Review Article

Aortopathy in repaired tetralogy of Fallot and David procedure

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Abstract: Tetralogy of Fallot (TOF) is a condition that often leads to long-term enlargement of the aortic root in after surgery. The aortic dilation is believed to be caused by histological abnormalities of the aortic media and the hemodynamic characteristics of increased aortic flow, compared to pulmonary flow. Severe cyanosis, severe right ventricular outflow tract (RVOT) obstruction, older age at repair, a larger aortic size at the time of repair, and a history of an aortopulmonary shunt parameters related to long-standing volume overload of the aortic root were the reported risk factors. Right aortic arch, male sex, and the association of chromosome 22q11 deletion were also reported to be risk factors. The enlargement of the aortic root can cause aortic regurgitation (AR), leading to left ventricular dysfunction and an increased risk of aortic dissection, necessitating surgical intervention. The outcomes of aortic valve repair for AR have improved, leading to an increasing trend of choosing this approach, particularly in younger patients who would otherwise require mechanical valve replacement, thereby avoiding the need for anticoagulation therapy. The indications and timing of prophylactic aortic root replacement in adult patients with congenital heart disease have not been described, and the current consensus recommends surgical intervention for an ascending aorta with a diameter of ≥55 mm. In this review article, we focus on valve-sparing root replacement (VSRR) in TOF.

Keywords: Aortic dilatation; tetralogy of Fallot (TOF); valve-sparing root replacement (VSRR)

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Introduction

Tetralogy of Fallot (TOF) is characterized by a hemodynamic feature in which the aortic blood flow is greater than the pulmonary artery blood flow, which contributes to aortic dilation (1,2). Risk factors for aortic dilatation reported in previous studies include the right aortic arch, severe pulmonary stenosis (PS), severe cyanosis at the time of repair, increased left ventricular end-diastolic diameter at the time of repair, older age at repair, and male sex (3).

Dilation of the aortic root can lead to aortic regurgitation (AR), which can cause left ventricular dysfunction and carry the risk of aortic dissection, necessitating surgical intervention in some cases. There is no clear consensus on the surgical techniques for managing AR and aortic root dilation in patients with TOF. Current American and European guidelines for the management of aortic diseases recommend valve-sparing surgery over valve replacement, especially in younger patients and when performed at experienced centers (4,5). However, there are no specific recommendations regarding the preferred valve-sparing technique. Homografts are considered as a viable option for aortic root replacement. While the survival rate with homografts in TOF is generally good, some patients develop accelerated degeneration due to mechanical factors (6).

Table 1 Dimensions of the aortic valve complex

Echocardiographic measurements	No remodeling (n=98)	Dilated SV and STJ (n=32)	SV remodeling (n=14)	STJ remodeling (n=12)	P value
Anulus (mm)	21 [20, 23]	25 [23, 28]	25 [24, 27]	24 [20, 27]	<0.001
SV (mm)	31±4	43±5	40±3	35±3	<0.001
STJ (mm)	29±4	39±4	33±4	34±2	<0.001
Ascending aorta (mm)	29±4	39±5	32±3	32±5	<0.001
GH (mm)	17.5±3	21±3	19±2	19±3	<0.001
CL (mm)	5.9 [5.1, 6.7]	5.8 [5.2, 7.1]	5.4 [4.9, 6.1]	6.2 [5.6, 6.4]	0.50
EH (mm)	9.6±2	11±3	9.8±1.7	11.6±2	0.004

Data obtained from reference (19). Data are presented as median [IQR] or mean ± SD. SV, sinus of Valsalva; STJ, sinotubular junction; GH, geometric height; CL, coaptation length; EH, effective height; IQR, interquartile range; SD, standard deviation.

Additionally, their use is not feasible in countries such as Japan, where homografts are difficult to obtain. In these countries, the choice is between valve-sparing aortic root and prosthetic valve replacement.

Mechanical valves used in aortic valve replacement remain associated with bleeding risks due to anticoagulant therapy, while bioprosthetic valves carry the risk of structural valve deterioration, necessitating reoperation. In adults with TOF, postoperative surgical mortality and valve thrombosis following mechanical valve replacement are low; however, infective endocarditis and bleeding complications are significant concerns (7).

Recent studies have shown that the rate of structural valve degeneration in bioprosthetic valves is significantly higher in younger patients, with reported rates of approximately 3.7% per year in patients aged <50 years and approximately 2% per year in those aged 50–60 years (8).

