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PREOPERATIVE CARDIAC CT ASSESSMENT OF THE PULMONARY ANNULUS AND RIGHT VENTRICULAR OUTFLOW TRACT IN TETRALOGY OF FALLOT: A RETROSPECTIVE STUDY WITH SURGICAL CORRELATION

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ABSTRACT

Background: Accurate preoperative characterization of the pulmonary valve annulus and right ventricular outflow tract (RVOT) is important in tetralogy of Fallot (TOF), particularly when assessing the likelihood of transannular enlargement at repair. Cardiac CT permits standardized multiplanar evaluation of pulmonary annular and RVOT morphology while simultaneously delineating pulmonary arterial, coronary, aortic arch, and collateral vascular anatomy.
Objective: To evaluate preoperative cardiac CT-derived pulmonary annular and RVOT parameters in TOF and assess their association with transannular patch (TAP) placement at definitive surgical repair.
Methods: This single-center retrospective observational study included all 26 eligible patients aged ≤10 years with TOF available in the institutional cardiac CT database between June 2025 and May 2026 who subsequently underwent complete surgical repair with documented TAP status. Pulmonary valve (PV) annular minimum and maximum diameters and area were measured on a standardized en-face double-oblique annular plane. PV Dmin Z-scores were derived using the CT-specific pediatric reference of Soszyn et al. with Haycock body surface area (BSA). The predefined principal CT variables were PV Dmin Z-score, PV-to-aortic annular minimum-diameter (PV/Ao Dmin) ratio, and minimum RVOT diameter. Operative TAP placement served as the surgical endpoint. Between-group comparisons and receiver operating characteristic (ROC) analysis with stratified bootstrap confidence intervals were performed. Multivariable modeling was not undertaken because of the limited sample size.
Results: Seventeen patients (65.4%) underwent TAP placement and nine (34.6%) underwent non-TAP repair. The TAP group had a smaller PV Dmin (10.10 ± 1.87 vs 12.19 ± 2.37 mm; $p=0.039$), a more negative PV Dmin Z-score (−2.51 ± 0.65 vs −1.50 ± 0.85; $p=0.008$), and a lower PV/Ao Dmin ratio (0.505 ± 0.065 vs 0.637 ± 0.049; $p<0.001$). Minimum RVOT diameter was smaller in the TAP group but did not differ significantly (5.28 ± 1.39 vs 6.17 ± 1.04 mm; $p=0.080$). PV/Ao Dmin ratio demonstrated the highest observed discrimination for TAP placement (AUC 0.961; 95% bootstrap CI 0.863–1.000), followed by PV Dmin Z-score (AUC 0.837) and minimum RVOT diameter (AUC 0.706).
Conclusion: Pulmonary annular hypoplasia on preoperative cardiac CT was associated with TAP placement. PV/Ao Dmin ratio and the CT-derived PV Dmin Z-score demonstrated the strongest discriminatory performance, whereas minimum RVOT diameter alone was less informative. Cardiac CT should be interpreted as an integrated quantitative and morphological tool supporting surgical planning rather than as a stand-alone operative decision method.

KEYWORDS: Tetralogy of Fallot; cardiac computed tomography; pulmonary valve annulus; right ventricular outflow tract; transannular patch; Z-score

INTRODUCTION

Tetralogy of Fallot (TOF) is characterized by ventricular septal defect, overriding of the aorta, right ventricular outflow tract (RVOT) obstruction, and secondary right ventricular hypertrophy. The severity and anatomical level of RVOT obstruction vary substantially and may involve the infundibulum, pulmonary valve, pulmonary annulus, supravalvar region, or multiple levels. Precise delineation of this anatomy is therefore central to preoperative assessment. Cardiac CT complements echocardiography by providing isotropic cross-sectional data for detailed multiplanar assessment of the RVOT, pulmonary arterial tree, aorta, coronary arterial course, and associated extracardiac vascular anatomy [1,2].
During complete repair, an important operative consideration is whether adequate relief of RVOT obstruction can be achieved while preserving the native pulmonary valve annulus or whether transannular patch (TAP) enlargement is performed. TAP effectively relieves significant annular obstruction but generally results in pulmonary regurgitation and may contribute to chronic right ventricular volume loading. Conversely, excessive emphasis on annular preservation may leave clinically relevant residual obstruction. Contemporary repair therefore aims to achieve adequate RVOT relief while preserving pulmonary valve competence when anatomically feasible [3,4].

