Predictive Value of Right Ventricular Pressure Measurement for Residual Pulmonary Stenosis in Tetralogy Repair

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ABSTRACT

Objective: The long-term outcome of tetralogy of Fallot repair depends on an adequate relief of right ventricular outflow tract obstruction and preservation of the pulmonary valve function. Since intraoperative transesophageal echocardiography is not routinely performed in small patients, we postulated that the post-bypass right ventricular pressure measured intraoperatively could predict residual pulmonary stenosis when evaluated by transthoracic echocardiography.

Materials and Methods: Of the 187 patients who underwent tetralogy repair between 2012 and 2019 at Siriraj Hospital, Thailand, 95 with right ventricular pressure measurements and pre-discharge echocardiography were included in the study. Their intraoperative parameters, and postoperative outcomes were analyzed. The tolerable pressure cutoff was determined.

Results: The median patient age was 3.9 years old (interquartile range 2.75–6). Fifty-three patients (54.6%) required the use of the transannular patch. Ten patients (10.3%) had significant residual pulmonary stenosis with a mean right ventricular systolic pressure of 64.0±10.6 mmHg compared with 48.7±14.4 mmHg for the other patients. There was an association between the pressure figure and the degree of residual pulmonary stenosis (rho=0.391, p=0.01). A systolic pressure above 49 mmHg predicted pulmonary stenosis with a likelihood ratio of 2.18 (1.94-2.80, 95%CI). The likelihood rose to 2.93 (2.44-4.01, 95%CI) if the pressure resulted in a right to left ventricular pressure ratio above 0.62. The patients whose figures did not exceed 49 mmHg experienced no significant residual obstruction, regardless of the pressure ratio.

Conclusion: Intraoperative measurement of the right ventricular pressure can predict residual pulmonary stenosis after tetralogy repair with a reassuring cutoff of 49 mmHg.

Keywords: Tetralogy of Fallot repair; right ventricular pressure; residual pulmonary stenosis; intraoperative assessment (Siriraj Med J 2022; 74: 225-232)

INTRODUCTION

Tetralogy of Fallot is the most common cyanotic congenital heart disease worldwide. The first corrective surgery was performed in the 1950s and the treatment has been evolving ever since.[1] The current strategies involve adequate relief of right ventricular outflow tract obstruction and optimal preservation of the right ventricular and pulmonary valve function, guided predominantly by intraoperative transesophageal echocardiography.[2,3]

Residual pulmonary stenosis or regurgitation after the repair is not infrequent and, to some extent, it can lead to progressive right ventricular dysfunction requiring

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subsequent reoperation to prevent sudden cardiac death.[4-6] In the light of a paradigm shift from complete relief of the right ventricular outflow tract obstruction to preserving the pulmonary valve and infundibulum during tetralogy repair, the adequacy of resection has gained elevated importance as some reports have revealed a high incidence of residual right ventricular outflow tract obstruction following valve-sparing surgery. even during short-term follow-up.[7]

Intraoperative echocardiography is not routinely performed in small children at many institutes, including at our institute, and instead, many surgeons measure the right ventricular pressure intraoperatively to predict the degree of residual pulmonary stenosis and to identify whether the problematic outflow justifies immediate revision.[8] Unfortunately, the maximum tolerable pressure is arbitrary and depends on the individual threshold of acceptance. Besides, the left to the right systolic ventricular pressure ratio alone is subject to errors as it depends on the systemic vascular resistance, which may vary across patients in response to the cardiopulmonary bypass.

We postulate that, in the absence of intraoperative echocardiography, the right ventricular systolic pressure can predict residual right ventricular outflow tract obstruction. Further, in this study, we tried to identify the pressure criteria for outflow tract revision.

MATERIALS AND METHODS

Patients

Between 2012 to 2019, 187 consecutive tetralogy of Fallot patients underwent total correction at Siriraj Hospital, Thailand. After exclusion of the patients without documented post-bypass right ventricular systolic pressure measurements and pre-discharge transthoracic echocardiography, 95 patients were included in the study analysis. The decision to measure the ventricular pressure primarily depended on the surgeon's routine. Table 1 shows the baseline characteristic and operative variables of the study population. The preoperative pulmonary valve z-value and McGoon ratio were obtained from the cardiac catheterization measurements. The clinical outcomes between the 95 included patients were similar to those of the rest patients (who were excluded because of no documented intraoperative right ventricular pressure measurement) concerning significant residual pulmonary stenosis and in-hospital care duration (the results not shown).