Valve-sparing root replacement (VSRR), represented by the Yacoub and David procedures, has been developed and is being applied to cases that previously underwent the Bentall procedure (9-11). VSRR has several advantages over aortic valve replacement. First, it preserves the dynamic native aortic annulus and valve tissue, providing hemodynamic benefits compared to the rigid stent of a prosthetic valve (12). Second, it avoids the use of mechanical valves, which are often required in this younger population, thereby reducing the risk of thromboembolic events and complications associated with anticoagulation therapy (13,14). In women wishing to conceive and give birth, aortic valve repair is often preferred, whenever possible, as it eliminates the need for anticoagulant therapy, thereby reducing the risks associated with childbirth. Finally, valve repair has been proposed to reduce the incidence of endocarditis (15). Therefore, considering factors such as age, valve morphology, and surgical outcomes of the facility, VSRR may be a viable option for women wishing to become pregnant and for younger patients, considering their specific conditions. This procedure should be performed with the premise of long-term follow-up and the potential need for reoperation when necessary.

Characteristics of aortic dilation in TOF

The primary cause of aortic dilation in TOF is chronic hemodynamic stress caused by preoperative volume overload in the aorta (2). Aortic root dilation is observed in 88% of children after repair of TOF (16). Pediatric patients with aortic root dilation show 87% with sinus of Valsalva (SV) enlargement and 61% with sinotubular junction (STJ) dilation (16). Moderate cystic medial necrosis is observed in the ascending aorta (17). We had previously investigated the morphology of aortic dilation, including conotruncal abnormalities and the length of the aortic valve (18); the prevalence rate of aortic root dilatation was 37% (58 of 156 patients). Among them, four had aortic root diameters ≥50 mm. The most common feature was SV and STJ dilatation. The geometric height and effective height (EH) were elongated (P<0.001 and P=0.004), and with dilation of the aortic root, the leaflets were also elongated, resulting in severe aortic valve regurgitation in few patients (*Table 1*, *Figure 1*). Valve leaflets maintain their coaptation by adapting to the dilation of the SV. The normal range of EH was 8–10 mm in healthy controls (19); however, in the SV + STJ dilation group, EH was longer than the normal

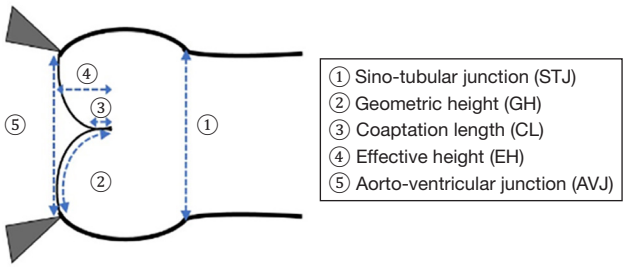

Figure 1 Measurement of the aortic complex.

value and was accompanied by elongation. In particular, EH elongates with SV dilation, and it is considered that a similar elongation of leaflets occurs in TOF (20). Severe AR was identified in two patients with TOF, and both showed a dilated annulus, SV, and STJ. Furthermore, the coaptation length was shorter than the normal value ($P<0.001$). All seven patients with moderate/severe AR were classified as having El Khoury type 1a (SV, STJ, and ascending aorta dilatation) or 1b (SV and STJ dilatation) aortic valve dysfunction. No cases of aortic valve prolapse or degenerative aortic valve changes resulted in significant AR. Aortic dilation is associated with the development of AR, and even mild to moderate AR can lead to a decrease in left ventricular ejection fraction (LVEF), making regular monitoring essential (21).