Pulmonary annular Z-score is commonly used to quantify annular hypoplasia; however, proposed thresholds associated with TAP vary according to the normative dataset, measurement technique, patient population, pulmonary valve morphology, institutional practice, and surgical strategy [5,7,8]. Internally normalized indices such as the pulmonary-to-aortic annular ratio provide an alternative approach that reduces dependence on external body-size reference datasets, while area-based annular ratios may provide complementary characterization of annular geometry [3,9,10].
Cardiac CT is well suited to quantify these annular parameters while simultaneously demonstrating surgically relevant features such as the level of RVOT obstruction, pulmonary valve morphology, branch pulmonary arterial dimensions, coronary arteries crossing the RVOT, aortic arch sidedness, and systemic-to-pulmonary collateral arteries [1,2,11–13]. The present study therefore evaluates preoperative cardiac CT-derived pulmonary annular and RVOT parameters in children with TOF and examines their association with subsequent TAP placement while documenting additional cardiovascular anatomy relevant to operative planning.

Aim and Objectives
Aim
To evaluate preoperative cardiac CT-derived pulmonary annular and RVOT parameters in tetralogy of Fallot and assess their association with TAP placement at definitive surgical repair.

Objectives
1.To quantify pulmonary annular and RVOT dimensions on preoperative cardiac CT.
2.To compare predefined CT-derived pulmonary annular and RVOT parameters between TAP and non-TAP surgical groups.
3.To evaluate the discriminatory performance of PV Dmin Z-score, PV/Ao Dmin ratio, and minimum RVOT diameter for TAP placement.
4.To describe additional surgically relevant cardiovascular anatomy demonstrated by cardiac CT.

MATERIALS AND METHODS
Study Design and Population
This single-center retrospective observational study was conducted in the Department of Radiodiagnosis, Narayan Medical College and Hospital (NMCH), Sasaram, Bihar, India. Institutional cardiac CT records were reviewed for the period from June 2025 to May 2026. A total of 26 patients aged ≤10 years with TOF were available in the institutional cardiac CT database during this period, and all patients fulfilling the eligibility criteria were included.
Patients were eligible if they had confirmed TOF, diagnostic-quality preoperative cardiac CT suitable for pulmonary annular and RVOT assessment, subsequently underwent complete surgical repair, and had clear operative documentation regarding TAP placement. The age restriction was applied to maintain a relatively homogeneous pediatric surgical cohort.
Exclusion criteria were CT image quality inadequate for reliable annular or RVOT assessment, previous surgical or catheter-based intervention materially altering native RVOT or pulmonary arterial anatomy, unavailable or unclear operative documentation regarding TAP placement, or missing anthropometric data required for normalized measurements. No additional eligible cases were available during the predefined study period.
Age at CT was recorded in months. Sex, height, and weight were documented, and BSA was calculated using the Haycock formula: BSA (m^2) = 0.024265 × height (cm)^0.3964 × weight (kg)^0.5378.
Institutional Ethics Committee approval was obtained for retrospective analysis of the data. The requirement for individual informed consent was waived because of the retrospective study design.

Cardiac CT Acquisition and Reconstruction
All examinations were performed on a 128-slice SOMATOM go.Top CT system using an ECG-synchronized pediatric institutional cardiac CT angiography protocol.
Acquisition parameters were individualized according to patient size, heart rate, clinical indication, and image-quality requirements in accordance with pediatric cardiac CT dose-optimization principles. Low tube-voltage acquisition, generally within the 70–100 kVp range in appropriately sized pediatric patients, and automatic tube-current modulation were used where feasible. The shortest practical gantry rotation time and restricted craniocaudal scan coverage were employed to minimize motion and radiation exposure. ECG synchronization was used to reduce cardiac motion and facilitate assessment of the pulmonary annulus, RVOT, and coronary arterial anatomy [14,15].
Nonionic iodinated contrast material was administered intravenously, with contrast volume and injection rate individualized according to body size and intravenous access. Scan timing was optimized to achieve diagnostic opacification of the cardiac chambers and great vessels relevant to congenital cardiac assessment; a saline flush was used when technically feasible.
Thin-section axial images were reconstructed using the available iterative reconstruction algorithm. Multiplanar reformations (MPR), including dedicated double-oblique reconstructions, were used for quantitative measurements. Maximum-intensity-projection (MIP) and three-dimensional volume-rendered technique (VRT) images were used for anatomical visualization and surgical orientation; quantitative measurements were not obtained from VRT images.
CT Image Analysis and Measurements
CT datasets were retrospectively reviewed using multiplanar reconstruction. Measurements were obtained perpendicular to the long axis of the relevant cardiovascular structure or on dedicated double-oblique annular planes to minimize obliquity-related measurement error.
Pulmonary Valve Annulus

