Alternative to pulmonary allograft for reconstruction of right ventricular outflow tract in small patients undergoing the Ross procedure†

Tatsuya Odaa, Takaya Hoashia,*, Koji Kagisakia, Isao Shiraishib, Toshikatsu Yagiharaa and Hajime Ichikawa

a Department of Pediatric Cardiovascular Surgery, National Cerebral and Cardiovascular Center, Suita, Japan
b Department of Cardiology, National Cerebral and Cardiovascular Center, Suita, Japan
* Corresponding author. 5-7-1 Fujishiro-dai, Suita, Osaka 565-8565, Japan. Tel: +81-6-6833-5012; fax: +81-6-6833-9865; e-mail: thoashi@surg1.med.osaka-u.ac.jp (T. Hoashi).

Received 12 September 2011; received in revised form 24 November 2011; accepted 27 November 2011

Abstract

OBJECTIVES: Small pulmonary allografts are difficult to obtain, thus we now use a tailor-made right ventricle to pulmonary artery (RV-PA) conduit for the Ross procedure, consisting of a fresh non-treated autologous pericardial (AP) patch for the posterior wall and expanded polytetrafluoroethylene (ePTFE) monocusp patch for the anterior wall. Long-term durability and RV function were assessed.

METHODS: Between 1997 and 2011, tailor-made conduits were used for right ventricular outflow tract (RVOT) reconstruction in 38 consecutive Ross procedures. Patients were divided into two groups by type of material used for reconstruction of the RVOT anterior wall: Group A (n = 11), pedicled AP patch with ePTFE monocusp valve; Group B (n = 27), ePTFE patch with the ePTFE monocusp valve. The posterior wall was reconstructed with an AP patch in both. We examined survival and freedom from re-intervention, haemodynamic indices by cardiac catheterization, efficacy of the RVOT by ultrasound cardiography (UCG) and exercise capacity at 3 years after the operation. The mean follow-up period was 6.0 ± 0.5 years.

RESULTS: No patients required re-intervention for neo-aortic valve. Overall survival and freedom from re-intervention for RVOT reconstruction at 10 years were 100 and 100%, respectively, in Group A, and 92.6 and 89.4%, respectively, in Group B. No patients showed an RVOT pressure gradient greater than 25 mmHg by cardiac catheterization at 1 year after the operation. All showed less than 2.5 m/s of RVOT flow estimated by Doppler UCG at 6 years. RV function in both groups was preserved at normal in spite of a higher incidence of free RVOT insufficiency in Group A (P = 0.018). Exercise capacity was also preserved at normal in both groups.

CONCLUSIONS: In paediatric patients undergoing the Ross procedure, a tailor-made conduit might be helpful to avoid growth-related RVOT obstruction. The incidence of free RVOT insufficiency was lower than with an anterior ePTFE patch, thus our method may be a better option to preserve RV function for a longer period.

Keywords: Ross • Pediatric • Right ventricular outflow tract reconstruction

INTRODUCTION

Because of haemodynamic superiority, as well as avoidance of anticoagulant therapy and growth potential of the pulmonary autograft, the Ross procedure is still considered to be the procedure of choice for irreparable aortic disease in paediatric patients [1–5]. However, concerns have been raised regarding the consequences of trading one-valve disease for the possibility of ‘iatrogenic’ two-valve disease. Thus, right ventricular outflow tract (RVOT) reconstruction must be carefully performed as much as possible to avoid early/frequent reoperations, and also preserve right ventricular function.

Although pulmonary allografts are commonly used for RVOT reconstruction in Europe and USA, those are scarcely available in other countries, including Japan [6]. Moreover, a reoperation for allograft obstruction is common because of limited durability and its timing is much earlier in paediatric patients when compared with adults, because of the occurrence of patient-graft size mismatch or shrinkage of an oversized conduit [7–11].

To overcome these difficulties, we use a tailor-made right ventricle to pulmonary artery (RV-PA) conduit, in which the posterior wall is treated with a fresh autologous pericardial (AP) patch and the anterior wall with a monocusp patch. This study focused on the mid-term outcomes of our RVOT reconstruction technique in paediatric patients who underwent the Ross procedure.