VSRR

VSRR pioneered by David and Yacoub, has standardized the treatment of aortic root lesions and laid the foundation for applying repair techniques to the aortic valve (9-11). Procedures for preserving the native valve include root remodeling (Yacoub procedure) and aortic valve reimplantation (David procedure). When the annular diameter is small, the Yacoub procedure, which preserves the annulus, is preferred. Conversely, when the annular diameter increases, the David procedure, which covers the annulus with an artificial conduit up to the annular level, is selected. In Yacoub procedure after excising the dilated SV wall, an artificial conduit trimmed into three tongues along the curved aortic wall, remaining along the attachment of the aortic valve cusps is anastomosed. The coronary arteries are reconstructed, and the distal end of the artificial conduit is anastomosed to the proximal end of the ascending aorta. In David procedure, the structure of the aortic root after excising the SV is accommodated within a tubular artificial conduit, and the end of the artificial conduit is sutured to the left ventricular outflow tract junction. The residual aortic wall at the attachment of the aortic valve cusps is internally sutured to the artificial conduit. Yacoub procedure is advantageous because of the relatively straightforward technique and more natural behavior of the preserved aortic valve; thus, better durability of the valve is expected. David procedure offers advantages such as multiple suture lines facilitating hemostasis and preventing late annular expansion, as the aortic valve annulus is fixed at the end of the artificial conduit. These modifications aim to prevent late annular enlargement in remodeling, such as applying thick PTFE sutures or strip-shaped felt circumferentially to the annular region (22).

VSRR (David procedure) results in superior treatment outcomes in terms of valve-related complications compared to composite valve graft conduit replacement procedures such as Bentall or "Bio-Bentall" technique, as well as improves survival rates (23). It is performed even in patients with connective tissue disorders such as Marfan syndrome (24). Furthermore, it is often adopted in cases with severe aortic root dilation accompanied by significant regurgitation and in severe AR without aortic root aneurysm. A meta-analysis involving over 7,000 reported cases reported low perioperative mortality rate, ranging from 1% to 2%, with an average rate of 7% for emergency surgeries (typically acute aortic dissections) and 4.6% for reoperations (25). The most common postoperative complication is surgical bleeding requiring thoracic reoperation, with an incidence rate of approximately 5% (25). In a report by David *et al.*, the 15-year survival rate of 333 surgical cases (mean age 46 years) was 78%, the rate of freedom from reoperation was 97%, the rate of freedom from moderate or severe AR was 96%, and the rate of freedom from thromboembolic events was 93%, demonstrating excellent outcomes (26). However, these favorable results were obtained after the exclusion of patients with severe valve degeneration. Furthermore, surgical outcomes can be significantly influenced by a surgeon's experience (27). During follow-up, valve-sparing surgery has been associated with an extremely low incidence of valve-related complications (23). In particular, endocarditis and valve thromboembolism have rarely been reported. This is consistent with the findings of studies comparing composite valve graft replacement with VSRR (28,29) and those by Ouzounian *et al.*, who showed that the VSRR is associated with reduced cardiac mortality and valve-related complications (30).

Several cases of performing VSRR (David procedure)

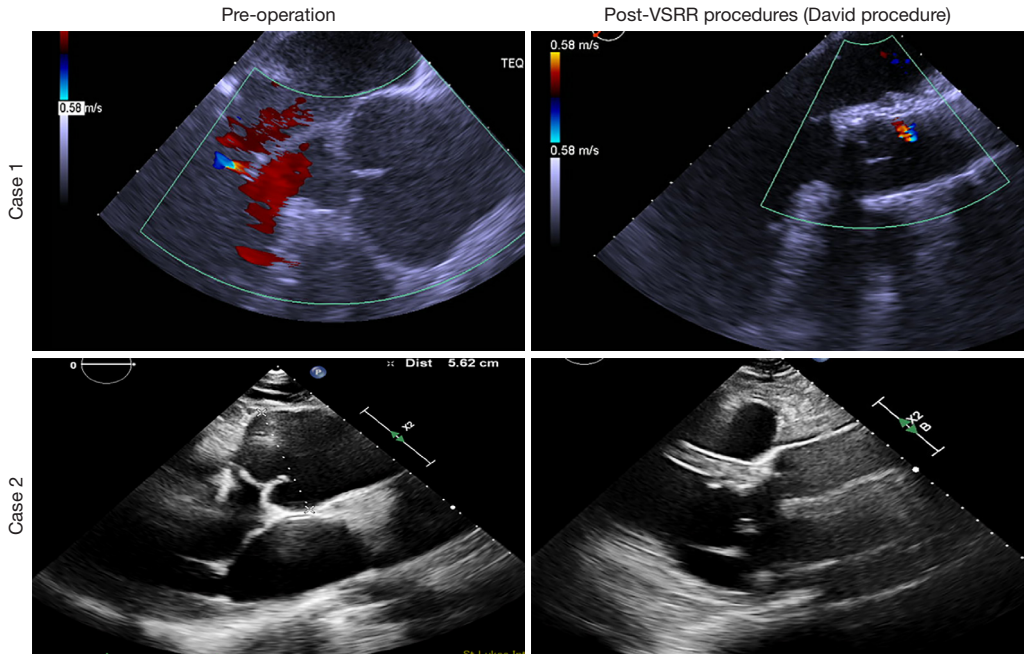

Figure 2 Echocardiographic images before and after surgery. VSRR, valve-sparing root replacement; TEQ, tissue equalization; Dist, distance.

