Computed tomography for evaluating right ventricle and pulmonary artery in pediatric tetralogy of Fallot: correlation with post-operative pulmonary regurgitation

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Pulmonary regurgitation (PR) is the most common complication after tetralogy of Fallot (TOF) surgical repair, and long-term PR might result in cardiovascular events. The aim of this study was to assess the influence of pre-operative right ventricle (RV) and pulmonary artery (PA) parameters assessed by dual-source computed tomography on post-operative PR. A total of 41 TOF patients who underwent trans-valve surgical repair were retrospectively recruited. The RV and PA parameters evaluated by pre-operative DSCT were compared between the PR and non-PR groups. Our result revealed that the PA parameters (McGoon ratio, Nakata index, and LPA diameter) and RV parameters (RV length diameter and RV short diameter) all showed significant differences between the two groups (all p < 0.05). There was a significant correlation between PR and LPA diameter (r = 0.361), McGoon ratio (r = 0.413), and Nakata index (r = 0.482). Receiver operating characteristic analysis also revealed a moderate sensitivity and specificity of LPA (66.33%; 82.60%), McGoon ratio (83.33%, 56.52%), and Nakata index (83.33%; 60.87%) for predicting the occurrence of PR. This study indicated that these pre-operative indices calculated by DSCT are associated with post-operative PR and that these pre-operative PA and RV parameters may serve as novel predictors of the risk of PR.
**Table 1.** Baseline characteristics of TOF patients. Note: Data given as the mean ± SD; TOF, tetralogy of Fallot; PR, pulmonary regurgitation. *P < 0.05.

|                         | PR (n = 20) | non-PR (n = 35) | P value |
|-------------------------|------------|-----------------|---------|
| Age, y                  | 1.58 ± 1.12| 1.74 ± 1.45     | 0.665   |
| Male gender, n          | 10(50%)    | 19(54.3%)       | 0.803   |
| Body surface area, m²   | 0.46 ± 0.96| 0.47 ± 0.11     | 0.734   |
| Heart rate, bpm         | 128.75 ± 21.36| 127.31 ± 15.70 | 0.776   |
| Systolic pressure, mmHg| 95.80 ± 13.45| 95.58 ± 21.87   | 0.967   |
| Diastolic pressure, mmHg| 53.70 ± 8.55| 57.76 ± 17.25   | 0.332   |
| Height, cm              | 73.48 ± 2.637| 73.44 ± 7.40    | 0.982   |
| Weight, kg              | 9.41 ± 2.11| 10.27 ± 3.18    | 0.248   |
| Trans-valve surgery, n  | 18(90%)    | 23(65.7%)       | 0.027*  |

**Table 2.** Measurements of right ventricular and pulmonary artery by DSCT compared to post-operative pulmonary regurgitation in patients with trans-valve surgery. Note: Data given as the mean ± SD. RV, Right ventricle; MPA, main pulmonary artery; LPA, left pulmonary artery; RPA, right pulmonary artery. *P < 0.05; **P < 0.01.

|                         | RV (n = 18) | non-PR (n = 23) | Independent t test (p) | Spearman coefficient (r) |
|-------------------------|------------|-----------------|------------------------|--------------------------|
| **Right Ventricle**     |            |                 |                        |                          |
| RVLD, mm/m²             | 60.64 ± 15.47| 72.64 ± 14.95   | 0.004                  | −0.457**                 |
| RVSD, mm/m²             | 34.89 ± 6.50| 39.48 ± 7.60    | 0.031                  | −0.341*                  |
| RV wall thickness, mm/m²| 18.61 ± 3.35| 18.88 ± 3.88    | 0.478                  | −0.112                   |
| RVOT diameter, mm/m²    | 9.51 ± 3.63 | 10.06 ± 4.52    | 0.958                  | 0.008                    |
| RVOT length, mm/m²      | 26.50 ± 10.11| 23.42 ± 9.06    | 0.358                  | 0.145                    |
| **Pulmonary Artery**    |            |                 |                        |                          |
| MPA, mm/m²              | 21.88 ± 6.96| 21.63 ± 7.79    | 0.834                  | −0.033                   |
| LPA, mm/m²              | 20.96 ± 5.99| 15.89 ± 5.96    | 0.022                  | 0.361**                  |
| RPA, mm/m²              | 17.88 ± 5.44| 16.56 ± 4.60    | 0.885                  | 0.023                    |
| Nakata index, mm²/m²    | 391.29 ± 137.39| 268.60 ± 77.63 | 0.002                  | 0.482**                  |

**Results**

**Patient characteristics.** A total of 55 patients who did not pre-operative PR were enrolled in the study, these included 20 patients in whom post-operative PR was confirmed by TTE and 35 patients who did not have postoperative PR. Of the 55 patients, there were 41 patients had received trans-valve surgery. In the post-operative PR group, 18 patients had received trans-valve surgery (90.0%), and in the non-PR group, 23 patients had received trans-valve surgery.