The pulmonary valve annulus was localized at the basal leaflet hinge points. A standardized en-face annular plane perpendicular to the pulmonary root was reconstructed. Minimum pulmonary annular diameter (PV Dmin), maximum pulmonary annular diameter (PV Dmax), and cross-sectional annular area by direct planimetry were recorded. PV Dmin was predefined as the principal linear pulmonary annular measurement.

Pulmonary valve morphology was assessed when leaflet visualization was considered diagnostic and categorized as tricuspid, bicuspid, unicuspid, dysplastic/other, or indeterminate when confident morphological classification was not possible.

Pulmonary Annular Z-score

Pulmonary valve annular minimum-diameter Z-scores were calculated using the published CT-derived pediatric normative equation of Soszyn et al. [5]. Body surface area was calculated using the Haycock formula, and the minimum-diameter equation was applied consistently to PV Dmin measurements throughout the cohort. The subsequently published corrigendum was reviewed and incorporated where applicable.[6] Because published Z-scores depend on the normative population and measurement methodology, these values were interpreted specifically within the Soszyn CT-derived reference framework.

Aortic Annulus and Normalized Annular Ratios

The aortic annulus was reconstructed on an analogous en-face double-oblique plane. Minimum diameter (Ao Dmin), maximum diameter (Ao Dmax), and cross-sectional area were recorded. PV/Ao Dmin ratio was calculated as PV Dmin/Ao Dmin, and PV/Ao area ratio as pulmonary annular area/aortic annular area. The PV/Ao Dmin ratio was predefined as a principal normalized annular parameter.

Right Ventricular Outflow Tract

Minimum RVOT diameter was measured at the narrowest identifiable portion of the outflow tract on an appropriately oriented long-axis MPR and was predefined as the principal RVOT measurement. The dominant anatomical level of obstruction was categorized as infundibular/subvalvar, valvar, supravalvar, multilevel, or indeterminate.

Pulmonary Arteries and Descending Aorta

Main pulmonary artery (MPA), right pulmonary artery (RPA), and left pulmonary artery (LPA) diameters were measured perpendicular to the respective vessel axes. Branch pulmonary arterial cross-sectional areas were obtained by direct planimetry when available or calculated using a circular approximation when this method had been used in the retrospective dataset.

The Nakata index was calculated as (RPA cross-sectional area + LPA cross-sectional area)/BSA. The descending thoracic aortic diameter (DAO) was measured perpendicular to the vessel axis at a comparable distal thoracic level above the diaphragmatic hiatus. The McGoon ratio was calculated as (RPA diameter + LPA diameter)/DAO diameter, and PV/DAO ratio as PV Dmin/DAO diameter.

Additional Surgically Relevant Anatomy

Coronary arterial origin and proximal course were systematically assessed, with particular attention to a major coronary artery or large conal branch crossing the RVOT. Additional findings documented included aortic arch sidedness, major aortopulmonary collateral arteries (MAPCAs), patent ductus arteriosus (PDA), branch pulmonary arterial stenosis or hypoplasia, and other relevant cardiovascular anomalies.

Variable Hierarchy and Surgical Correlation

The predefined principal CT variables were PV Dmin Z-score, PV/Ao Dmin ratio, and minimum RVOT diameter. PV/Ao area ratio and PV/DAO ratio were treated as secondary exploratory normalized indices. Pulmonary valve morphology, level of RVOT obstruction, pulmonary arterial dimensions and indices, coronary anatomy, aortic arch sidedness, ductal anatomy, and MAPCAs were evaluated primarily as surgically relevant anatomical variables. Operative TAP placement, categorized as yes or no from the surgical record, served as the reference surgical endpoint.