MATERIALS AND METHODS

Patients

Between 1997 and 2011, a total of 74 patients underwent the Ross procedure at our centre, of those 54 patients were under
In 38 of 54 patients, RVOT reconstruction was performed with a tailor-made conduit, in which the posterior wall was treated with a fresh AP patch, and the anterior wall with an expanded polytetrafluoroethylene (ePTFE) monocusp pedicled auto-pericardium (Group A, n = 11) or ePTFE patch (Group B, n = 27) (Fig. 1). Mean age and body weight at the operation were 9.2 ± 5.3 years old and 33.4 ± 18.2 kg, respectively, in Group A, and 5.6 ± 5.2 years old and 20.4 ± 17.0 kg, respectively, in Group B. Patients younger than 1 year at the time of the operation comprised 9.1% (1/11) of Group A and 25.9% (7/27) of Group B (Fig. 1). Other preoperative characteristics are presented in Table 1. The National Cerebral and Cardiovascular Center Institutional Review Board approved the study and waived the need to obtain patient consent.

### Surgical criteria of the Ross operation

Since small-sized aortic or pulmonary allografts are not presently available, the Ross operation is the favoured approach at our institution for growing patients under 18 years old with two adequately sized ventricles and irreparable aortic valve disease, in cases where a pulmonary autograft is clinically feasible.

When patients with undersize aortic annulus underwent aortic valve replacement with a prosthetic valve, there was no choice but to perform the Ross operation, even when annulus enlargement was concomitantly performed. Otherwise, the advantages and disadvantages of the Ross procedure were carefully informed to the parents of patients, and then the operative methods decided after obtaining informed consent. During the study period, 7 patients under 18 years of age underwent aortic valve replacement using a mechanical valve and 10 a Konno ventriculoplasty with aortic valve replacement using a mechanical valve.

### Surgical procedures

A standard bicaval cardiopulmonary bypass with mild hypothermia (34°C) was established through a median sternotomy. In the Ross–Konno procedure, the RV free wall flap is attached in a longer manner when compared with the standard Ross procedure to augment the Konno incision. In the present patients, the neo-aortic root was reconstructed using a standard root replacement technique with coronary reimplantation. Aortic annulus enlargement (Ross–Konno procedure) was performed in five patients for associated left ventricular outflow tract obstruction, while annulus reduction was performed in five.

For RVOT reconstruction, fresh and non-treated auto-pericardium were trimmed as the posterior auto-pericardial patch for reconstruction of the posterior wall. As shown in Fig. 2A, the size of the fresh auto-pericardial patch used for the posterior wall was decided by considering the following criteria: (i) the width of the distal part is wide enough to augment the whole circumference of the opened pulmonary bifurcation, which can prevent later bifurcation and/or branch pulmonary artery obstruction; (ii) the width of the proximal part can be fitted to cover the opened infundibular septum, or posterior half of the opened right ventricle. Care should be taken to anastomosis it to bare myocardium of the infundibulum, but rather the remaining endocardium, in order to avoid uncontrollable haemorrhaging thereafter; (iii) the length of the patch is the same as the linear distance of the resected portion of the pulmonary trunk. Next, the size of the opened part of the right ventricle was measured using a bougie and the width of the material for the anterior wall was determined in order to make a naturally curved shaped conduit while keeping the same diameter of the opened part of the right ventricle.
A shell-shaped ePTFE monocusp was constructed from a 0.1-mm thick ePTFE sheet with a width slightly greater than a half length of the RVOT circumference, about 1.2-fold. The monocusp was attached to the anterior portion at half of the length of the RVOT circumference so as to constrain RVOT blood flow when the cusp is opened (Fig. 2B). Finally, the opening anterior part of the RVOT was covered with a monocusp patch made of the pedicled auto-pericardium in Group A or an ePTFE patch with a thickness of 0.6 mm in Group B (Fig. 2C).

Follow-up examinations

Long-term follow-up examinations were completed in the whole cohort, with a mean follow-up period of 6.4 ± 4.1 years (range, 0.1–14.2 years). For early haemodynamic assessment, RVOT pressure gradient, right ventricular end-diastolic pressure (RVEDP), right ventricular end-diastolic volume (RVEDV) and right ventricular ejection fraction (RVEF) were determined at 1.1 ± 0.3 years (range, 0.9–1.2 years) after the operation using a catheter examination. For continuous haemodynamic assessment, RVOT pressure gradient, RVOT insufficiency and tricuspid regurgitation were examined using echocardiography. Free RVOT insufficiency was qualitatively defined when a regurgitant jet was observed from the entire annulus width with diastolic flow reversal in the branch pulmonary arteries by Doppler echocardiography. The prevalence of a functioning monocusp valve was continuously assessed by 2D echocardiography. Tricuspid insufficiency grades of none, trivial, mild, moderate and severe were assigned according to a subjective scale. A standardized exercise capacity test was performed at 3.2 ± 2.8 years (range, 1.0–10.0 years) after the operation to determine the adverse effects of RVOT reconstruction.