The demographic and clinical data for patients with or without PR are as given below: age (1.58 ± 1.12 years vs. 1.74 ± 1.45 years; p = 0.665), systolic pressure (95.80 ± 13.45 mmHg vs. 95.58 ± 21.87 mmHg; p = 0.967), and diastolic pressure (53.70 ± 8.55 mmHg vs. 57.76 ± 17.25 mmHg; p = 0.33) (Table 1).

**Measurements of RV and PA in patients with trans-valve surgery.** The 41 patients who had received trans-valve surgery were further divided into PR and non-PR groups. The PA parameters including Nakata index (391.29 ± 137.39 mm²/m² vs. 268.60 ± 77.63 mm²/m²; p < 0.0001), and left pulmonary artery (LPA) diameter (20.96 ± 5.99 mm/m² vs. 15.89 ± 5.96 mm/m²; p < 0.05) in the PR group were significantly higher compared with those in the non-PR group. No significant statistical difference was observed with respect to MPA (21.88 ± 6.96 mm/m² vs. 21.63 ± 7.79 mm/m²) and RPA diameter (17.88 ± 5.44 mm/m² vs. 16.56 ± 6.00 mm/m²) (Table 2).

Regarding the RV parameters, the right ventricular length diameter (RVLD: 60.64 ± 15.47 mm/m² vs. 72.64 ± 14.95 mm/m²; p < 0.001) and the right ventricular short diameter (RVSD: 34.89 ± 6.50 mm/m² vs. 39.48 ± 7.60 mm/m²; p < 0.05) were significantly higher in the PR group compared with those in non-PR group. No significant difference was observed with respect to RV wall thickness (18.61 ± 3.35 mm/m² vs. 18.88 ± 3.88 mm/m²), RVOT diameter (9.51 ± 3.63 mm/m² vs. 10.06 ± 4.52 mm/m²), and RVOT length (26.50 ± 10.11 mm/m² vs. 23.42 ± 9.06 mm/m²) (Table 2).
Relationship between measurements and PR. For TOF patients who underwent trans-valve surgery, there was a positive correlation between PA parameters (LPA diameter, McGoon ratio, and Nakata index) and the occurrence of post-operative PR ($r = 0.361$, $0.413$, and $0.482$, respectively; all $p < 0.05$).

The diameters of the right ventricle (RVLD and RVSD) exhibited a negative correlation with PR ($r = -0.457$ and $-0.341$, respectively; all $p < 0.05$) (Table 2).

ROC analysis showed that a McGoon ratio $> 1.63$, Nakata index $> 270.05$, and LPA diameter $> 18.29$ based on DSCT were optimal cutoff values that predicted the risk of post-operative PR [McGoon ratio: sensitivity 83.3%, specificity 56.5%, and area under the curve (AUC): 0.74; Nakata index: sensitivity 83.3%, specificity 60.9% (AUC: 0.78); LPA: sensitivity 66.7%, specificity 82.6% (AUC: 0.71)]. The Youden index of the three parameters (McGoon ratio, Nakata index and LPA diameter) was 0.40, 0.44 and 0.49, respectively (Fig. 1).

As for RV parameters, the RVLD $< 63.65$ and RVSD $< 37.75$ showed a moderate sensitivity for predicting post-operative PR [RVLD: sensitivity 66.7%, specificity 82.6% (AUC:0.77); RVSD: sensitivity 77.8%, specificity 60.9% (AUC:0.70)]. The Youden index of RVLD and RVSD were 0.49 and 0.39 (Fig. 1).

Inter-observer and intra-observer variability. Two experienced radiologists finished the intra- and inter-observer variability and all the indexes and size values using DSCT were calculated. The ICCs of intra-observer variability for the measurements were 0.878–0.997; the ICCs of inter-observer variability for the measurements were 0.824–0.996 (Table 3).

Radiation dose estimation. As infant patients are susceptible to ionizing radiation, the radiation dose in our study was as low as could be reasonably achieved. The mean DLP for patients between 4 months and 1 year of old was 46.63 $\pm$ 24.81 mGy-cm; the mean ED based on DLP was 1.26 $\pm$ 0.62 mSv. The mean DLP for patients between 1 and 6 years of old was 37.29 $\pm$ 15.12 mGy-cm and the mean ED was 0.67 $\pm$ 0.27 mSv.

