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Intraoperative Transesophageal Echocardiography Guidance Improves Recovery After Pediatric Tetralogy of Fallot Repair

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Abstract

Background

Intraoperative transesophageal echocardiography (TEE) may optimize surgical repair and early recovery in Tetralogy of Fallot (TOF), but medium-term hemodynamic data from resource-limited settings are limited. This study evaluated whether TEE guidance during TOF repair improves postoperative hemodynamics and clinical outcomes in children.

Methods

In this single-center retrospective cohort, consecutive patients < 18 years undergoing complete TOF repair between January 2022 and December 2024 at a tertiary children's hospital in Tashkent, Uzbekistan, were included. Patients received either intraoperative TEE guidance (TEE group, n = 79) or conventional assessment (No-TEE group, n = 49). Hemodynamic and echocardiographic parameters (SpO2, ejection fraction, right ventricle–pulmonary artery [RV–PA] gradient, valvular regurgitation) were assessed up to one year; regression and propensity-matched analyses evaluated prolonged hospitalization and residual ventricular septal leakage.

Results

Baseline characteristics were broadly similar, apart from slightly higher preoperative SpO2 in the TEE group. TEE guidance was associated with higher postoperative SpO2, faster ventricular recovery, less atrioventricular valve regurgitation, and shorter hospital stay. TEE independently reduced the odds of prolonged hospitalization and residual ventricular septal leakage.

Conclusions

Intraoperative TEE during TOF repair was safe and associated with improved hemodynamic recovery, better valve competence, and shorter hospitalization. These findings support routine TEE use in centers with appropriate expertise and justify prospective multicenter studies to confirm causality and define long-term outcomes.

Introduction

Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart defect, accounting for approximately 5 to 7% of all congenital cardiac malformations. Complete surgical repair in infancy or early childhood remains the definitive treatment, typically involving closure of the ventricular septal defect and relief of right ventricular outflow tract obstruction under cardiopulmonary bypass. Despite advances in surgical technique and perioperative care, residual anatomical and functional lesions remain common after repair and are important determinants of early postoperative morbidity, the need for reoperation, and long-term outcome 1–3.

Intraoperative transesophageal echocardiography has emerged as a valuable real-time imaging modality during congenital cardiac surgery, allowing immediate assessment of repair adequacy, detection of residual defects, and evaluation of ventricular function before chest closure. Multiple observational studies have demonstrated that Transesophageal Echocardiography (TEE) findings alter surgical management in 10 to 15% of pediatric cardiac procedures, most notably during valve repairs and complex outflow tract reconstructions characteristic of Tetralogy of Fallot. Recent evidence suggests that Transesophageal Echocardiography (TEE)-guided repair may reduce postoperative complications and intensive care unit stay, although data on medium-term hemodynamic outcomes and survival remain limited, particularly in resource-constrained settings. A recent study from a Tashkent center reported promising early postoperative results with intraoperative Transesophageal Echocardiography (TEE) in Tetralogy of Fallot (TOF) patients, but comprehensive longitudinal hemodynamic trajectories and valve function data extending beyond the immediate postoperative period have not been thoroughly examined 4–7.

We conducted this retrospective cohort study to compare hemodynamic recovery trajectories, valve function, and clinical outcomes over one year of follow-up between patients who underwent Transesophageal Echocardiography (TEE)-guided surgical repair and those managed with conventional intraoperative assessment alone. We hypothesized that intraoperative Transesophageal Echocardiography (TEE) guidance would be associated with improved oxygen saturation, earlier recovery of ventricular function, reduced valvular regurgitation, and shorter hospital stays 8–11.

Materials and Methods

Study Design, Setting, and Ethical Approval

This retrospective comparative cohort study was conducted at the National Children's Medical Center in Tashkent, Uzbekistan. The study protocol was approved by the institutional ethics committee of National Children's Medical Center under #NCMC/EC/001/02-2026, February 20, 2026. The requirement for individual informed consent was waived owing to the retrospective design and use of anonymized data. The study was conducted and reported in accordance with the STROBE guidelines for observational research 12–15.

Study Population and Eligibility

All consecutive pediatric patients (age < 18 years) who underwent complete surgical repair of Tetralogy of Fallot (TOF) at our institution between January 2022 and December 2024 were screened for eligibility. Patients with confirmed Tetralogy of Fallot (TOF) diagnosis undergoing elective or semi-elective total intracardiac correction under cardiopulmonary bypass were included. Exclusion criteria were incomplete perioperative or follow-up data, prior intracardiac

repair, or concurrent major non-cardiac congenital anomalies; prior palliative shunting was not an exclusion criterion. A total of 128 patients were included: 79 in the Transesophageal Echocardiography (TEE)-guided group and 49 in the conventional No-Transesophageal Echocardiography (TEE) group. Group assignments reflected surgeon preference, echocardiographer availability, and evolving institutional protocols rather than randomization 16,17.