Statistical Analysis

Continuous variables were examined for distributional characteristics and summarized as mean ± standard deviation when approximately normally distributed and median with interquartile range when non-normally distributed. Distribution was assessed using graphical inspection and appropriate tests of normality where applicable.

Between-group comparisons were performed using the independent-samples Student t test or Welch t test where appropriate for normally distributed continuous variables and the Mann–Whitney U test for non-normally distributed variables. Categorical variables were summarized as frequencies and percentages. Where inferential comparison was clinically relevant and cell counts permitted, the chi-square test, Fisher exact test, or an exact extension for multicategory contingency tables was used.

Receiver operating characteristic curves were generated for the three predefined principal continuous CT variables using TAP placement as the positive surgical outcome. AUCs and 95% confidence intervals were estimated using stratified bootstrap resampling with 5,000 resamples.

Exploratory thresholds maximizing the Youden index were derived from the same study cohort. Consequently, corresponding sensitivity and specificity estimates were considered internally derived and hypothesis-generating rather

than externally validated clinical thresholds. Sensitivity and specificity were reported with exact binomial 95% confidence intervals. Secondary exploratory ROC analyses were performed for PV/Ao area ratio and PV/DAO ratio.
Given the limited cohort size and number of outcome events, multivariable predictive modeling was not undertaken to minimize overfitting. The analysis therefore focused on between-group associations and exploratory discrimination rather than independent prediction. A two-sided p value <0.05 was considered statistically significant for the principal analyses. No formal multiplicity correction was applied to secondary exploratory comparisons, which were interpreted as hypothesis-generating.

RESULTS

Study Population

The study cohort comprised 26 children with TOF, of whom 17 (65.4%) underwent TAP placement and nine (34.6%) underwent non-TAP repair.
Overall, 14/26 (53.8%) patients were male. Sex distribution did not differ significantly between the TAP and non-TAP groups (7/17 [41.2%] vs 7/9 [77.8%]; Fisher exact p=0.110). Age, height, weight, and BSA were also comparable between the two groups.

Pulmonary Annular and RVOT Measurements

Patients undergoing TAP placement demonstrated smaller pulmonary annular dimensions. Mean PV Dmin was 10.10 ± 1.87 mm in the TAP group compared with 12.19 ± 2.37 mm in the non-TAP group (p=0.039). PV Dmin Z-score was significantly more negative in the TAP group (−2.51 ± 0.65 vs −1.50 ± 0.85; p=0.008).
The strongest between-group difference among the predefined principal variables was observed for PV/Ao Dmin ratio, which was significantly lower in patients undergoing TAP placement (0.505 ± 0.065 vs 0.637 ± 0.049; p<0.001). Minimum RVOT diameter was smaller in the TAP group (5.28 ± 1.39 vs 6.17 ± 1.04 mm), although the difference did not reach statistical significance (p=0.080).
Secondary normalized annular parameters showed a concordant pattern. PV/Ao area ratio was lower in the TAP group (0.270 ± 0.076 vs 0.414 ± 0.065; p<0.001), as was PV/DAO ratio (0.664 ± 0.122 vs 0.827 ± 0.133; p=0.008). Nakata index and McGoon ratio did not differ significantly between groups.

Table 1. Comparison of principal and selected secondary CT-derived parameters between TAP and non-TAP groups.

Parameter	TAP (n=17)	Non-TAP (n=9)	p value
Age at CT, months	58.82 ± 33.40	59.78 ± 27.81	0.939
Sex, male, n (%)	7 (41.2%)	7 (77.8%)	0.110*
Height, cm	102.11 ± 16.60	102.72 ± 14.44	0.924
Weight, kg	18.16 ± 5.34	17.81 ± 4.85	0.869
BSA, m^2	0.719 ± 0.160	0.714 ± 0.143	0.930
PV Dmin, mm	10.10 ± 1.87	12.19 ± 2.37	0.039
PV Dmin Z-score (Soszyn CT)	−2.51 ± 0.65	−1.50 ± 0.85	0.008
PV/Ao Dmin ratio	0.505 ± 0.065	0.637 ± 0.049	<0.001
PV/Ao area ratio	0.270 ± 0.076	0.414 ± 0.065	<0.001
PV/DAO ratio	0.664 ± 0.122	0.827 ± 0.133	0.008
Minimum RVOT diameter, mm	5.28 ± 1.39	6.17 ± 1.04	0.080
Nakata index, mm^2/m^2	164.79 ± 47.11	148.35 ± 47.83	0.414
McGoon ratio	1.10 ± 0.09	1.08 ± 0.20	0.757