The study was approved by Siriraj Institutional Review Board (COA no. Si 003/2020). The patient consent is waived as it contained minimal risk to the subject.

TABLE 1. Patient characteristics.

Variables		Study patients (n = 95)
Age, y	mean±SD	6.0±6.7
median [IQR]		3.9 [2.75–6]
Weight, kg	mean±SD	15.7±8.7
median [IQR]		13 [10.5–17.8]
Preoperative PV z-score		-2.14±1.52
McGoon ratio		2.21±0.47
Bypass time, min		165.5±58.7
Cross-clamping time, min		121.2±39.2
Transannular patch, n (%)		52 (54.7)
Direct RVSP, mmHg		50.3±14.8
Direct Prv/Plv ratio		0.60±0.18
PostOp TTE RVOT PPG, mmHg		25.2±14.3
missing, n (%)		15 (15.8)
PostOp TTE PS grade, n (%)		
none		16 (16.8)
mild		69 (72.6)
moderate		10 (10.5)
severe		0
Significant residual PS, n (%)		10 (10.5)
ICU stay, d	mean±SD	3.2±6.6
median [IQR]		2 [1, 3]
Hospital stay, d	mean±SD	9.8±7.4
median [IQR]		8 [7–11]

Abbreviations: ICU; intensive care unit, Plv; left ventricular pressure, Prv; right ventricular pressure, PostOp; postoperative, PPG; peak pressure gradient, PS; pulmonary stenosis, PV; pulmonary valve, RVOT; right ventricular outflow tract, RVSP; right ventricular systolic pressure, TTE; transthoracic echocardiography.

Surgical technique and right ventricular pressure measurement

All repairs were conducted through median sternotomy with cardiopulmonary bypass under mild systemic hypothermia. Intermittent, antegrade cold blood cardioplegia was given for myocardial protection. The surgical approach was transatrial and transpulmonary and/or transventricular in all the patients depending on the degree of infundibular hypoplasia and on the anatomy of the ventricular septal defect. The right

ventricular outflow was managed with either annular-preserving repair or standard transannular patch repair with monocusp creation using a 0.1 mm-thick expanded polytetrafluoroethylene membrane according to the intraoperative annular measurement. The patch size was tailored for a normal pulmonary valve size for the age and height of the patient. After the patients had come off the bypass, all the transducers were calibrated, and the right ventricular pressure was obtained by direct puncture to the right ventricular free wall using a 25 mm-long, 22-gauge needle connected to the pressure transducer system. The left ventricular pressure was simultaneously estimated by the peripheral arterial line and an arterial outlet pressure monitoring device.

Postoperative course and transthoracic echocardiography

In the intensive care unit, the hemodynamic support and ventilator management were adjusted according to the clinical progress by the attending physicians. Postoperative echocardiography was performed by pediatric cardiologists before hospital discharge or otherwise as clinically indicated. The pressure gradient across the right ventricular outflow tract, degree of pulmonary stenosis, and regurgitation were noted.

Definitions

The degree of residual pulmonary stenosis was estimated using transthoracic echocardiography by a combination of the morphologic appearance, and the measured peak velocity and peak pressure gradient across the pulmonary valve.

- Mild: peak velocity < 3 m/s, peak gradient < 36 mmHg
- Moderate: peak velocity = 3–4 m/s, peak gradient = 36–64 mmHg
- Severe: peak velocity > 4 m/s, peak gradient > 64 mmHg

Significant residual pulmonary stenosis is defined as a moderate or greater degree of pulmonary stenosis.

Statistical analysis

Based on the expected correlation coefficient of 0.3, a minimum sample size of 85 was required to estimate Spearman's rank correlation with a power of 0.8 and a significance level of 0.05. Descriptive statistics were used to present the baseline characteristics of the patients. Continuous variables were presented as the mean with the standard deviation or the median with the interquartile range. The differences were evaluated using the Student's t-test or Mann–Whitney U test, as appropriate. Categorical variables were presented as number and percentage, and differences were evaluated using the chi-square test or Fischer's exact test, as appropriate. A p-value < 0.05 was set as the threshold for statistical significance. Receiver operating characteristic (ROC) curves were generated to determine the optimal cutoff values for the variables in the prediction of significant residual outflow tract obstruction. All the data were analyzed using the SPSS™ software version 20.0 (SPSS Inc., IBM Company, Chicago, Illinois, USA).