Technique and Anesthetic Management

All procedures were performed via median sternotomy under cardiopulmonary bypass with moderate hypothermia (28–32°C). Complete repair comprised patch closure of the ventricular septal defect (VSD) and relief of right ventricular outflow tract obstruction (RVOTO) by infundibular resection, pulmonary valvotomy, or transannular patch augmentation according to individual anatomy. Myocardial protection used intermittent antegrade cold crystalloid or blood cardioplegia. The anesthetic protocol was identical in both groups: induction with fentanyl, midazolam, and rocuronium; maintenance with isoflurane and continuous fentanyl infusion; and volume-controlled ventilation targeting normocapnia 16–18.

Intraoperative Transesophageal Echocardiography (TEE) Protocol

In the Transesophageal Echocardiography (TEE)-guided group, an appropriately sized multiplane pediatric Transesophageal Echocardiography (TEE) probe was inserted following anesthetic induction and before sternotomy. Pre-bypass examination confirmed the morphological diagnosis, delineated ventricular septal defect (VSD) anatomy, assessed valve function, and estimated the baseline RV–PA pressure gradient. After weaning from cardiopulmonary bypass and prior to protamine administration, a post-repair examination evaluated ventricular septal defect (VSD) closure completeness, right ventricular outflow tract obstruction (RVOTO) relief, residual RV–PA gradient, biventricular systolic function, and valve competence. Findings were communicated to the surgical team in real time. Return to bypass for revision was indicated by predefined criteria: residual ventricular septal defect (VSD) jet velocity > 2.5 m/s, atrioventricular valve regurgitation ≥ Grade 2, or residual RV–PA gradient > 40 mmHg. To ensure the diagnostic accuracy and physiological consistency of intraoperative Transesophageal Echocardiography (TEE) assessments, echocardiographic findings were confirmed with real-time cardio monitoring data and direct invasive pressure measurements. Continuous monitoring included heart rate, invasive arterial blood pressure, and peripheral oxygen saturation (SpO_2). After completion of intracardiac repair, direct measurements of right ventricular and main pulmonary artery pressures were obtained using intraoperative tensiometric techniques. Agreement between invasive hemodynamic data and Transesophageal Echocardiography (TEE)-derived gradients was evaluated to confirm the reliability of post-repair echocardiographic assessment.

In the No- Transesophageal Echocardiography (TEE) group, surgical adequacy was assessed by direct visual inspection, intracardiac pressure measurements along with tensiometry, and post-bypass clinical parameters alone; no post-repair imaging was performed before chest closure 19–22.

Data Collection and Outcome Measures

Anamnestic data was extracted retrospectively, and follow-up data was collected prospectively from electronic medical records, operative reports, anesthesia charts, intensive care unit flow sheets, and outpatient echocardiography databases. Baseline characteristics included sex, weight, height, body surface area (Mosteller formula), history of prior palliation, and preoperative clinical and echocardiographic parameters. Serial variables were recorded at six timepoints: preoperatively, immediately postoperatively, on postoperative days 1 and 4, and at six-month and one-year follow-up. At each timepoint, the following were assessed: peripheral oxygen saturation (SpO_2) by pulse oximetry, heart rate, systolic and diastolic blood pressure, left ventricular ejection fraction (EF) by the modified Simpson biplane method, Right ventricle–pulmonary artery (RV–PA) gradient by continuous-wave Doppler, and mitral, tricuspid, and pulmonary regurgitation graded 0–3 by color Doppler per standard guidelines. Residual ventricular septal leakage was recorded as a binary variable at each postoperative timepoint. Additional outcomes included postoperative hospital length of stay, in-hospital mortality, reoperation within one year, and postoperative rhythm disturbances.

The primary outcome was the postoperative peripheral oxygen saturation (SpO_2) recovery trajectory across six timepoints. Secondary outcomes included longitudinal trajectories of ejection fraction (EF), Right ventricle–pulmonary artery (RV–PA) gradient, heart rate, and systolic blood pressure; serial valvular regurgitation grades; hospital length of stay; in-hospital mortality; rates of reoperation, residual leakage, and rhythm disturbances; and event-free survival at one year (freedom from death or major adverse cardiac events).

Statistical Analysis

All analyses were performed in R version 4.5.2 (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables are presented as mean ± SD or median (IQR) based on normality assessed by the Shapiro-Wilk test and were compared using the T-test or Mann-Whitney U test. Categorical variables are presented as frequencies and percentages and were compared using chi-square or Fisher exact test. Statistical significance was set at $p < 0.05$.

Longitudinal hemodynamic and echocardiographic trajectories across the six timepoints were modeled using linear mixed-effects models (lme4 and lmerTest packages), incorporating group, time, and their interaction as fixed effects and a per-patient random intercept. A significant group-by-time interaction indicated divergent recovery trajectories; post-hoc pairwise comparisons used the Wilcoxon rank-sum test with Bonferroni correction. Ordinal valve regurgitation grades were compared between groups at each timepoint using the Mann-Whitney U test and within groups over time using the Friedman test.

Independent predictors of in-hospital mortality, prolonged stay (> 10 days), and residual ventricular septal leakage were identified using multivariable logistic regression, with Transesophageal Echocardiography (TEE) use, body weight, prior palliation, preoperative peripheral oxygen saturation (SpO_2), and Right

ventricle–pulmonary artery (RV–PA) gradient entered as a priori covariates. Results are reported as adjusted odds ratio (OR) (95% CI).