Statistical analysis

Continuous data obtained in this study are expressed as the mean ± standard deviation (range). All statistical analyses were performed with PASW Statistics 18 software (SPSS Inc., Chicago, IL, USA). Survival rate and freedom from re-operation rate were calculated using the Kaplan–Meier method. A log-rank test was applied for comparisons between time-related variables. The Mann–Whitney U-test was used to compare continuous variables, and the Chi-square test was used to compare categorical data between the two groups. Values of \( P < 0.05 \) were considered to be significant. The normal size of the RVEDV was calculated from body surface area, according to the method of Kirklin and Barratt-Boyes [12].

RESULTS

Intraoperative outcomes

Mean cardiopulmonary bypass time was 247.4 ± 37.2 minutes in Group A and 280.4 ± 62.3 minutes in Group B, while mean cross-clamp time was 114.1 ± 22.7 and 150.0 ± 27.3 minutes,
respectively \((P = 0.001)\). Concomitant procedures included ventricular septal defect repair in two patients, mitral valve repair in one and aortic arch repair in one.

Overall outcomes

The cumulative overall survival rates at 1, 5 and 10 years after the operation were 100, 100 and 100%, respectively, in Group A, and 92.6, 92.6 and 92.6%, respectively, in Group B (Fig. 3A). There were two early mortalities in Group B. The first case was a 6-month-old infant with acute aortic insufficiency caused by infective endocarditis, who died on postoperative day 21 because of a protracted systemic infection. The other case was a 4-month-old infant with critical aortic stenosis and moderate pulmonary insufficiency/stenosis. Since no suitably sized aortic allograft or other materials were available, we decided to perform the Ross operation as palliative and salvage surgery. The patient developed cardiogenic shock derived from neo-aortic insufficiency on postoperative day 1.

None of the patients required re-intervention for a neo-aortic valve. Freedom from re-intervention for RVOT reconstruction at 1, 5 and 10 years was 100, 100 and 100%, respectively, in Group A, and 100, 89.4 and 89.4%, respectively, in Group B (Fig. 3B). In Group B, 3 of the 27 patients underwent RVOT re-intervention, of whom 2 later underwent redo RVOT reconstruction with an ePTFE valved conduit concomitant with tricuspid annuloplasty for severe tricuspid insufficiency at 2.5 and 3.5 years, respectively, after the Ross procedure. At the time of reoperation, the peak pressure gradient across the RVOT was less than 10 mmHg in both patients, while there was no free RVOT insufficiency. The remaining patient underwent balloon pulmonary angioplasty for RVOT obstruction at 1 year after the Ross procedure.

Early haemodynamic assessment

Catheter examination was performed at 1.1 ± 0.2 years after the operation, which showed that RVEF was maintained in both groups (Group A: 54.2 ± 9.4%, range 38.0–70.0%; Group B: 57.0 ± 9.2%, 44.0–89.0%) (Fig. 4A) and peak pressure gradient across RVOT in all patients in both groups was less than 25 mmHg (Group A: 6.9 ± 7.6 mmHg, 0–18.0 mmHg; Group B: 4.2 ± 3.3 mmHg, 0–12.0 mmHg) (Fig. 4B). On the other hand, %RVEDV in Group B was significantly greater than that in Group A (106.0 ± 22.4% of normal, range 80.0–152.0% vs. 127.9 ± 34.2% of normal, range 73.0–171.0%; \(P = 0.035\)) (Fig. 4C). RVEDP was not significantly different between the groups (Group A: 7.8 ± 1.6 mmHg, 6.0–10.0 mmHg; Group B: 8.0 ± 2.4 mmHg, range 3.0–12.0 mmHg; \(P = 0.61\)) (Fig. 4D).

Continuous haemodynamic assessment

During the follow-up period, serial changes in peak pressure gradient across RVOT determined by echocardiography in all 36 survivors was less than 15 mmHg (Fig. 5).

Free RVOT insufficiency was detected within 1 year after the operation in 8 of the 11 patients (72.7%) in Group A and 5 of the 24 (20.8%) in Group B (\(P = 0.002\)) (Fig. 6A). On the other hand, freedom from free RVOT insufficiency assessed by the Kaplan–Meier method at 5 years was 32.7% in Group A and 74.3% in Group B (log-rank, \(P = 0.285\)) (Fig. 6B).