Discussion
In this study, we demonstrated that PR is more likely to occur in patients who have undergone trans-valve surgery (90.0%). Pre-surgical PA measurements including the McGoon ratio, Nakata index and LPA diameter had a positive correlation with PR. Meanwhile, the right ventricle diameters (RVLD and RVSD) had a negative correlation with PR. We postulated that these PA indexes and RV diameters might serve as novel predictors of PR and facilitate clinical intervention and management for TOF patients.

TOF is the most common cyanotic CHD and accounts for 7–10% of all CHD$^{14}$. Infant patients with TOF usually require early surgical repair to reduce the risk of death$^{15,16}$. The surgery includes the infundibulotomy with or without trans-valve repair. PR is the most serious complication after the surgical repair, persistent PR might lead to RV dilatation, ventricular arrhythmias, and even cardiac event decades$^{16,17–21}$. ACC/AHA 2008 Guidelines for
with that of RPA25. In the event of compensatory PR after the trans-valve surgery, more blood should stream from the PV level, which results in immediate PR post-operatively; further, the widely developed and even expanded PA streams back more blood to the surgical incision at the PV level, which increases the risk of PR. The phenomenon might be explained as follows: a great amount of blood that streams back toward the heart is largely from the LPA24, and the contribution of LPA to total regurgitation flow is far greater compared with that of RPA25. In the event of compensatory PR after the trans-valve surgery, more blood should stream from the wider LPA back to the relatively narrow pulmonary annulus as compared with that from RPA. Another finding of this study was that RV linear dimensions were also related to PR. The RVLD and RVSD both showed a negative correlation with the PR. Different form the size of PA, the size of RV reflects the pre-load of the pulmonary valve, namely a relatively smaller size of RV represents a lower diastolic and systolic volume before the surgery. We presume that the smaller volume may make it harder to compensate the abrupt increase in blood flow after repair and the relatively higher pressure would at least result in transient PR. However, our measurements pertained only to the early stage of post-operative period. The hemodynamic characteristics reflected in the pre-operative RV parameters and how changes in these measures on the long follow-up may provide more clues on this issue.

In our study, there was a good reproducibility of the inter- and intra-observer variabilities. With the fast scanning speed and high temporal resolution, the DSCT can provide more accurate information for PA and RV parameters. The accurate measurements can not only reflect the patients’ individual details, but also help to predict the occurrence of post-operative PR in TOF patients. PR is the most common complication after the first surgery. None of the patients had PR before surgery, however, immediate post-operative TTE showed the presence and different degrees of regurgitation. Patients with trans-valve surgery presented a higher probability of PR (90.0% vs. 65.7%). Although the mechanism of development of PR is not completely understood. One of proposed cause is the injury to the pulmonary valve and the surrounding tissue during the trans-valve incision crossing the pulmonary valve annulus, a surgical process considered in patients in whom the pulmonary valve annulus is too small23. Our results are consistent with this theory and we assumed that the injury to the pulmonary valve and the surrounding tissue during the trans-valve incision might be the culprit.

For patients who received trans-valve surgery, the McGoon ratio, Nakata index, and the LPA diameter shown a positive correlation with PR. The above artery development parameters reflect the degree of distal stenosis of pulmonary bifurcation and a McGoon ratio higher than 1.2 and a Nakata index higher than 150 mm2/m2 are considered as essential indicators for one-stage surgery. A previous study mentioned that larger and expansile PA exhibited a tendency for higher PR fractions; the author proposed that PR was exacerbated by PA compliance but was limited by more proximal resistance26. Similarly, in our study, the McGoon ratio value and Nakata index value were significantly higher in the patients who developed PR. The expanded PA might attenuate the vascular elasticity and lead to reduced PA compliance. What’s more, the blood flowing through the PA is venous blood; however, the PA lacks an intravenous valve. We assumed that the well-developed and even expanded PA streams back more blood to the surgical incision at the PV level, which results in instant PR post-operatively; further, the relatively narrow valve compared with the large diameter of the pulmonary bifurcation adds to this possibility.