Propensity scores for Transesophageal Echocardiography (TEE) use were estimated from baseline covariates and used for nearest-neighbor 1:1 matching (caliper 0.2 SD; MatchIt package). Covariate balance was confirmed by standardized mean differences < 0.10, and key outcomes were re-analyzed in the matched cohort as a sensitivity analysis.

Event-free survival at one year was estimated by the Kaplan-Meier method and compared using the log-rank test. An adjusted Cox proportional hazards model estimated the HR for Transesophageal Echocardiography (TEE) use controlling for weight, preoperative peripheral oxygen saturation (SpO_2), and RV–PA gradient, with the proportional hazards assumption verified by Schoenfeld residuals. Results are reported as HR (95% CI).

Results

Patient Characteristics and Baseline Comparisons

A total of 128 pediatric patients who underwent complete surgical repair of Tetralogy of Fallot (TOF) were included in the analysis. Of these, 79 patients were in the intraoperative Transesophageal Echocardiography (TEE)-guided group (median age: 14.5 months; IQR: 8.4–25.4), and 49 were in the conventional no-Transesophageal Echocardiography (TEE) group (median age: 10.1 months; IQR: 7.23–18.9), with p = 0.08. The overall cohort was predominantly male (71%), with a mean weight of 10.0 ± 6.4 kilograms, mean height of 77.5 ± 18.6 centimeters, and mean body surface area of 0.5 ± 0.2 square meters. The two groups were well matched at baseline with respect to sex distribution (p = 0.40), weight (p = 0.20), height (p = 0.12), body surface area (p = 0.12), preoperative ejection fraction (64.2 ± 4.3% in the Transesophageal Echocardiography (TEE) group versus 64.5 ± 6.5% in the No- Transesophageal Echocardiography (TEE) group; p = 0.30), preoperative Right ventricle–pulmonary artery (RV–PA) gradient (74.9 ± 12.0 versus 72.5 ± 8.6 millimeters of mercury; p = 0.30), and preoperative heart rate (p = 0.09). The only statistically significant baseline difference was preoperative oxygen saturation, which was modestly higher in the Transesophageal Echocardiography (TEE) group than in the No- Transesophageal Echocardiography (TEE) group (83.6 ± 9.9% versus 80.2 ± 9.8%; p = 0.03) (Table 1).

Table 1
Demographic and Preoperative Clinical Characteristics of the Study Population Overall and Stratified by Use of Intraoperative Transesophageal Echocardiography (TEE)

Characteristic	Overall N = 128*	No_TEE N = 49*	TEE N = 79*	p-value†
Gender				0.40
Female	37 (29%)	12 (24%)	26 (32%)	
Male	90 (71%)	37 (76%)	53 (68%)	
Age (months)	11.8 (7.3–23.7)	10.1 (7.23–18.9)	14.5 (8.4–25.4)	0.08
Weight (kg)	10.0 ± 6.4	10.9 ± 8.4	9.4 ± 4.7	0.20
Height (cm)	77.5 ± 18.6	80.6 ± 21.6	75.6 ± 16.2	0.12
BSA (m^2)	0.5 ± 0.2	0.5 ± 0.2	0.4 ± 0.2	0.12
Preoperative SpO_2 (%)	82.3 ± 9.9	80.2 ± 9.8	83.6 ± 9.9	**0.03**
Preoperative EF (%)	64.3 ± 5.2	64.5 ± 6.5	64.2 ± 4.3	0.30
Preoperative RV-PA gradient (mmHg)	74.0 ± 10.9	72.5 ± 8.6	74.9 ± 12.0	0.30
Preoperative heart rate (bpm)	127.6 ± 15.7	124.8 ± 15.5	129.4 ± 15.8	0.09
Systolic BP (mmHg)	95.8 ± 12.4	97.9 ± 11.6	94.4 ± 12.8	0.10
Diastolic BP (mmHg)	57.4 ± 11.0	58.7 ± 9.7	56.5 ± 11.7	0.20
Mitral regurgitation grade	2 (1.6%)	1 (2.0%)	1 (1.3%)	> 0.90
Tricuspid regurgitation grade				
0	92 (72%)	39 (80%)	53 (67%)	0.40
1	34 (27%)	10 (20%)	24 (30%)	
2	1 (0.8%)	0 (0%)	1 (1.3%)	
3	1 (0.8%)	0 (0%)	1 (1.3%)	

* Values are presented as n (%), mean ± SD (or SEM) or median (Q1, Q3)

†Pearson's Chi-squared test; Wilcoxon rank sum test; Fisher's exact test

Postoperative Hemodynamic Trajectories

Postoperative oxygen saturation was significantly higher in the Transesophageal Echocardiography (TEE) -guided group than in the No- Transesophageal Echocardiography (TEE) group immediately after surgery (98.9 ± 1.5% versus 95.6 ± 14.0%; p < 0.001) and remained elevated on postoperative day 1 (98.2 ± 1.3% versus 96.9 ± 2.3%; p < 0.001). The magnitude of the between-group difference progressively narrowed by postoperative day 4 (p = 0.06) and was no longer statistically significant at the six-month follow-up visit (p = 0.82) but re-emerged at one-year follow-up (98.1 ± 0.7% versus 97.5 ± 0.9%; p < 0.001). Linear mixed-effects modeling confirmed a statistically significant main effect of group (F = 10.83, p = 0.002) and time (F = 166.5, p < 0.001) on oxygen saturation trajectory, but the group-by-time interaction did not reach statistical significance (F = 1.78, p = 0.12), suggesting that the Transesophageal Echocardiography (TEE) group maintained a consistently higher saturation level across all timepoints rather than demonstrating a divergent trajectory (Fig. 1A, Table S1).