after TOF repair have been reported (31,32). A notable characteristic of the studies is that the included patients were relatively young, aged between 30 and 50 years at the time of surgery, and none of the studies included patients with severe AR. In all cases, the diameter of the ascending aorta was 55 mm or less. Relatively young age at surgery and intact aortic valve leaflets are important factors in VSRR. The postoperative assessment of TOF often requires preoperative CT or MRI examination when planning a subsequent median sternotomy. This is crucial for understanding associated complications and the anatomical relationship of the aorta. First, in a normal heart, the angle between the aorta and left ventricle is 35–45°, whereas in TOF, the aorta is positioned horizontally (33). This horizontal positioning can make visualization of the aortic valve challenging during VSRR. Additionally, a right aortic arch has been reported in 25% of TOF cases, and the aorta tends to dilate easily in these patients (34). Second, in cases of coronary artery anomalies, it is essential to identify their course before commencing surgery. Other preoperative considerations include checking for calcification of the ventricular septal defect patch and the development of collateral blood vessels and assessing whether the right ventricular outflow tract (RVOT) is situated along the midline. These factors contribute to a reduction in surgical risk. Moreover, for cases requiring simultaneous treatment of arrhythmias, RVOT, or pulmonary valves, surgical techniques involving the aorta must be planned to ensure that the procedure can be completed within an appropriate timeframe.

Cases of VSRR procedures

We encountered two cases of VSRR, depicted in *Figures 2,3*.

Case 1

A patient in their 50s underwent intracardiac repair at 5 years of age. Although AR was mild, VSRR (David procedure) was performed because of the enlargement of the SV to 60 mm (*Figure 2*). Basal replacement was performed using a 30 mm Valsalva graft. The geometric heights of the three cusps were maintained between 19 and 24 mm. The AR resolved postoperatively.

Case 2

A patient in their 40s underwent intracardiac repair at 3 years of age. In their 30s, the patient underwent tricuspid valve repair for severe tricuspid valve regurgitation. Although AR was mild, VSRR (David procedure) was performed because of the enlargement of the SV and