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In our results, the LPA diameter was a better predictor of PR than RPA. The LPA diameter value was significantly different between these two groups and showed a moderate positive correlation with the presence of PR. The ROC analysis demonstrated a moderate predictive value of LPA diameter (AUC:0.71). However, the RPA diameters was not significantly different between these two group, and it did not show a significant correlation with the PR. The phenomenon might be explained as follows: a great amount of blood that streams back toward the heart is largely from the LPA24, and the contribution of LPA to total regurgitation flow is far greater compared with that of RPA25. In the event of compensatory PR after the trans-valve surgery, more blood should stream from the wider LPA back to the relatively narrow pulmonary annulus as compared with that from RPA. Another finding of this study was that RV linear dimensions were also related to PR. The RVLD and RVSD both showed a negative correlation with the PR. Different form the size of PA, the size of RV reflects the pre-load of the pulmonary valve, namely a relatively smaller size of RV represents a lower diastolic and systolic volume before the surgery. We presume that the smaller volume may make it harder to compensate the abrupt increase in blood flow after repair and the relatively higher pressure would at least result in transient PR. However, our measurements pertained only to the early stage of post-operative period. The hemodynamic characteristics reflected in the pre-operative RV parameters and how changes in these measures on the long follow-up may provide more clues on this issue.

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### Table 3. Interobserver and Intraobserver variability of diameters and indexes.

| Parameter   | Interobserver Variability | Intraobserver Variability |
|-------------|---------------------------|---------------------------|
| RVLD        | 0.991 0.997 0.995 0.994   | 0.995 0.994               |
| RVSD        | 0.878 0.929 0.824 0.983   |                           |
| RV wall thickness | 0.978 0.978 0.966 0.978 |                           |
| RVOT diameter | 0.989 0.992 0.988 0.995  |                           |
| RVOT length  | 0.935 0.993 0.946 0.995   |                           |
| McGoon ratio | 0.965 0.984 0.973 0.980   |                           |
| Nakata index | 0.966 0.983 0.998 0.982   |                           |
| MPA         | 0.993 0.997 0.995 0.996   |                           |
| LPA         | 0.997 0.995 0.995 0.994   |                           |
| RPA         | 0.985 0.983 0.993 0.992   |                           |

Note: Abbreviations as in Table 2.
TOF surgical repair and is especially associated with the trans-valve surgery, however, most of patients can tolerate for several years or even decades. In the event of severe PR, the surgeon should suggest the patients to undergo the PVR. Therefore, we may help predict the risk of PR after the one-stage operation using DSCT. The surgeon should recommend regular follow-up examination of these patients in the post-operative period.

There were several limitations in this study. First, there was a likely assembly bias. Patients selected for DSCT were all from our institution. Second, only pre-operative and immediate post-operatively changes were assessed; continued follow-up of these patients is required to determine the long-term predictive value. Third, although the radiation dose was prominently reduced through DSCT, and much lower than cardiac catheterization, infant patients are still vulnerable to ionizing radiation.

In conclusion, this study demonstrated that PA developmental parameters and RV size might be associated with post-operative PR. An increase in the LPA diameter, McGoon ratio, and Nakata index or smaller size of RV may indicate an increased risk of PR. These easily acquired pre-operative DSCT measurements can not only be used as surgical indications, but also have a certain correlation with PR incidence; these may be considered as anatomic predictive factors for the occurrence of PR.

Materials and Methods

Study population. This retrospective study collected 98 patients with DSCT confirmed by TOF at our hospital from January 2011 to September 2016. The exclusion criteria included (a) no-surgical patients or surgery after the age of six, (b)surgical results confirmed as not TOF, (c) incomplete clinical data, (d) Patients with poor clinical conditions. Finally, 55 patients (29 males and 26 females) with an average age of 1.67 ± 1.32 years (range: 5 months–6 years) were included in the study. Of the 55 patients, there are 41 patients received infundibulotomy with an incision across the pulmonary valve annulus, and the other 14 patients without pulmonary valve incision.

This study was approved by the institutional review board of West China hospital (No. 14–163), and we pledged to abide by the declaration of Helsinki (2000 EDITION) in accordance with the relevant medical research rules of China in the study. Ensure that all patients and patients’ parents signed the relevant informed consent, and having been informed of potential adverse reactions to the iodinated contrast agent and radiation.