Left ventricular ejection fraction exhibited a statistically significant group-by-time interaction (F = 6.21, p < 0.001), indicating that the two groups followed divergent recovery trajectories over time. At the six-month follow-up, ejection fraction was markedly higher in the Transesophageal Echocardiography (TEE)-guided group than in the No-Transesophageal Echocardiography (TEE) group (66.6 ± 4.2% versus 62.3 ± 5.2%; Bonferroni-adjusted p < 0.001). However, this difference did not persist at the one-year follow-up visit, where ejection fractions were similar between groups (64.2 ± 7.5% versus 65.2 ± 2.5%; <), suggesting delayed but eventual recovery in the No- Transesophageal Echocardiography (TEE) group (Fig. 1B, Table S1).

The right ventricle–pulmonary artery (RV–PA) pressure gradient decreased substantially over time in both groups, as evidenced by a strong time effect in the mixed-effects model (F = 1014.6, p < 0.001). A statistically significant group-by-time interaction was detected (F = 3.32, p = 0.011), suggesting differential rates of gradient reduction between groups; however, none of the Bonferroni-corrected pairwise comparisons at individual timepoints reached statistical significance (all adjusted p > 0.30), indicating that the interaction was driven by subtle differences in trajectory shape rather than by large differences at specific timepoints (Fig. 1D, Table S1).

Heart rate trajectories also demonstrated a significant group-by-time interaction (F = 8.54, p < 0.001). The Transesophageal Echocardiography (TEE)-guided group exhibited a higher heart rate immediately after surgery compared with the No-Transesophageal Echocardiography (TEE) group (138.3 ± 14.4 versus 131.0 ± 23.0 beats per minute; p = 0.023). By one-year follow-up, however, this pattern reversed, with the Transesophageal Echocardiography (TEE) group demonstrating a significantly lower heart rate than the No- Transesophageal Echocardiography (TEE) group (119.6 ± 10.4 versus 125.5 ± 6.6 beats per minute; p = 0.006), possibly reflecting more complete hemodynamic optimization and reduced compensatory tachycardia in the Transesophageal Echocardiography (TEE)-guided patients (Fig. 1C, Table S1).

Systolic blood pressure changed significantly over time in both groups (F = 91.2, p < 0.001), reflecting normal growth-related increases, but showed no significant group effect (p = 0.36) and no group-by-time interaction (p = 0.62). A marginal difference between-group was noted only at the one-year timepoint (111.7 ± 6.5 versus 114.3 ± 5.9 millimeters of mercury; p = 0.05), the clinical relevance of which is uncertain (Table S1).

Clinical Outcomes and Adverse Events

Postoperative hospital length of stay was similar in both groups (9.6 ± 3.0 days in the Transesophageal Echocardiography (TEE) group versus 10.7 ± 4.3 days in the No- Transesophageal Echocardiography (TEE) group; p = 0.12) (Table S1). Crude rates of in-hospital mortality, surgical reoperation, residual ventricular septal leakage, and postoperative rhythm disturbances were statistically comparable between groups when analyzed as binary outcomes (all p > 0.30) (Table S2).

Valvular Regurgitation Over Time

Mitral regurgitation grade was comparable between the two groups immediately after repair (median 0 in both groups; p = 0.53) but diverged during follow-up. During six months, mitral regurgitation was significantly lower in the Transesophageal Echocardiography (TEE)-guided group (p < 0.001), and this difference persisted at one year (p < 0.001). Tricuspid regurgitation followed a similar pattern, with no significant difference immediately postoperatively but significant divergence emerging at six months (p = 0.04) and becoming more pronounced at one year (median grade 1 in the Transesophageal Echocardiography (TEE) group versus grade 2 in the No- Transesophageal Echocardiography (TEE) group; p < 0.001). Pulmonary regurgitation grade was comparable between groups immediately after repair (median grade 2 in both groups; p = 0.51) and remained similar at subsequent timepoints. Within the Transesophageal Echocardiography (TEE)-guided group, Friedman tests confirmed statistically significant within-group changes in both mitral regurgitation (χ^2 = 24.9, degrees of freedom = 3, p < 0.001) and tricuspid regurgitation grades (χ^2 = 111.1, degrees of freedom = 3, p < 0.001) across the four follow-up timepoints, indicating progressive improvement in valve function over time (Table S3).