Values are mean ± SD unless otherwise indicated. *Fisher exact test. PV Dmin Z-score, PV/Ao Dmin ratio, and minimum RVOT diameter were predefined principal CT variables; PV/Ao area ratio and PV/DAO ratio were secondary exploratory indices.

Figure 1. Representative preoperative cardiac CT morphometry in TOF according to subsequent surgical repair strategy. (A–C) TAP case: (A) MPA, RPA, LPA, and descending thoracic aortic measurements, with marked LPA narrowing; (B) en-face pulmonary valve annulus demonstrating a minimum diameter of 7.31 mm and area of 0.45 cm²; and (C) en-face aortic annulus demonstrating a minimum diameter of 23.03 mm, yielding a PV/Ao Dmin ratio of 0.32. (D–F) Non-TAP case with right-sided aortic arch: (D) MPA, RPA, LPA, and descending thoracic aortic measurements, with a MAPCA arising from the descending thoracic aorta; (E) en-face pulmonary valve annulus demonstrating a minimum diameter of 14.28 mm and area of 1.91 cm²; and (F) en-face aortic annulus demonstrating a minimum diameter of 25.20 mm, yielding a PV/Ao Dmin ratio of 0.57.

ROC Analysis

Among the three predefined principal CT variables, PV/Ao Dmin ratio demonstrated the highest observed discrimination for TAP placement, with an AUC of 0.961 (95% bootstrap CI 0.863–1.000). PV Dmin Z-score demonstrated an AUC of 0.837 (95% bootstrap CI 0.641–0.980), whereas minimum RVOT diameter demonstrated more modest discrimination with an AUC of 0.706 (95% bootstrap CI 0.490–0.902).

The internally derived Youden thresholds were ≤0.571 for PV/Ao Dmin ratio, ≤−2.43 for PV Dmin Z-score, and ≤5.82 mm for minimum RVOT diameter. Secondary exploratory ROC analysis yielded an AUC of 0.941 (95% bootstrap CI 0.817–1.000) for PV/Ao area ratio and 0.810 (95% bootstrap CI 0.588–0.974) for PV/DAO ratio.

Table 2. ROC performance of CT-derived parameters for TAP placement.

Parameter	AUC	Bootstrap 95% CI	Exploratory cutoff	Sensitivity (95% CI)	Specificity (95% CI)
PV/Ao Dmin ratio	0.961	0.863–1.000	≤0.571	94.1% (71.3–99.9)	100% (66.4–100)
PV Dmin Z-score	0.837	0.641–0.980	≤−2.43	70.6% (44.0–89.7)	88.9% (51.8–99.7)
Minimum RVOT diameter	0.706	0.490–0.902	≤5.82 mm	70.6% (44.0–89.7)	77.8% (40.0–97.2)
PV/Ao area ratio†	0.941	0.817–1.000	≤0.327	88.2% (63.6–98.5)	100% (66.4–100)
PV/DAO ratio†	0.810	0.588–0.974	≤0.718	76.5% (50.1–93.2)	88.9% (51.8–99.7)

†Secondary exploratory analysis. Lower values were associated with TAP placement. Youden thresholds were derived and evaluated within the same study cohort and should not be interpreted as externally validated operative cutoffs.

