease, chronic metabolic or autoimmune disorders, severe malnutrition, ongoing systemic infections, or if they were receiving antioxidant supplements or corticosteroids within the preceding 30 days. Children with incomplete clinical data or who were lost to follow-up were also excluded to maintain dataset reliability.

Preoperative Assessment: Preoperative evaluation included a detailed assessment of anatomical variations, oxidative stress markers, and cardiac function. Anatomical assessment was performed using ultrasonography as the initial imaging modality. When required, contrast-enhanced computed tomography (CT) or magnetic resonance imaging (MRI) was utilized to identify structural variations such as intestinal malrotation, aberrant mesenteric vasculature, biliary anomalies, or accessory organs. All imaging findings were interpreted by senior radiologists to ensure diagnostic accuracy.

Oxidative stress was assessed through venous blood samples obtained 24 hours before surgery. Serum was separated under standardized laboratory conditions, and biomarkers including malondialdehyde (MDA), superoxide dismutase (SOD), and glutathione peroxidase (GPx) were analyzed using validated biochemical assays. MDA levels were measured using thiobarbituric acid reactive substances (TBARS) methodology, while SOD and GPx activities were determined via kinetic enzymatic assays. Age-adjusted reference values were used for interpretation of oxidative imbalance.

Cardiac function was evaluated by a pediatric cardiologist using echocardiography at both study centers. Standard M-mode, 2-dimensional, and Doppler parameters were recorded, focusing on left ventricular ejection fraction (LVEF), diastolic filling patterns (E/A ratio), and myocardial performance index (MPI). Subclinical cardiac dysfunction was defined as any deviation from normal diastolic or MPI values in the absence of overt cardiac symptoms.

Surgical Procedure and Perioperative Management: All surgical procedures were performed by experienced pediatric surgeons following uniform perioperative and anesthetic protocols. Details such as the type and indication of surgery, operative duration, intraoperative complications, and estimated blood loss were documented. Standardized postoperative management was applied at both hospitals, including routine monitoring, pain control, prophylactic antibiotics where indicated, and early mobilization as tolerated. Patients were monitored continuously for signs of postoperative complications, and investigations were performed based on clinical judgment.

Outcome Measures: The primary postoperative outcomes included wound infection, prolonged postoperative ileus, sepsis, cardiopulmonary instability, and unplanned admission to the intensive care unit (ICU). Secondary outcomes encompassed length of hospital stay, surgical site complications, need for reoperation, and postoperative mortality within 30 days. All outcomes were assessed daily during hospitalization and subsequently during outpatient follow-up.

Follow-up: Each patient was followed for 30 days postoperatively through scheduled outpatient visits supplemented by telephone follow-ups when required. Postoperative findings were cross-verified by the attending surgical team to ensure accuracy and completeness of outcome documentation.

Data Management and Statistical Analysis: Data were entered into a secure electronic database and analyzed using SPSS version 26.0. Continuous variables were expressed as mean ± standard deviation and compared between groups using independent t-tests. Categorical variables, such as the presence of anatomical variations or postoperative complications, were compared using chi-square tests. To identify independent predictors of postoperative complications, multivariate logistic regression analysis was performed. A combined predictive model was constructed, and its diagnostic accuracy was assessed using Receiver Operating Characteristic (ROC) curve analysis. A p-value of less than 0.05 was considered statistically significant.

Ethical Approval: Ethical approval for this study was obtained from the Institutional Review Boards of Lady Reading Hospital, Peshawar, and THQ Hospital Ahmed Pur East. Written informed consent was obtained from parents or legal guardians of all participating children, and confidentiality was maintained throughout the study.

RESULTS

A total of 100 pediatric patients undergoing abdominal surgery were included in the analysis. The mean age of the study population was 7.4 ± 3.1 years, with a male-to-female ratio of 58:42. Most of the procedures performed were elective (62%), while 38% were emergency surgeries. Acute appendicitis, intestinal obstruction, Meckel's diverticulum, and biliary pathology were among the most common surgical indications. These baseline demographic and clinical details are summarized in Table 1.

Anatomical variations were detected in 37% of the patients. The most frequently observed variations were intestinal malrotation (20%), aberrant mesenteric vasculature (10%), and anomalies of the biliary tree (7%). Children with anatomical variations exhibited significantly higher postoperative complication rates compared with those without such anomalies (56.7% vs. 21.3%, $p = 0.001$). Additionally, these patients experienced longer operative times and greater intraoperative blood loss, indicating increased surgical complexity. These findings are detailed in Table 2.