Multivariable Logistic Regression Analysis

On multivariable logistic regression adjusting for weight, preoperative oxygen saturation, right ventricle–pulmonary artery (RV–PA) gradient, and history of prior palliation, Transesophageal Echocardiography (TEE) use was not an independent predictor of in-hospital mortality (adjusted odds ratio 0.47; 95% confidence interval 0.11 to 1.92; p = 0.30) or residual ventricular septal leakage (adjusted odds ratio 1.01; 95% confidence interval 0.49 to 2.09; p > 0.90). However, Transesophageal Echocardiography (TEE) use was independently associated with a significantly reduced risk of prolonged hospital stay defined as greater than 10 days (adjusted odds ratio 0.36; 95% confidence interval 0.16 to 0.79; p = 0.01), even after controlling baseline severity markers and the presence of postoperative complications (Table S4).

Propensity Score Matched Analysis

After nearest-neighbor propensity score matching with a caliper width of 0.2, adequate covariate balance was achieved between the matched groups. The key findings from the unmatched analysis were confirmed in the matched cohort. The Transesophageal Echocardiography (TEE)-guided group maintained significantly higher postoperative oxygen saturation (99.3 ± 1.2% versus 95.4 ± 15.0%; p < 0.001), higher ejection fraction on postoperative day 1 (62.0 ± 3.7%

versus 58.9 ± 7.1%; p < 0.001), and higher ejection fraction at six months (67.1 ± 4.3% versus 62.1 ± 5.4%; p < 0.001). Right ventricle–pulmonary artery (RV–PA) pressure gradients and postoperative length of stay remained statistically comparable between the matched groups at all timepoints (all p > 0.30), confirming that the findings were robust to adjustment for measured confounders (Table S5).

Survival Analysis

Over the one-year follow-up period, Kaplan-Meier analysis demonstrated consistently higher event-free survival probability in the Transesophageal Echocardiography (TEE)-guided group compared with the No-Transesophageal Echocardiography (TEE) group (Fig. 5). At one-year follow-up, 4 events occurred among 79 patients in the Transesophageal Echocardiography (TEE) group (5.1% event rate) compared with 7 events among 49 patients in the No-Transesophageal Echocardiography (TEE) group (14.3% event rate). The log-rank test indicated a trend toward improved event-free survival in the Transesophageal Echocardiography (TEE)-guided group that approached but did not reach conventional statistical significance ($\chi^2 = 3.20$, degrees of freedom = 1, p = 0.07) (Fig. 2).

On adjusted Cox proportional hazards regression, Transesophageal Echocardiography (TEE) guidance was associated with a 65% reduction in the hazard of death or major adverse events (hazard ratio 0.35; 95% confidence interval 0.10 to 1.21; p = 0.10) after controlling for weight, preoperative oxygen saturation, and preoperative right ventricle–pulmonary artery (RV–PA) gradient. None of the covariates reached independent statistical significance: weight (hazard ratio 0.97; 95% confidence interval 0.87 to 1.09; p = 0.70), preoperative oxygen saturation (hazard ratio 1.00; 95% confidence interval 0.94 to 1.05; p = 0.90), and right ventricle–pulmonary artery (RV–PA) gradient (hazard ratio 0.99; 95% confidence interval 0.93 to 1.05; p = 0.70). While the confidence interval for the Transesophageal Echocardiography (TEE) effect crosses unity, the consistent direction of the hazard ratio combined with the early and sustained separation of the Kaplan-Meier curves suggests a clinically meaningful survival benefit that warrants confirmation in larger prospective studies (Table S6).

Discussion

In this retrospective cohort study of 128 pediatric patients undergoing complete surgical repair of Tetralogy of Fallot (TOF), we found that intraoperative Transesophageal Echocardiography (TEE) guidance was associated with significantly higher postoperative oxygen saturation throughout the first year of follow-up, more rapid recovery of left ventricular ejection fraction at six months, less severe mitral and tricuspid regurgitation at medium-term follow-up, and a 64% reduction in the odds of prolonged hospital stay exceeding 10 days. Although crude event rates and hospital length of stay did not differ significantly between groups, adjusted analyses accounting for baseline differences and measured confounders revealed consistent benefits favoring the Transesophageal Echocardiography (TEE)-guided approach. These findings support the routine use of intraoperative Transesophageal Echocardiography (TEE) during Tetralogy of Fallot (TOF) repair to optimize immediate surgical outcomes and facilitate earlier hemodynamic recovery 23–26.

Our results are consistent with prior literature demonstrating that intraoperative Transesophageal Echocardiography (TEE) influences surgical decision-making in 10 to 15% of congenital cardiac procedures. In the landmark Mayo Clinic series of 1002 cases, Randolph and colleagues reported that Transesophageal Echocardiography (TEE) had major impact on patient care in 13.8% of procedures overall, with the highest impact rates observed during valve repairs and complex outflow tract reconstructions. A subsequent two-center observational study confirmed these findings and emphasized that surgical alterations were required in 12.7% of cases and medical management changes in an additional 19.4%. More recently, Jalilov and colleagues from our institution reported that intraoperative Transesophageal Echocardiography (TEE) during Tetralogy of Fallot (TOF) repair facilitated timely identification and correction of residual defects, reduced postoperative complications, and shortened intensive care unit stay. Our study extends these observations by demonstrating sustained hemodynamic benefits over one year of follow-up, including persistently higher oxygen saturation, accelerated ventricular functional recovery, and progressive reduction in atrioventricular valve regurgitation severity in the Transesophageal Echocardiography (TEE)-guided cohort.