Dual-source computed tomography. All examinations were performed using a DSCT scanner (Somatom Definition; Siemens Medical Solutions, Forchheim, Germany). Short-term sedation (concentration: 10%, 0.5 ml/kg) was achieved by intravenous injection of chloral hydrate prior to the cardiac DSCT examinations. Scanning was performed using a retrospective ECG-gated protocol with the following acquisition parameters: tube voltage of 80 kV , tube current of 100 mAs, gantry rotation time of 0.28 s, and pitch of 0.2–0.5 (according the heart rate with a higher pitch used for higher heart rates). The ECG-pulsing window was set on Auto. Scanning was performed in the craniocaudal direction from the inlet of the thorax to 2 cm below the diaphragm level with a scan cycle including systolic and diastolic phases. The nonionic contrast agent (370 mg/ml iopamidol; Bracco, Italy) was injected into an antecubital vein at a rate of 1.2–2.5 ml/s, followed by 20 ml of saline solution at the same flow rate. The injected volume was adjusted according body weight (1.5 ml/kg). Bolus tracking was used in the region of interest (ROI) in the descending aorta with a predefined threshold of 100 HU. Image acquisition was triggered following a delay of 5 s when the ROI attenuation threshold reached 100 HU. The workstation (Syngo; Siemens Medical System, Forchheim, Germany) processed all acquired data. A slice thickness of 0.75 mm and an increment of 0.75 mm were chosen for image reconstruction.

Echocardiography. All patients underwent TTE using a Philips SONOS 7500 ultrasound system (Philips Medical Systems, Bothell, WA, USA) pre-operatively and immediately after surgical repaired to detect the occurrence of PR. The examination included M-mode, two-dimensional, continuous wave, and Color Doppler Flow Imaging as recommended by the American Commission on echocardiography. Post-operative PR was detected by color Doppler flow mapping and continuous wave Doppler, and the results presented as a binary carriable (present and not present). All the TTE images and detection of PR were acquired by an experienced echocardiographer.

DSCT Image analysis. Two experienced radiologists analyzed each subject, recorded the measurements, and calculated the index. All diameters were measured using the computer caliper during systole. The multiple planar reconstruction (MPR) was used for DSCT image analysis. Recordings and assessments of RV and PA followed the American Society of Echocardiography guidelines.

The main pulmonary artery (MPA) was measured at the site of pulmonary bifurcation in the axial slices, while the right pulmonary artery (RPA) and left pulmonary artery (LPA) were measured proximal to the first branching point of each artery (Fig. 2A). RV wall thickness was measured from the subcostal four-chamber view, preferably at the level of the tip of the anterior tricuspid leaflet. The size of RV was measured from an apical four-chamber view (Fig. 2B). The RVOT proximal dimension can be measured from the anterior aortic wall to the RV free wall above the aortic valve and immediately under the pulmonary valve respectively (Fig. 2C,D). The McGoon ratio was calculated using the equation of left and right pulmonary arterial diameter summation divided by the aorta diameter at diaphragm level. The Nakata index was calculated by the summation of LPA, RPA, and collateral vessels cross-section areas divided by body surface areas (Fig. 2E–F). The first radiologist completed all the image analyzes and measurements, then repeated the measurements 2 weeks later to determine the intra-observer variability of DSCT measurements. For the inter-observer variability, a second radiologist blindly repeated the image analyzes and measurements. The occurrence of PR was observed by the echocardiographic investigator immediately after surgery.
Radiation dose estimation. Radiation dose parameters, including volume CT dose index (CTDVol) and dose-length product (DLP), were automatically displayed on the CT console after the examination. Infant-specific DLP conversion coefficients, based on the 2007 recommendations of the International Commission on Radiological Protection, were used to calculate the effective dose (ED) using conversion coefficients of 0.039 for patients < 4 months of age, 0.026 for patients between 4 months and 1 year of age, and 0.018 for patients between 1 and 6 years of age.

Statistical analysis. The data were analyzed using the SPSS software for Windows (version 19.0, SPSS Inc., Chicago, IL, USA) and MedCalc software (version 9.3.0.0, MedCalc software, Mariakerke, Belgium). The McGoon ratio and Nakata index were calculated using PA diameters and cross-section areas. Continuous variables were expressed as mean ± standard deviations (SD). Categorical variables were expressed as numbers. The significant differences of these measurements between the PR and non-PR group in trans-valve surgical group were analyzed using an non-parametric test. Spearman’s rank correlation test was used to evaluate the association between these pre-operative parameters and the occurrence of PR. Receiver operating characteristic (ROC) analyses calculated the sensitivity and specificity of the effective parameters to predict post-operative PR. The intraclass correlation coefficient (ICC) was used to assess the inter-observer and intra-observer variability. A two-tailed p-value of < 0.05 was considered statistically significance.

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**Author Contributions**

Y.G. wrote the draft and final edit of this manuscript. Z.G.Y. and Y.K.G. contributed to the conception of the study and final approval of the version to be submitted. K.S. and helped to design the study and data analyses. K.Y.D. contributed to the quantitative data analysis and preparation of the manuscript. H.Y.X. helped perform the analysis with constructive discussions.

**Additional Information**

**Competing Interests:** The authors declare no competing interests.

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