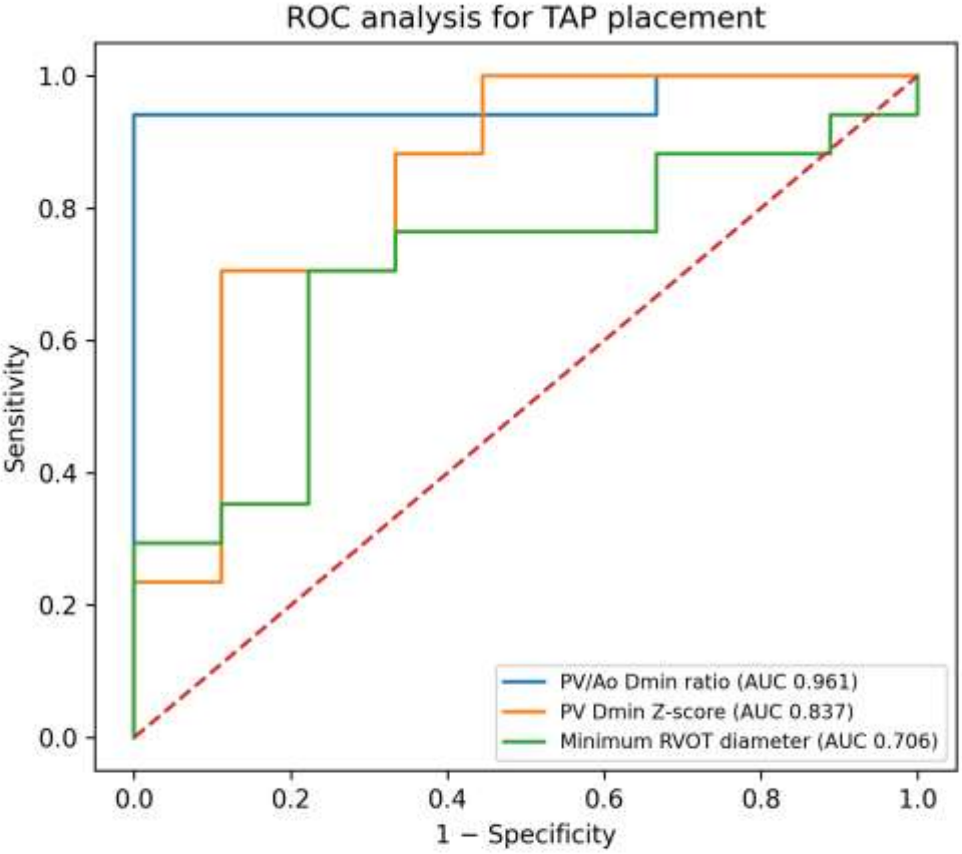

Figure 2. Receiver operating characteristic curves for the three predefined principal CT variables for discrimination of TAP placement. PV/Ao Dmin ratio demonstrated the highest observed AUC, followed by PV Dmin Z-score and minimum RVOT diameter.

Surgically Relevant CT Anatomy

Beyond quantitative annular and RVOT assessment, cardiac CT demonstrated several anatomical features relevant to operative planning. Multilevel RVOT obstruction was present in 7/26 patients, and bicuspid pulmonary valve morphology was identified in 9/26. A major coronary artery or large conal branch crossing the RVOT was identified in 3/26 patients. A right-sided aortic arch was present in 6/26 patients, MAPCAs in 3/26, and PDA in 3/26.

Because of the small number of observations within individual anatomical categories, these findings were treated descriptively and were not interpreted as independent predictors of TAP placement.

DISCUSSION

This retrospective study evaluated pulmonary annular and RVOT measurements obtained from preoperative cardiac CT in children with TOF and correlated them with subsequent TAP placement. The principal finding was that TAP repair was associated with greater pulmonary annular hypoplasia. Among the predefined CT parameters, PV/Ao Dmin ratio demonstrated the highest observed discriminatory performance, followed by the CT-derived PV Dmin Z-score. Minimum RVOT diameter alone showed weaker discrimination and was not significantly different between surgical groups.

The finding for PV/Ao Dmin ratio is consistent with previous surgical literature examining pulmonary-to-aortic annular relationships. Choi et al. reported a lower great-artery annular ratio in patients undergoing transannular enlargement, with values of approximately 0.51 compared with 0.67 in patients undergoing annulus-preserving repair and an AUC of 0.900; their reported optimal ratio was 0.56 [3]. Lyu et al. subsequently reported a cutoff of approximately 0.55 with an AUC of 0.85 [10]. In the present cohort, the corresponding ratio was 0.505 in the TAP group and 0.637 in the non-TAP group, with an internally derived threshold of 0.571. The similarity in direction and magnitude supports the potential value of assessing pulmonary annular dimensions relative to aortic annular size rather than relying solely on absolute pulmonary annular diameter.