The attached ePTFE monocusp valve was functional in 3 of the 11 patients (27.3%) in Group A and 19 of the 24 (79.2%) in Group B (\(P = 0.003\)) at 1 year after the operation, and in 2 of the 11 patients (18.2%) in Group A and 13 of the 20 (79.2%) in Group B (\(P = 0.003\)) at 5 years after the operation (Fig. 6C).

Greater than moderate tricuspid insufficiency was detected in 1 of the 11 patients (9.1%) in Group A and 7 of the 24 (29.2%) in Group B at 1 year after the operation (\(P = 0.15\)), and in 1 of the 11 (9.1%) and 6 of the 20 patients (30.0%), respectively, at 5 years after the operation (\(P = 0.14\)).

Exercise capacity test

The exercise capacity test results at 3.2 ± 2.8 years (1.0–10.0 years) after the operation showed that mean peak VO2 was preserved within a normal range in both groups, with no significant differences between them (Group A: 33.0 ± 4.6 l/min/kg; Group B: 30.6 ± 9.6 l/min/kg; \(P = 0.33\)) (Fig. 7).
DISCUSSION

The present study found good mid-term outcomes in patients who received our tailor-made RV to PA conduit, which consisted of a fresh, non-treated auto-pericardial posterior wall, and monocusp ePTFE or auto-pericardial anterior wall. We consider that ePTFE patch is a more suitable material for the anterior wall based on the following results: (i) freedom from re-intervention for RVOT at 10 years was 100% in Group A and 89.4% in Group B; (ii) although two patients underwent redo RVOT reconstruction in Group B, neither showed stenosis nor significant insufficiency at the time of the reoperation; (iii) peak pressure gradient across the RVOT did not exceed 15 mmHg in any patient during the follow-up period; (iv) although late free RVOT insufficiency was equally observed in both groups, which progressed earlier, as well as right ventricular dilatation in Group A; (v) exercise capacity was maintained in both groups.

Although we anticipated potential growth of the pedicled auto-pericardium and used it as an anterior wall during the early study period, expansion of the anterior wall causes stretching of ePTFE monocusp, which results in early free RVOT insufficiency. Instead, we have been using an ePTFE patch with a thickness of 0.6 mm as a rigid base for an attached monocusp valve since 2001, which has significantly improved monocusp valve function. Indeed, movement by the monocusp valve could be observed by echocardiography up to 7 years after the operation. Interestingly, RVOT stenosis was not detected when an ePTFE patch was used as an anterior wall, possibly due to natural dilation of the posterior wall provided by the fresh, non-treated auto-pericardial patch.

There is no question that a pulmonary allograft is the best available material for RVOT reconstruction associated with the Ross procedure. Although several investigators have reported good short- or mid-term durability of other materials, progressive obstruction is still inevitable [13–17]. Proper size selection and technical modifications for suppressing immune response, such as bicuspidalization, cryo-preservation or may prolong durability and improving long-term results [18–22].

Figure 4: Right heart structure function determined by a catheter examination at 1.1 year after the operation. (A) RVEF. (B) Peak pressure gradient across right ventricular outflow tract (RVOT). (C) Percent of normal right ventricular end-diastolic volume (%RVEDV). (D) RVEDP.

Figure 5: Serial changes in peak pressure gradient across right ventricular outflow tract.
The occurrence of RVOT insufficiency is a concern related to our reconstruction technique. Reoperation for RVOT should be performed before symptoms of right ventricular failure are manifested. However, the optimal timing of redo RVOT reconstruction for such insufficiency is unclear. In contrast to aortic insufficiency, forward pulmonary blood flow can be maintained indirectly by the work of the left heart via systemic venous return and right atrial contraction. Free pulmonary insufficiency is usually associated with a regurgitant fraction of about 40% [23–24], although symptoms are rare before the age of 30 in patients with isolated pulmonary insufficiency, as previously reported [25]. Although careful follow-up examinations should be mandatory, we consider that the present reconstruction technique is an acceptable alternative to a pulmonary allograft for avoiding RVOT obstruction and reoperation.

**STUDY LIMITATION**

The present study was not conducted in a randomized or prospective manner, thus the evolution of surgical techniques over time might have had effects on patient outcomes. However, the mechanism of early and frequent free RVOTO insufficiency in Group A was self-growth (or dilatation) of the pedicled auto-pericardium, which stretched the attached monocusp. Thus, we believe that the use of an anterior ePTFE patch is a better option.