RESULTS

No operative mortality was observed. The pre-discharge transthoracic echocardiography was performed at the median post-operative day 5 (interquartile range 1-6). The mean intraoperative right ventricular systolic pressure after the repair was 50.3±14.8 mmHg (range 17–83 mmHg). The mean intraoperative right to left systolic ventricular pressure ratio was 0.60±0.18 (range 0.21–1.08). Concerning the degrees of postoperative tricuspid regurgitation, only 5 patients experienced moderate tricuspid regurgitation while the rest had no or mild regurgitation. Table 2 shows comparisons between the two surgical approaches: the transannular and non-transannular techniques. The transannular patch repair group was associated with less residual outflow obstruction, more pulmonary regurgitation, and a longer ICU stay and hospital stay.

Ten patients (10.5%) were documented to have significant residual right ventricular outflow tract obstruction with a higher systolic right ventricular pressure and pressure ratio. None of them underwent surgical revision at the index admission. Comparisons between the patients with and without significant residual pulmonary stenosis are shown in Table 3. The patients with residual subpulmonary obstruction required less transannular patching and subsequently a shorter in-hospital care duration. The characteristics of the patients with significant residual pulmonary stenosis are shown in Table 4.

Through Spearman's rank correlation analysis, we found a correlation between the systolic right ventricular pressure and the degree of postoperative residual pulmonary stenosis (rho = 0.391; p = 0.01). The right to left systolic ventricular pressure ratio was also correlated with the degree of postoperative residual pulmonary stenosis (rho = 0.369; p = 0.01). Through ROC curve analysis, we analyzed each intraoperative pressure parameter and the combination of both to identify the diagnostic cutoff for significant residual pulmonary stenosis identified by pre-discharge transthoracic echocardiography. The results are depicted in Fig 1. A systolic right ventricular

TABLE 2. Comparison of two outflow reconstruction techniques among the study patients.

Variables		Transannular approach (n = 52)	Transatrial/Pulmonary (n = 43)	P-value
Age, y	mean±SD	5.1±4.9	7.1±8.3	0.15
median [IQR]		3.4 [2.8–6.2]	4.8 [2.8–6.0]	0.43
Weight, kg	mean±SD	14.5±6.9	17.1±10.5	0.16
median [IQR]		12.2 [10.4–16.3]	14 [10.5–18.5]	0.27
Preoperative PV z-score		-2.82±1.47	-1.30±1.14	**<0.001**
McGoon ratio		2.21±0.47	2.27±0.59	0.58
Bypass time, min		176.1±68.5	148.7±40.1	**0.022**
Cross-clamping, min		129.5±42.3	108.4±32	**0.007**
Direct RVSP, mmHg		52±15	48.5±14.7	0.26
Direct Prv/Plv ratio		0.62±0.19	0.58±0.18	0.26
PostOp TTE PS grade, n (%)				0.46
none		8 (15.4)	7 (16.3)	
mild		41 (76.9)	27 (62.8)	
moderate		2 (3.8)	8 (18.6)	
severe		0	0	
Significant residual PS, n (%)		2 (3.8)	8 (18.6)	**0.039**
PostOp TTE PR grade, n (%)				**<0.001**
none		0	7 (16.3)	
mild		4 (7.7)	10 (23.3)	
moderate		20 (38.5)	21 (48.8)	
severe		27 (51.9)	4 (9.3)	
PostOp TTE RVOT PPG, mmHg		24.4±13.9	25.6±13.5	0.72
missing, n (%)		9 (17.3)	7 (16.3)	
IS at ICU arrival	mean±SD	11.3±12.7	8.2±6.2	0.15
median [IQR]		7.5 [5–15]	7 [4–13]	0.38
ICU stay, d	mean±SD	4.3±8.8	2±1.5	0.09
median [IQR]		2.5 [1–4]	1 [1–2]	**0.006**
Hospital stay, d	mean±SD	11.5±10	8.1±2.7	**0.032**
median [IQR]		10 [7–11.8]	8 [6–10]	**0.007**

Abbreviations: ICU; intensive care unit, IS; inotropic score, Plv; left ventricular pressure, Prv; right ventricular pressure, PostOp; postoperative, PPG; peak pressure gradient, PR; pulmonary regurgitation, PS; pulmonary stenosis, PV; pulmonary valve, RVOT; right ventricular outflow tract, RVSP; right ventricular systolic pressure, TTE; transthoracic echocardiography.