An internally normalized ratio also has a practical advantage for CT assessment because both pulmonary and aortic annuli can be measured from the same examination using comparable double-oblique multiplanar techniques. Unlike a BSA-derived Z-score, the PV/Ao ratio does not depend on an external normative dataset. Nevertheless, the AUC of 0.961 observed in this study requires cautious interpretation. The exploratory threshold of ≤0.571 produced a sensitivity of 94.1% and apparent specificity of 100%; however, the latter estimate was derived from only nine non-TAP patients and had a wide 95% confidence interval. The threshold should therefore be regarded as hypothesis-generating rather than as a clinical decision boundary.

PV Dmin Z-score provided complementary body-size-normalized assessment. Patients undergoing TAP had significantly more negative Z-scores, and the parameter demonstrated good discrimination. An advantage of the present methodology was the consistent use of a CT-derived pediatric reference rather than application of an echocardiographic nomogram to CT measurements. Soszyn et al. established CT-derived normative pulmonary annular measurements and Z-scores [5], with a subsequent corrigendum addressing reference values for selected parameters [6].

However, pulmonary annular Z-scores require careful interpretation across studies. Awori et al. demonstrated that different normative datasets may yield materially different Z-scores for the same anatomical measurement [7], while the systematic review by Sinha et al. found no universally accepted preoperative Z-score threshold for successful valve-sparing TOF repair [8]. The exploratory value of ≤−2.43 observed in this study should therefore be interpreted only in relation to the Soszyn CT-derived reference and should not be directly equated with thresholds derived from echocardiographic datasets.

The secondary PV/Ao area ratio showed a similar association with TAP placement and strong exploratory discrimination. Zhao et al. likewise reported lower pulmonary-to-aortic annular area ratios in patients receiving TAP [9]. Diameter- and area-based ratios, however, describe closely related components of annular geometry and are likely correlated. Their concordant performance in the present cohort therefore strengthens the anatomical observation of pulmonary annular hypoplasia but does not establish independent or incremental predictive value. The secondary PV/DAO ratio was also lower in the TAP group, although its discriminatory performance was less pronounced than that of PV/Ao Dmin ratio; it may therefore serve as an additional normalized morphometric parameter but does not appear to offer an advantage over direct pulmonary-to-aortic annular normalization in this dataset.

In contrast, minimum RVOT diameter alone was less discriminatory. This is anatomically plausible because RVOT obstruction in TOF is not adequately represented by a single linear measurement. Obstruction may arise from varying combinations of infundibular hypertrophy, pulmonary valve abnormality, annular hypoplasia, and supravalvar narrowing, while the infundibular component may also have a dynamic component. Minimum RVOT diameter remains useful as part of structured CT assessment but should not be interpreted independently of the overall morphology.

This distinction between morphometry and morphology is particularly relevant to surgical planning. Feasibility of pulmonary valve preservation depends not only on annular dimensions but also on pulmonary valve cusp morphology, commissural configuration, infundibular anatomy, and the distribution of outflow obstruction. Choi et al. demonstrated the importance of pulmonary valve morphology in determining valve-preserving surgical strategy [11]. Thus, the absence of statistically testable associations for individual morphological variables in a small cohort should not be interpreted as absence of clinical importance.

Similarly, Nakata index and McGoon ratio did not differ significantly between TAP and non-TAP groups. This suggests that the principal morphometric distinction in the present cohort was concentrated at the pulmonary annulus rather than representing generalized branch pulmonary arterial hypoplasia. Branch pulmonary arterial dimensions remain important, however, because stenosis, asymmetry, or hypoplasia may independently influence operative reconstruction.

Cardiac CT also provided information beyond quantitative assessment of the pulmonary annulus. A major coronary artery or large conal branch crossing the RVOT was identified in three patients. Recognition of such anatomy is critical because it may influence the location and extent of ventriculotomy or require an alternative RVOT reconstruction strategy. Goo reported high concordance between preoperative cardiac CT and surgical findings for coronary anatomy in children with TOF or Fallot-type double-outlet right ventricle [12]. A meta-analysis by Koppel et al. further demonstrated that anomalous coronary arteries or large conal branches crossing the RVOT are clinically relevant in a meaningful minority of TOF patients [13].