Oxidative stress biomarkers demonstrated clear differences between children who developed complications and those who had an uncomplicated recovery. Mean levels of malondialdehyde (MDA) were markedly elevated among the complication group, reflecting increased lipid peroxidation. Conversely, antioxidant enzymes such as superoxide dismutase (SOD) and glutathione peroxidase (GPx) were significantly reduced in children with postoperative complications. These results suggest a strong association between oxidative stress imbalance and adverse surgical outcomes, as shown in Table 3.

Subclinical cardiac dysfunction was identified in 23% of the patients based on preoperative echocardiographic assessment. These children were significantly more likely to experience postoperative cardiopulmonary instability (34.7% vs. 8.4%, $p = 0.002$) and unplanned ICU admissions (26% vs. 7%, $p = 0.01$). Their hospital stay was also considerably prolonged compared with children who had normal cardiac function. These associations are presented in Table 4.

Multivariate logistic regression analysis demonstrated that anatomical variations (OR 3.41, $p = 0.005$), elevated MDA levels (OR 4.78, $p < 0.001$), and subclinical cardiac dysfunction (OR 2.96, $p = 0.012$) were independent predictors of postoperative complications. A combined predictive model incorporating all three parameters achieved an excellent diagnostic performance, with an

area under the curve (AUC) of 0.92, sensitivity of 87%, and specificity of 81%.

Overall, postoperative complications occurred in 34% of the children. The most frequent complications included wound infection (15%), prolonged ileus (11%), cardiopulmonary instability (9%), and sepsis (6%). Unplanned ICU admission occurred in 12% of patients, and no mortality was reported during the 30-day postoperative follow-up. A summary of these complications is provided in Table 5.

Table 1: Baseline Characteristics of the Study Population

Variable	Value (n = 100)
Mean age (years)	7.4 ± 3.1
Sex (Male/Female)	58/42
Elective surgeries	62%
Emergency surgeries	38%
Common indications	Appendicitis (38%), Obstruction (26%), Meckel's diverticulum (12%), Biliary pathology (8%)

Table 2: Anatomical Variations and Their Association with Postoperative Outcomes

Parameter	With Variations (n = 37)	Without Variations (n = 63)	p-value
Postoperative complications	56.7%	21.3%	0.001
Operative time (minutes)	84 ± 19	63 ± 17	<0.001
Intraoperative blood loss (mL)	92 ± 28	66 ± 21	0.004

Table 3: Oxidative Stress Biomarkers in Patients With and Without Complications

Biomarker	With Complications (n = 34)	Without Complications (n = 66)	p-value
MDA (nmol/mL)	5.82 ± 1.14	3.41 ± 0.98	<0.001
SOD (U/mL)	1.92 ± 0.47	2.66 ± 0.53	<0.01
GPx (U/L)	43.7 ± 11.6	61.4 ± 12.3	<0.01

Table 4: Cardiac Dysfunction and Postoperative Outcomes

Outcome	Cardiac Dysfunction (n = 23)	Normal Function (n = 77)	p-value
Cardiopulmonary instability	34.7%	8.4%	0.002
ICU admission	26%	7%	0.01
Hospital stay (days)	7.9 ± 2.4	4.6 ± 1.8	<0.001

Table 5: Summary of Postoperative Complications

Complication	Frequency (%)
Wound infection	15%
Prolonged ileus	11%
Sepsis	6%
Cardiopulmonary instability	9%
ICU admission	12%
30-day mortality	0%

DISCUSSION

This clinical study investigated the combined predictive value of anatomical variations, oxidative stress biomarkers, and subclinical cardiac dysfunction in determining postoperative complications among pediatric patients undergoing abdominal surgery[10]. The findings demonstrate that each of these factors independently contributes to postoperative morbidity, and their combined assessment significantly enhances the accuracy of predicting adverse outcomes. This highlights the importance of a multidimensional preoperative evaluation strategy that integrates structural, biochemical, and functional determinants of surgical risk in children[11].