TABLE 3. Comparison of two outflow reconstruction techniques among the study patients.

Variables		Patients with significant residual PS (n = 10)	Patients without significant residual PS (n = 85)	P-value
Age, y	mean±SD	3.8±2.0	6.3±7.0	**0.019**
median [IQR]		3.3 [2.3–5.3]	4.3 [2.8–6.3]	0.31
Weight, kg	mean±SD	14.2±5.0	15.9±9.1	0.39
median [IQR]		13.3 [10–17.6]	13 [10.6–17.8]	0.85
Preoperative PV z-score		-1.59±0.74	-2.21±1.58	0.22
McGoon ratio		2.58±0.57	2.17±0.44	0.05
Bypass time, min		144±24.9	168±61	**0.028**
Cross-clamping time, min		109.6±29.5	122.6±40.1	0.23
Transannular patch, n (%)		2 (20)	49 (57.6)	**0.039**
Direct RVSP, mmHg		64±10.6	48.7±14.5	**0.001**
Direct Prv/Plv ratio		0.76±0.13	0.58±0.18	**0.002**
PostOp TTE RVOT PPG, mmHg		46.7±10.2	21.8±10.9	**<0.001**
missing, n (%)		0	14 (16.5)	
IS at ICU arrival	mean±SD	8.6±6.9	9.9±10.7	0.60
median [IQR]		7 [4–11.3]	6.8 [4.4–15]	0.89
ICU stay, d	mean±SD	1.7±1.9	3.5±6.9	0.07
median [IQR]		1 [1–1.3]	2 [1–3]	**0.018**
Hospital stay, d	mean±SD	7.7±1.8	9.3±3.6	**0.042**
median [IQR]		7 [6.8–8.5]	8 [7–11]	0.27

Abbreviations: ICU; intensive care unit, IS; inotropic score, Plv; left ventricular pressure, Prv; right ventricular pressure, PostOp; postoperative, PPG; peak pressure gradient, PS; pulmonary stenosis, PV; pulmonary valve, RVOT; right ventricular outflow tract, RVSP; right ventricular systolic pressure, TTE; transthoracic echocardiography.

pressure above 49 mmHg predicted postoperative residual pulmonary stenosis with a likelihood ratio of 2.18 (95%CI 1.94–2.80). A systolic right to left ventricular pressure ratio above 0.62 predicted postoperative residual pulmonary stenosis with a likelihood ratio of 2.57 (95%CI 2.21–3.42). The combination of both pressure criteria raised the likelihood of residual outflow obstruction to 2.93 (95%CI 2.44–4.01). Fig 2 shows the outflow tract decision flowchart according to our results. None of the study patients whose ventricular pressure did not meet both criteria experienced significant residual outflow obstruction.

DISCUSSION

We found an association between right ventricular systolic pressure and the degree of pulmonary stenosis. As a predictor for residual right ventricular outflow tract obstruction, the absolute figure of the intraoperative pressure performed comparably to the pressure ratio (an almost identical area under the ROC curve). When we combined both parameters, the predictive value from the likelihood ratio increased considerably. Apart from the pressure ratio, this information implies how high the right ventricular pressure is also matters, especially when the right to left systolic pressure ratio approaches the

TABLE 4. Characteristics of the patients with significant residual pulmonary stenosis.

Patient	Gender	Preoperative PV z-score	McGoon ratio	Technique	RVSP, mmHg	Prv/lv ratio	PostOp TTE RVOT PPG, mmHg	IS at ICU arrival	ICU stay, day	Hospital stay, day
1	M	-2.06	2.73	Subannular, valvulotomy	52	0.66	39	4	1	6
2	F	-1.5	2.3	Subannular, valvulotomy	50	0.63	49	15	2	6
3	M	-1.18	3.5	Supravalve, valvulotomy	69	0.69	47	11.7	8	12
4	F	-2.6	3	**Transannular, monocusp**	67	0.76	55	20	4	10
5	M	-1.9	2.5	Supravalve, valvulotomy	64	0.75	42	7	1	8
6	M	-1.63	1.5	Sub/supravalve patch, valvulotomy	50	0.70	38	5	1	8
7	M	-2.4	2	Supravalve, valvulotomy	81	0.70	55	10	1	7
8	F	-1.79	3.12	**Transannular, monocusp**	75	0.90	66	7.5	1	7
9	M	-0.4	2.53	Supravalve, valvulotomy	70	1.08	41	5	1	8
10	M	-0.4	2.6	Transatrial	62	0.73	44	10	1	7

Abbreviations: ICU; intensive care unit, IS; inotropic score, Plv; left ventricular pressure, Prv; right ventricular pressure, PostOp; postoperative, PPG; peak pressure gradient, PV; pulmonary valve, RVOT; right ventricular outflow tract, RVSP; right ventricular systolic pressure, TTE; transthoracic Echocardiography.