The value of cardiac CT in TOF should therefore not be reduced to a single annular measurement. When CT is clinically indicated, a single examination can provide standardized evaluation of the pulmonary annulus and RVOT while simultaneously defining the pulmonary arteries, coronary course, aortic arch, PDA, and MAPCAs. The present study was not designed to compare CT with echocardiography and should not be interpreted as demonstrating superiority of CT. Rather, it illustrates the quantitative and anatomical information that can be derived from appropriately performed preoperative cardiac CT.

The objective of preoperative assessment is also not simply to predict or avoid TAP. TAP provides effective relief of substantial annular obstruction but may result in chronic pulmonary regurgitation, whereas overly restrictive valve preservation may leave significant residual stenosis. Blais et al. demonstrated important long-term differences between valve-sparing and TAP strategies while emphasizing the balance between pulmonary regurgitation and residual obstruction [4]. Preoperative imaging should therefore contribute to individualized surgical planning rather than dictate a predetermined operative technique.

Several limitations should be acknowledged. First, this was a retrospective single-center study with only 26 patients, which limits statistical precision and external generalizability. The wide confidence intervals surrounding several ROC estimates reflect this limitation. Second, only patients who underwent preoperative cardiac CT and subsequently had complete repair with documented TAP status were included, which may introduce referral and selection bias and limits extrapolation to the entire TOF population. Third, TAP placement is a multifactorial surgical endpoint influenced by annular size, pulmonary valve morphology, infundibular anatomy, intraoperative inspection, response to muscle resection or valvotomy, residual gradients, and surgeon-specific practice. CT measurements therefore cannot independently determine operative strategy.

Fourth, multivariable modeling was intentionally avoided because of the limited sample size and number of outcome events; the study demonstrates association and discrimination rather than independent prediction. Fifth, the secondary analyses were exploratory, no formal correction for multiple comparisons was performed, and ROC thresholds were both derived and evaluated within the same cohort. Their performance may consequently be optimistic and requires external validation in larger cohorts. Sixth, direct quantitative comparison with echocardiographic or intraoperative annular measurements was unavailable. Formal interobserver and intraobserver reproducibility analysis was also not performed. Seventh, retrospective branch pulmonary artery area measurements were obtained by direct planimetry when available or by circular approximation, introducing potential methodological variability in derived pulmonary arterial indices. Finally, differences in acquisition and cardiac-phase sampling between the Soszyn normative cohort and the present ECG-synchronized CT examinations may influence absolute Z-score values, particularly at the extremes of body size [5].

Despite these limitations, the concordant behavior of multiple pulmonary annular measurements provides a consistent anatomical signal. The findings suggest that standardized pulmonary annular assessment—particularly PV/Ao Dmin ratio and CT-derived PV Dmin Z-score—may help characterize the likelihood of annular enlargement at subsequent repair, while assessment of the RVOT, pulmonary valve, pulmonary arteries, coronary arteries, arch anatomy, and collateral vessels provides the broader anatomical context required for operative planning.

CONCLUSION

Preoperative cardiac CT provides comprehensive quantitative and anatomical assessment of the pulmonary annulus and RVOT in children with tetralogy of Fallot. Pulmonary annular hypoplasia was associated with subsequent TAP placement. Among the predefined principal CT variables, PV/Ao Dmin ratio demonstrated the highest observed discriminatory performance, followed by the Soszyn CT-derived PV Dmin Z-score, whereas minimum RVOT diameter alone was less informative.

A structured cardiac CT assessment should integrate pulmonary annular dimensions and Z-score, PV/Ao ratio, pulmonary valve morphology, level and extent of RVOT obstruction, main and branch pulmonary arterial anatomy, coronary arterial course, and relevant aortic arch and collateral vascular abnormalities. These findings provide anatomical information relevant to planning valve-preserving versus transannular repair; however, no single CT-derived measurement or threshold should be used as an operative decision rule. Definitive surgical strategy remains dependent on integrated preoperative and intraoperative assessment.

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