The mechanisms underlying these benefits likely include more complete relief of right ventricular outflow tract obstruction, more precise closure of the ventricular septal defect without residual shunting or distortion of adjacent structures, earlier detection and surgical revision of suboptimal valve repairs, and better preservation of ventricular geometry and function through avoidance of prolonged bypass times associated with delayed recognition of residual lesions. The finding that ejection fraction diverged significantly at six months but converged by one year suggests that Transesophageal Echocardiography (TEE) guidance accelerates recovery but may not alter the ultimate functional ceiling, possibly because the No-Transesophageal Echocardiography (TEE) group eventually compensates through ventricular remodeling or because residual lesions in that group were minor enough to permit delayed recovery. Nevertheless, earlier recovery has clinical value in reducing postoperative morbidity, facilitating earlier hospital discharge, and improving short-term quality of life 27.

The reduction in prolonged hospital stay associated with Transesophageal Echocardiography (TEE) guidance is particularly notable from a health economics perspective. In resource-constrained settings where intensive care unit beds and pediatric cardiac surgical capacity are limited, strategies that safely reduce hospital length of stay by even one or two days can substantially increase surgical throughput and reduce per-patient costs. Our adjusted odds ratio of 0.36 for prolonged stay suggests that Transesophageal Echocardiography (TEE) guidance reduces the likelihood of extended hospitalization by approximately two-thirds after controlling baseline severity and complications, a clinically meaningful effect size that may justify the additional costs and expertise required for routine Transesophageal Echocardiography (TEE) implementation.

The trend toward improved event-free survival in the Transesophageal Echocardiography (TEE) -guided group, although not statistically significant in our relatively small sample, is hypothesis-generating and warrants further investigation. The hazard ratio of 0.35 with a confidence interval of 0.10 to 1.21 suggests substantial uncertainty in the magnitude of the effect, but the point estimate indicates a potentially large survival benefit. The Kaplan-Meier curves separated early in the postoperative period and remained divergent throughout follow-up, a pattern consistent with prevention of early deaths related to unrecognized residual lesions rather than late effects. Larger multicenter studies with greater statistical power will be required to definitively establish

whether Transesophageal Echocardiography (TEE) guidance confers a mortality benefit, but the direction and consistency of the association across multiple outcomes in our study are encouraging 28.

This study has several limitations. First, the retrospective design precludes causal inference, and unmeasured confounding may exist regarding surgeon characteristics (skill, risk tolerance) not captured by propensity matching. Second, modest single-center sample limits statistical power for rare outcomes and generalizability to institutions with different caseloads or expertise. Third, definitions of repair adequacy differed between groups (Transesophageal Echocardiography (TEE) criteria vs. clinical judgment), introducing measurement heterogeneity. Fourth, systematic data on specific Transesophageal Echocardiography (TEE) findings, return to bypass rates, and surgical modifications were not collected, limiting mechanistic insights. Fifth, follow-up beyond one year is needed to assess long-term reintervention rates and survival. Finally, cost-effectiveness analysis was not performed but is essential for policy recommendations, particularly in resource-limited settings 29.

Our findings support the routine use of intraoperative Transesophageal Echocardiography (TEE) during Tetralogy of Fallot (TOF) repair in centers where appropriately trained echocardiographers are available. The technology is safe even in small infants, and the consistent benefits observed across oxygen saturation, ventricular function, valve competence, and hospital length of stay justify the additional time and expertise required. Training programs in pediatric cardiac anesthesia and cardiology should prioritize advanced Transesophageal Echocardiography (TEE) education to ensure adequate workforce capacity for routine implementation.

Future research should address several key questions. First, prospective randomized controlled trials comparing Transesophageal Echocardiography (TEE)-guided repair with conventional management are needed to establish causality and quantify the magnitude of benefit with greater precision. While randomization may face ethical and practical challenges given the accumulating evidence favoring Transesophageal Echocardiography (TEE), equipoise may still exist in some settings. Second, multicenter studies pooling data from multiple institutions would increase statistical power for rare outcomes such as mortality and reintervention and would permit subgroup analyses to identify patient populations most likely to benefit from Transesophageal Echocardiography (TEE) guidance. Third, detailed mechanistic studies documenting the specific anatomical findings detected by Transesophageal Echocardiography (TEE), the frequency and nature of surgical revisions prompted by those findings, and the hemodynamic consequences of revision would clarify the causal pathway linking Transesophageal Echocardiography (TEE) use to improved outcomes. Fourth, cost-effectiveness analyses incorporating the costs of Transesophageal Echocardiography (TEE) equipment, echocardiographer training and time, additional operating room time, and savings from reduced hospital stay and complications are needed to guide resource allocation decisions in diverse healthcare systems. Finally, longer-term follow-up extending into adolescence and adulthood is required to determine whether early Transesophageal Echocardiography (TEE)-guided optimization translates into reduced need for reintervention, better exercise tolerance, and improved quality of life over the lifespan 28,30.