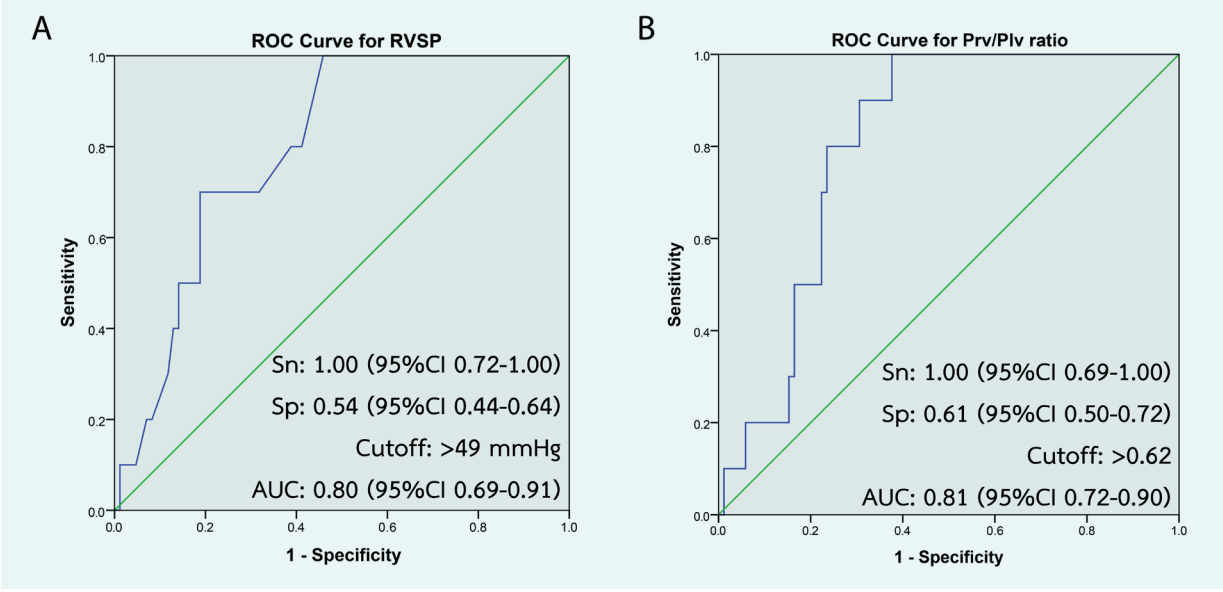

Fig 1. Receiver operating characteristic (ROC) curves of the predictors of right ventricular outflow tract obstruction. **(A)** Right ventricular systolic pressure (RVSP). **(B)** Right to left ventricular pressure ratio (Prv/Plv ratio).
Abbreviations: AUC; area under the curve, Sn; sensitivity, Sp; specificity.