Another limitation is that the anterior pedicled auto-pericardial patches were fresh and not treated, as we considered that growth of that part would later prevent RVOT obstruction. However, natural expansion of the posterior auto-pericardial patches effectively maintained non-obstructive RVOT, thus the results would have been different if the anterior pedicled auto-pericardial patch had been treated with glutaraldehyde.

**CONCLUSION**

In conclusion, we consider that the use of our tailor-made conduit is useful to avoid growth-related RVOT obstruction in paediatric patients undergoing the Ross procedure. Since the incidence of free RVOT insufficiency was lower with an anterior ePTFE patch in our patients, this may be a better option to preserve RV function for a longer period after surgery.

**Conflict of interest:** none declared.

**REFERENCES**


[11] Brown JW, Ruzmetov M, Rodefeld MD, Turrentine MW. Right ventricular outflow tract reconstruction with pulmonary allografts has a very well established reputation in this and similar groups of patients, it is the longevity that is very limited. That is why the solution proposed by Dr. Oda and his colleagues is an alternative, and 6.4 years follow-up seems to be long enough to prove the mid-term results and effectiveness of this tailor-made conduit.

In your study population, there were significant differences in patient size, age, and proportion of infants between both groups. In group B, patients were younger with a higher proportion of infants. On the other hand, patients in group A, with the pedicled autologous pericardial patch, underwent surgery before 2001. So the follow-up is substantially longer, and this group is quite small.

The only important difference that I can see in the results between your two groups of patients is less free RVOT insufficiency and less RV dilatation one year postoperatively in group B with a complete PTFE monocusp patch. So my first question relates to the methodology of your study. Do you not think that such demographically different groups, almost from two almost different surgical eras, are quite difficult to compare and draw conclusions from? Would you like to answer this now?

Dr Oda: For the first question, actually, yes, you are absolutely right. It is not fair to compare these two groups. The two groups were not comparable. Initially we tended to apply the pedicled autologous patch in most of the patients. However, since we tend to perform the Ross operation in the younger age group, our use of the pedicled autologous patch decreased. By then we thought the use of the free autologous patch to the posterior wall of the RVOT was very useful. Therefore, we continued to use this patch for the reconstruction of the anterior wall. We use the ePTFE monocusp patch.

In this present study, we believe that we could prove the usefulness of RVOT posterior reconstruction with autologous patch followed by RVOT anterior wall reconstruction with a separate patch. The growth or dilatation in the diameter of the conduit is mainly due to the use of autologous patch in this posterior wall.

Dr. Maruszewski: I understand that. My second question is practical. If you had pulmonary homografts available at any time, would you change your strategy from your self-made graft to the pulmonary homografts or not, using this experience?

Dr. Oda: Actually, no. We do not use them, especially in small patients less than 20 kg. Even if we have an ideal size of pulmonary homograft for the patients and if we use a small homograft to reconstruct the RVOT, the timing of the reconstruction of RVOT might be earlier than with our method.

Dr. Maruszewski: Okay. And my final question goes rather to your interventional cardiology colleagues. Do you know if your cardiologists see these patients as potential candidates for percutaneous implantation of self-expandable pulmonary valves and if there is any difference between the two groups in this aspect? Can they be replaced later with a percutaneous self-expandable valve?

Dr. Oda: It would be nice if we could place a self-expandable percutaneous pulmonary valve in the long-term follow-up period if they develop severe pulmonary insufficiency. However, we are not sure whether our conduit is suitable for the implantation of such devices a long time after the implantation. The shape and lens of the landing zone of this self-expandable valve is still important in planning the overall treatment of the patient. So you understand my question? I am saying that usually monocusps tend to disintegrate. We saw that you did not get a lot of residual gradients, and that is good. You have demonstrated that using PTFE is better than using pericardium, although it is associated with a much higher reoperation rate than with the pericardium. What is your interpretation of this? Did you understand my question? I am saying that usually monocusps tend to disintegrate over time. You have demonstrated that PTFE looks more suitable, but looking to your actual survival curves, the patients with the pericardium have been reoperated more often. Can you suggest any explanation?

Dr. H. Ichikawa (Suita, Japan): My name is Dr. Ichikawa. I am a coauthor. The reason for reoperation was not because of the monocus or stenosis. We had two reoperations, but these were required because of aortic problems. And then at the time of the aortic reoperation, we just revised the RVOT. So actually, if the monocus is very carefully designed (what we use is like a fan-shaped monocus patch), the patch keeps moving for many years, so we think the monocus patch is okay.