Conclusion

In conclusion, intraoperative transesophageal echocardiography guidance during complete surgical repair of Tetralogy of Fallot (TOF) was associated with higher postoperative oxygen saturation, more rapid ventricular functional recovery, less severe atrioventricular valve regurgitation, and shorter hospital stay in this retrospective cohort. These findings support the routine use of Transesophageal Echocardiography (TEE) during Tetralogy of Fallot (TOF) repair to optimize immediate surgical results and facilitate hemodynamic recovery, although prospective trials are needed to confirm causality and assess long-term outcomes.

Abbreviations

TEE
Transesophageal Echocardiography
TOF
Tetralogy of Fallot
RV
PA–Right ventricle–pulmonary artery (gradient/pressure)
SpO_2
Peripheral oxygen saturation
EF
Ejection fraction
VSD
Ventricular septal defect
RVOTO
Right ventricular outflow tract obstruction
ICU
Intensive care unit (in “intensive care unit stay”)
SD
Standard deviation (mean ± SD)
IQR
Interquartile range
OR
Odds ratio (adjusted odds ratio)

CI
Confidence interval (95% CI)
HR
Hazard ratio
STROBE
Strengthening the Reporting of Observational Studies in Epidemiology (guideline)

Declarations

Ethical Considerations

This study was approved by the Ethics Committee of Tashkent Medical Academy of the Republic of Uzbekistan on 5th February 2026 under #1/21-2294. The questionnaires were conducted anonymously, to ensure respondents' confidentiality. The study was conducted in accordance with the Declaration of Helsinki and national ethical guidelines.

Availability of Data

The data set used and analyzed in the current study is available from the corresponding author on reasonable request.

Authors' Contribution

G.M.J. and B.Y.U. conceived and designed the study. G.M.J., M.O.O., B.U.U., and A.S.Y. performed data collection and clinical data management. G.M.J. and B.F.K. performed the intraoperative TEE procedures and contributed to clinical interpretation. D.R.K. and S.M.K. contributed to echocardiographic assessment and data validation. U.K.M. and F.S.S supervised the statistical analysis, interpreted the results, and drafted the manuscript. All authors critically revised the manuscript for important intellectual content and approved the final version for submission.

Previous presentation in conferences: Not applicable

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IRB number: This study was approved by the institutional ethics committee of National Children's Medical Center under #NCMC/EC/001/02-2026, February 20, 2026.