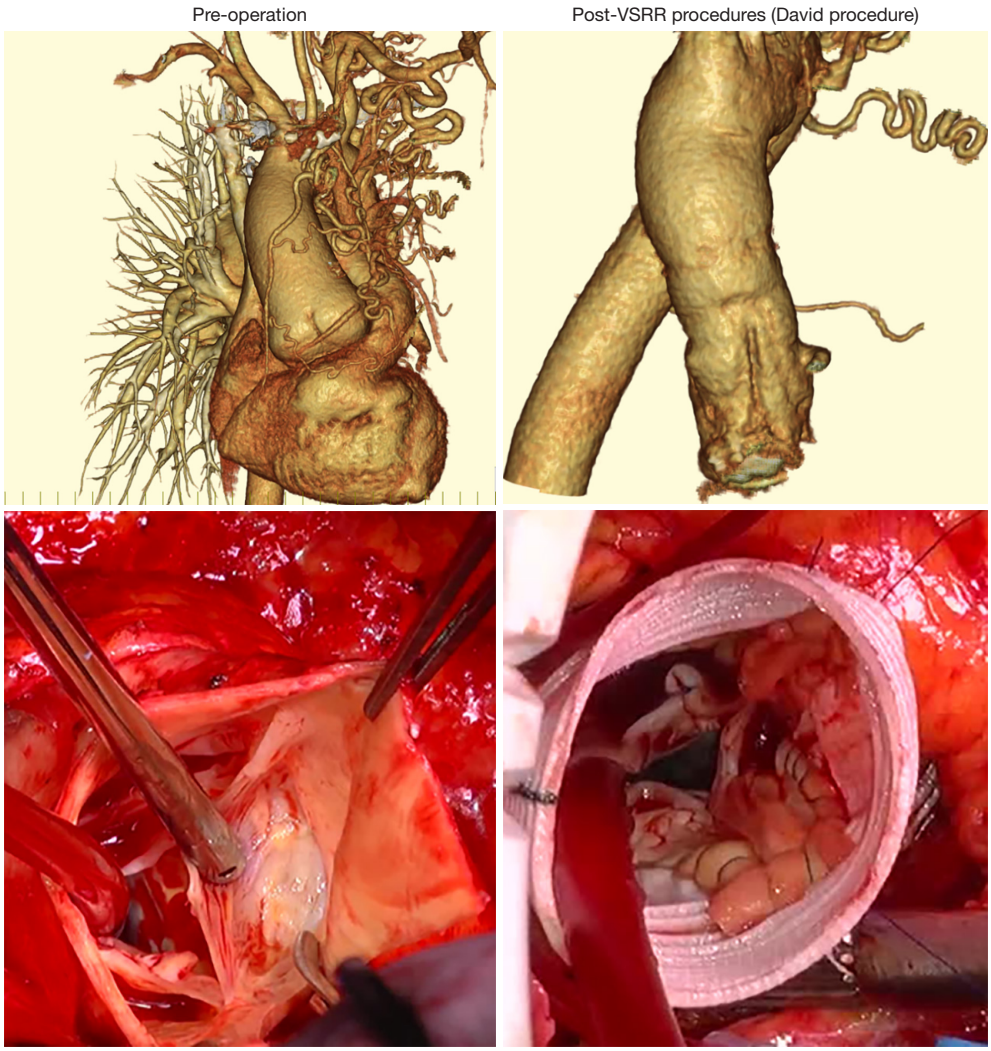

Figure 3 Computed tomography images before and after surgery and images of the aortic valve during surgery. VSRR, valve-sparing root replacement.

ascending aorta to 53 mm. VSRR was performed using a 30 mm Gelweave Valsalva graft for the aortic root. The cusps showed good characteristics, and the free margin was maintained at 19–21 mm, with trivial AR postoperatively.

Timing and precautions for surgical intervention

There is no clear consensus on the cutoff values or surgical techniques for managing AR and aortic root dilation in patients with TOF. VSRR for aortic root dilation is expected to prevent the occurrence of AR, even in its absence. A debate exists regarding the surgical indication based on aortic diameter. VSRR performed by skilled surgeons in young patients with aortic root dilation is a class I, evidence level C recommendation (35). VSRR following TOF repair successfully restores aortic function and reduces AR (36). Although aortic dissection in patients with postoperative TOF is extremely rare, cases have been documented by several institutions (37). The smallest aortic diameter at which dissection was performed was 55 mm (38). Other reports have described cases in which the aorta expanded to significantly dangerous levels, such as 60 and 90 mm (39-41). The indications and timing of prophylactic aortic root replacement in adult patients with congenital heart disease (CHD) have not been described, and the current consensus recommends surgical intervention for an ascending aorta

with a diameter of ≥55 mm (33,42,43). In cases where the ascending aorta is <50 mm, earlier intervention is recommended if there is an increase of >5–10 mm per year, a family history of aortic dissection, or moderate or greater AR (44). I believe that considering the cutoff values, there is also the issue of physical differences, so determining treatment indications with values suitable for each country is appropriate. Aortic diameter should be measured at end-diastole, with the distance being taken between the inner edges of the aortic wall, perpendicular to the wall, from the trailing edge of the anterior wall's outer membrane to the leading edge of the posterior wall's outer membrane. This measurement should be used for follow-up assessments. It is anticipated that as the number of VSRR cases for TOF increases, new insights, including prognosis, will emerge.

There is no clear consensus regarding the use of medications to prevent the progression of aortic dilation. Although uncommon, with a reported incidence of 0.5–4%, it is a serious complication with a high mortality rate (38,45). Therefore, careful postoperative follow-up and prompt evaluation are necessary to monitor the development of disease. The risk tends to increase after TOF repair surgery, highlighting the importance of regular follow-up imaging.

Conclusions

The choice between aortic valve repair and replacement must be made considering factors such as the patient's age and surgeon's experience. In younger patients, long-term follow-up data will potentially guide the decision-making processes. It is crucial to validate the outcomes of VSRR at centers with sufficient expertise.

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Footnote

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