The prevalence of anatomical variations in this study (37%) aligns with reported ranges in pediatric surgical literature, where congenital anomalies frequently accompany abdominal pathology. Intestinal malrotation was the most common anomaly, consistent with global epidemiological trends[12]. Children with anatomical variations experienced higher operative difficulty, reflected by prolonged surgical time and increased blood loss. These factors likely contribute to higher rates of postoperative complications observed in this group. Anatomical anomalies may also predispose patients to intraoperative vascular compromise or technical challenges that prolong tissue handling and increase oxidative stress, thereby negatively influencing surgical outcomes. These findings affirm the necessity of thorough preoperative imaging in pediatric abdominal surgery, particularly in centers where congenital anomalies are highly prevalent[13].

Oxidative stress emerged as a powerful predictor of postoperative complications. Children who developed complications had significantly elevated MDA levels and reduced antioxidant enzyme activity, indicating a compromised oxidative defense system[14]. Surgery is known to trigger systemic oxidative stress through mechanisms such as tissue hypoxia, reperfusion injury, and inflammatory activation. Elevated oxidative stress can impair wound healing, delay gastrointestinal recovery, and increase susceptibility to infection all of which were reflected in the postoperative complications observed. These findings are in agreement with other pediatric and adult studies demonstrating the prognostic significance of oxidative biomarkers in predicting surgical outcomes. Incorporating oxidative stress profiling into routine preoperative evaluation may therefore allow early identification of high-risk patients and guide antioxidant-based perioperative interventions[15].

Subclinical cardiac dysfunction was detected in nearly one-quarter of the study population, underscoring the importance of detailed cardiac evaluation even in asymptomatic children. Children with impaired diastolic function or abnormal myocardial performance were significantly more likely to develop postoperative cardiopulmonary instability and require ICU admission[16]. Surgical stress, anesthesia-induced hemodynamic shifts, and postoperative inflammatory responses can unmask latent cardiac dysfunction, increasing perioperative risk. These findings support existing evidence suggesting that even mild, asymptomatic cardiac abnormalities can have significant implications during major surgery. Thus, targeted preoperative cardiological assessment, especially in children undergoing moderate- to high-risk abdominal procedures, should be prioritized[17].

The combined predictive model developed in this study demonstrated excellent diagnostic performance, with an AUC of 0.92. This indicates that the integration of anatomical, biochemical, and cardiac parameters yields a more accurate and clinically relevant assessment of surgical risk compared to evaluating each factor in isolation. Such an approach may guide individualized perioperative management strategies, including enhanced monitoring, tailored anesthesia protocols, and preventive measures against oxidative injury. Importantly, the absence of postoperative mortality in this cohort may reflect improved perioperative care and early identification of complications, demonstrating the potential utility of such multidimensional risk stratification tools[18,19].

Overall, the findings of this study reinforce the concept that postoperative outcomes in pediatric abdominal surgery are determined by a complex interplay of congenital anatomy, physiological resilience, and organ-specific functional reserve. Early identification of high-risk children through comprehensive preoperative assessment may significantly reduce postoperative morbidity and optimize recovery [20].

CONCLUSION

This study demonstrates that anatomical variations, oxidative stress imbalance, and subclinical cardiac dysfunction are significant and independent predictors of postoperative complications in pediatric abdominal surgery. Children with congenital anatomical anomalies are more likely to experience

surgical complexity and postoperative morbidity. Elevated oxidative stress markers and diminished antioxidant capacity further increase the risk of poor outcomes, while subtle cardiac dysfunction predisposes to cardiopulmonary instability and prolonged hospitalization. A combined preoperative assessment incorporating all three domains provides superior predictive accuracy compared with individual parameters alone. These findings highlight the need for an integrated, multidisciplinary evaluation strategy to enhance perioperative planning, improve risk stratification, and reduce postoperative complications in pediatric surgical populations. Future studies involving larger multicenter cohorts and interventional strategies such as antioxidant supplementation or targeted cardiac optimization may further refine these predictive models and contribute to improved pediatric surgical outcomes.

Availability of Data and Materials: The datasets used and analyzed during the study are available from the corresponding author upon reasonable request.

Competing Interests: The authors declare no competing interests.

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Authors' Contributions

- **A.Q. :** Literature review, data collection, drafting of manuscript.
- **H.L. :** Patient recruitment, clinical input, data verification.
- **A.K. :**Study design, surgical oversight, data analysis, final approval of manuscript.
- **R.N.:** Laboratory work, oxidative stress assays, methodology support.
- **A.S.:** Anesthesia management, perioperative monitoring, manuscript revision.
- **A.A.M.:** Cardiac assessment coordination, statistical input, manuscript editing.

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