Research registration number: Not applicable

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Figures

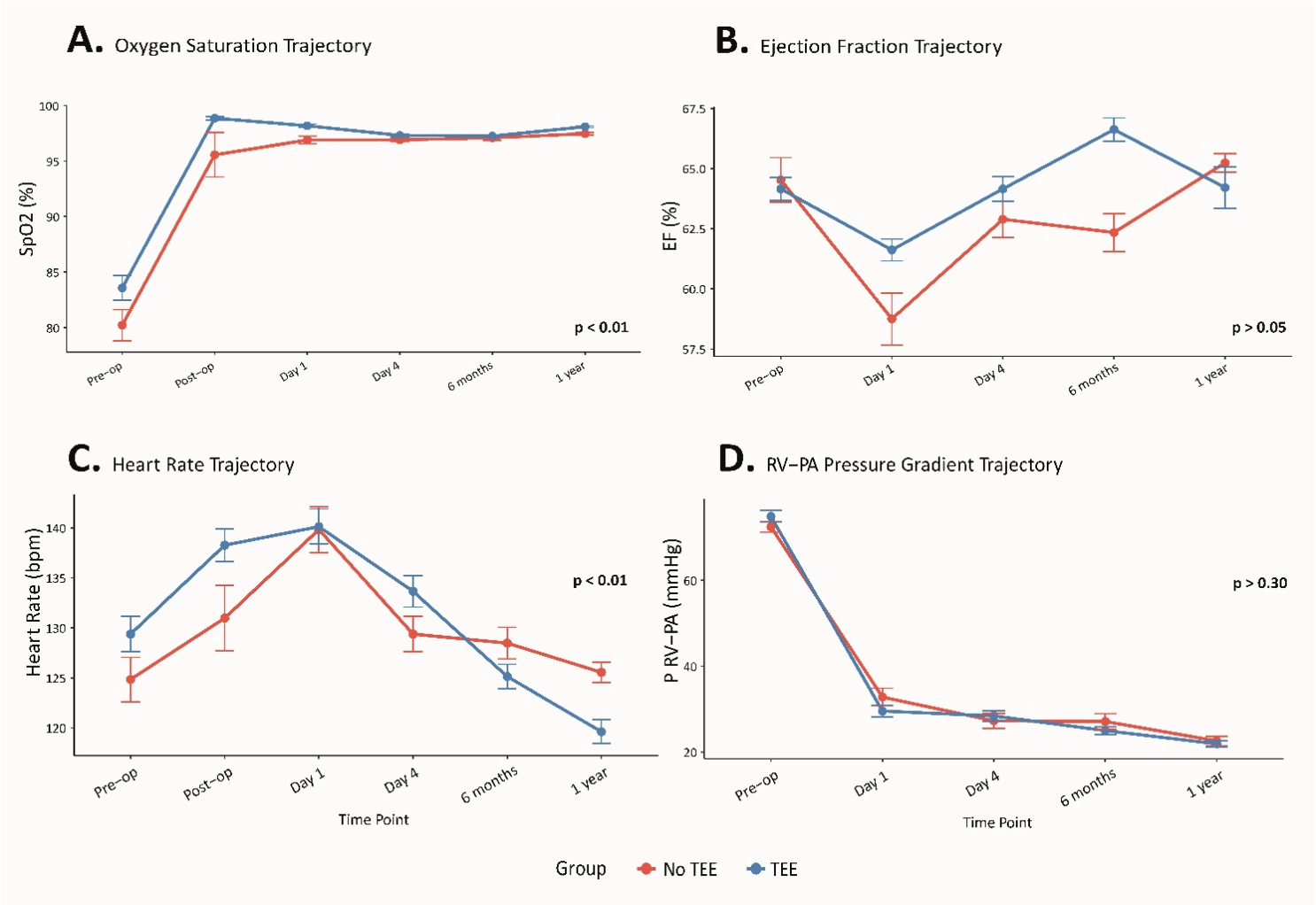


Figure 1

Trajectories of key cardiopulmonary parameters: oxygen saturation (A), ejection fraction (B), heart rate (C), and RV–PA pressure gradient (D).

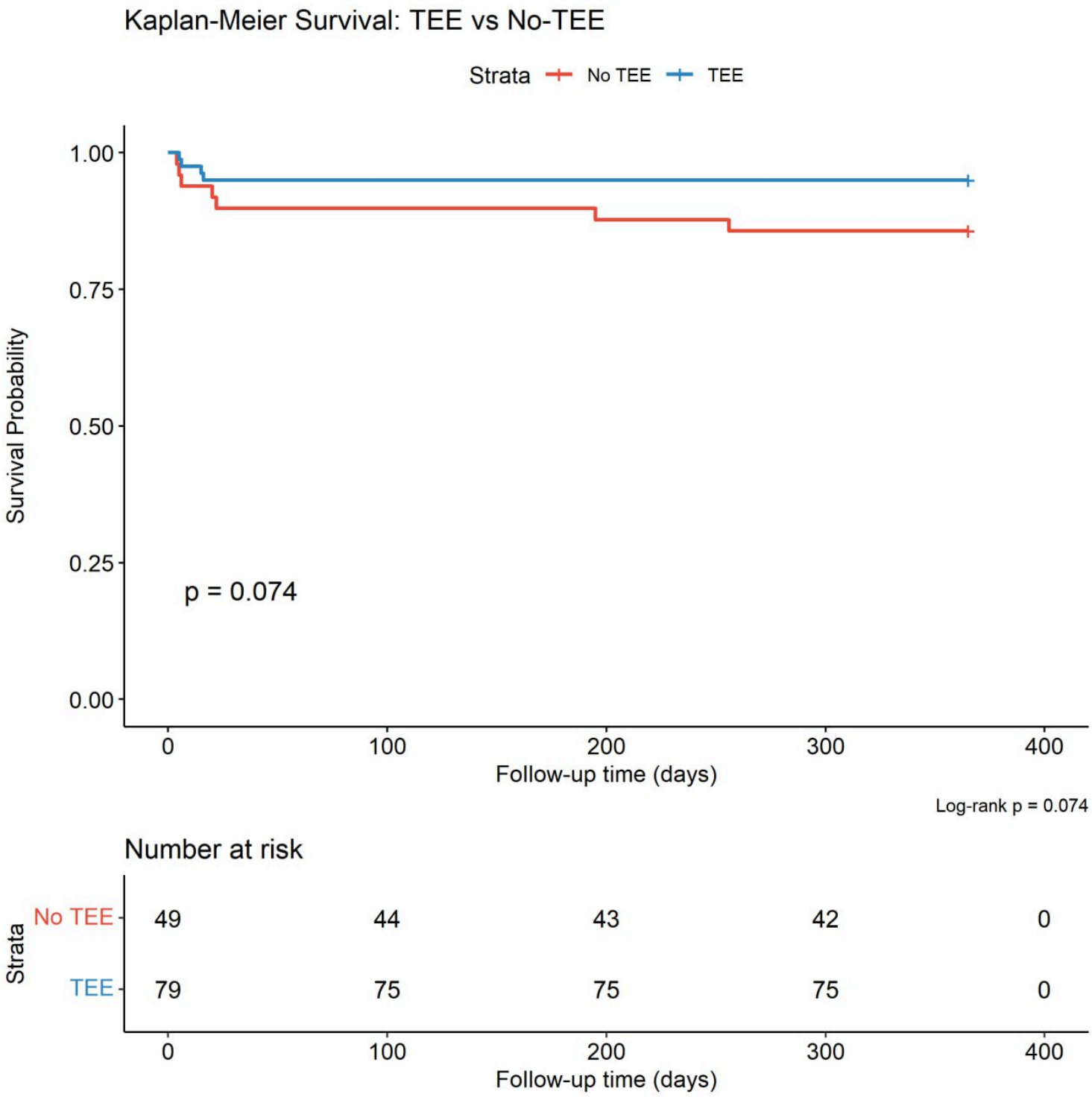


Figure 2

Kaplan–Meier estimates of overall survival in patients with and without Transesophageal Echocardiography (TEE)

Supplementary Files

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