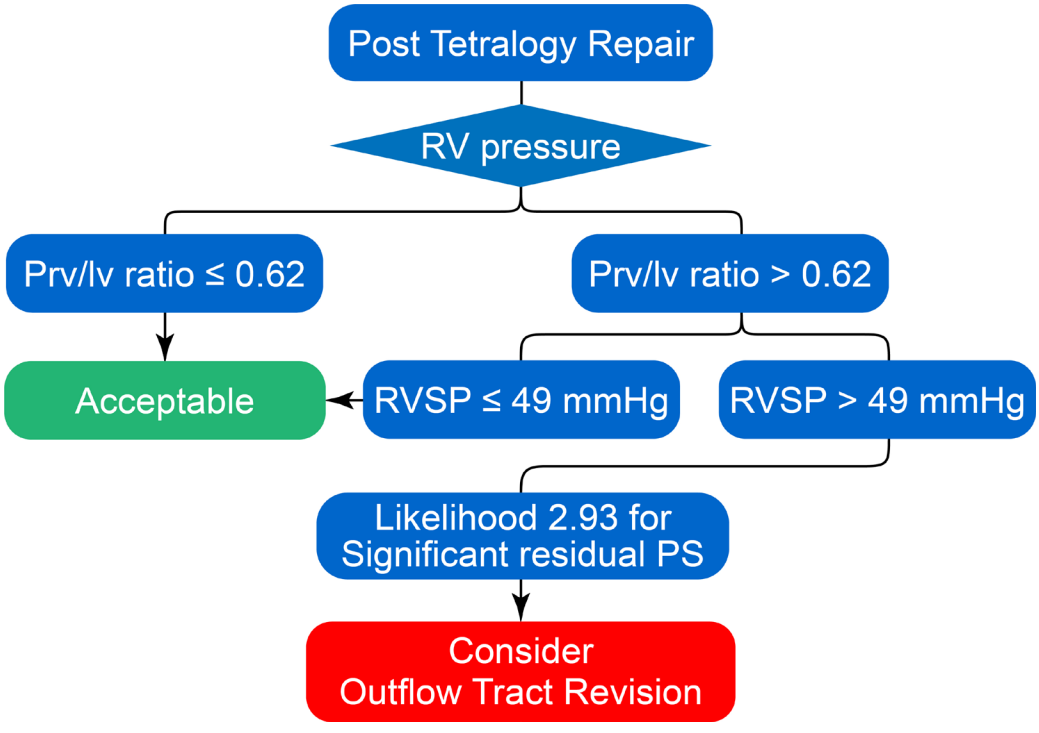

Fig 2. Outflow tract assessment decision flowchart
Abbreviations: Prv/lv; right ventricular to left ventricular systolic pressure ratio, PS; pulmonary stenosis, RV; right ventricle, RVSP; right ventricular systolic pressure.

published revision criteria. Although in the majority of the cases both the pressure and pressure ratio went in the same direction and magnitude, in some patients with a relatively low systolic blood pressure initially off the pump, use of the pressure ratio alone tended to overestimate the residual outflow obstruction. Only one of the sixteen patients (specifically, patient #9) with an initial systolic blood pressure below 70 mmHg experienced significant residual pulmonary stenosis despite a mean pressure ratio of 0.75±0.29 in the group with hypotension. Adding the absolute right ventricular pressure to the consideration could prevent unnecessary intervention in this context. To the best of our knowledge, this piece of information has not been reported before in the literature.

Regarding the pressure ratio cutoff value of 0.62, which is quite low compared with other reports[2,9], this figure was selected as a reassuring cutoff, not the revision one. As the specificity of the test suggested, some patients whose measurement exceeded these criteria eventually fell into the insignificant residual outflow stenosis at the sonographic follow-up. This implies that even if both proposed criteria are met, the surgeon should logically identify the culprit location and consider the possibility of further resection without scarifying the pulmonary valve integrity before commencing the second pump run. The reason behind this is possibly due to the heterogeneous nature of postoperative Fallot's outflow tract restriction (i.e., fixed or dynamic)[10], which, unfortunately, might need intraoperative echocardiography to differentiate.[3]

Unsurprisingly, the patients who needed the pulmonary valve ring enlarged performed worse than those with an intact pulmonary valve ring in terms of the pulmonary valve integrity and in-hospital care duration (Table 2). In contrast to a previous report[8], our study demonstrated better in-hospital outcomes among the patients with significant residual outflow tract obstruction (shorter ICU and hospital stay). This result could probably be attributed to the effect of the transannular approach and the resultant pulmonary insufficiency rather than the gradient itself (the transannular patching requirement of the patients with insignificant residual stenosis was almost triple that of the significant counterpart, Table 3).

It is to be noted that our study had limitations due to its retrospective nature and short period of follow-up. Also, changes in the outflow tract gradient over time were monitored only in selected patients. Furthermore, as we did not have a patient with critical residual outflow tract obstruction in our series, the diagnostic cutoff of such a condition was, therefore, unattainable. Longer-term follow-up of such a 'significant' patient is needed to elucidate the clinical significance of such findings.

CONCLUSION

In the setting without intraoperative transesophageal echocardiography, the direct measurement of right ventricular pressure can predict the adequacy of outflow tract reconstruction during the repair of tetralogy patients. Adding an absolute pressure criterion of 49 mmHg to the pressure ratio could prevent unnecessary surgical revision and protect pulmonary valve integrity.

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