The modified Ross operation using a Dacron prosthetic vascular jacket does prevent pulmonary autograft dilatation at 4.5-year follow-up

Faleh Al Rashidi, Misha Bhat, Peter Höglund, Carl Meurling, Anders Roijer, Bansi Koul

Abstract

Objective: Following the Ross operation, pulmonary autografts tend to dilate over time. This study researches the fate of the pulmonary autograft — at 4.5 years following the modified Ross operation — with special reference to the impact of the modification on (a) pulmonary autograft dilatation, (b) the neo-aortic root geometry, (c) neo-aortic valve function and (d) the coronary artery reserve. Methods: A total of 26 patients who underwent the Ross operation were included in this study; of these, 13 consecutive patients underwent a modified Ross operation in which the free-standing autograft root was supported externally by a Dacron vascular prosthetic jacket (DVPJ). These patients were compared to a cohort of 13 matched patients who were operated on using the conventional Ross technique; all patients were followed up prospectively by echocardiography studies. The patients who underwent the modified Ross operation were also subjected to bicycle ergometry. Results: At the 47-month median follow-up, there was no significant increase in the size of the entire neo-aortic root in the patients who underwent the modified Ross operation; in addition, the geometry of the neo-aortic root was also preserved and the left ventricular function had improved significantly, whilst the aortic valve function and excursion remained satisfactory. All patients, with one exception, in the modified Ross operation group exhibited normal exercise capacity. By contrast, there were significant differences in diameters of the aortic root — between the two surgical techniques in favour of the modified Ross technique — following a median follow-up of 23 months in the patients subjected to the conventional Ross operation. Conclusions: Provision of external support to the entire pulmonary autograft with a DVPJ prevents its dilatation following free-standing pulmonary autograft Ross operation when evaluated at the 4.5-year follow-up. The function and the geometry of the neo-aortic root are not affected negatively by this modification and the patients demonstrated normal exercise capacity.

Keywords: Dacron prosthetic vascular jacket; Echocardiography; Pulmonary autograft; Ross operation

1. Introduction

Aortic valve replacement using the free-standing pulmonary autograft (conventional Ross operation) runs potential risks of autograft dilatation and autograft valve dysfunction.

Recent studies have shown that the variation in freedom from autograft dilatation following the conventional Ross operation ranges between 43% and 48% at 5—10 years follow-up [1,2]. Further, the freedom from significant autograft valve insufficiency ranges between 91—98% and 63—88% at 5 and 10-year follow-up respectively [1,3—9]. The freedom from autograft reoperation, however, ranges between 94—99% at 5 years and 72—93% at 10 years [1,3,5,7—11]. A significant pulmonary autograft dilatation can occur as early as 7—10 days following the conventional Ross operation, with a further significant increase in the first year [12—14]. The mean rate of the pulmonary autograft dilatation is estimated at ≤1.4 percentage points per year [2,4]. It is evident that the mid- and long-term fate of the pulmonary autograft following the conventional Ross operation is not optimal.

We reported in our previous clinical study with the conventional Ross operation that patients with bicuspid aortic valve disease and aortic insufficiency suffered from significant autograft dilatation at the sinus of Valsalva dilatation after a mean follow-up of 19 months [15]. Intraoperative external support of the neo-aortic annulus (AA) and the neo-sino-tubular junction (STJ) with Dacron or Teflon strips seems to prevent dilatation at these sites post-operatively [4,8]. However, dilatation of the neo-aortic sinuses of Valsalva (SVs) continues to remain an unsolved problem. Dilated autografts carry risk of re-operation, rupture and dissection [16]. To prevent or minimise the problem of pulmonary autograft dilatation, the Ross operation has been modified by supporting the entire pulmonary
autograft externally with a Dacron vascular prosthetic jacket (DVPJ). The size of the DVPJ is tailored individually to match the size of the pulmonary autograft [17]. In this study, the fate of the pulmonary autograft has been prospectively evaluated with trans-thoracic echocardiography (TTE) and bicycle ergometry at the 4.5-year follow-up following operation with the modified technique.

2. Materials and methods

A total of 26 patients underwent the Ross operation in this study (Table 1); of these, 13 patients consecutively underwent the modified Ross operation from April 2003 in which the free-standing pulmonary autograft root was supported externally with an appropriately sized DVPJ (Vascutek-Gelweave, Vascutek Ltd., Renfrewshire, Scotland — Modified Ross group). These patients were compared with a cohort of 13 patients — matched for age, sex, aortic valve lesion, the New York Heart Association (NYHA) functional class and left ventricular ejection fraction — who were operated using the conventional Ross operation technique (conventional Ross group), performed immediately prior to the introduction of the modified Ross technique. All patients were operated upon by one surgeon (BK).

2.1. Surgical technique

2.1.1. Modified Ross operation

The technique of the modified Ross operation has been reported by us earlier [17]. In brief, following excision of the aortic valve, the aortic annulus diameter was downsized at the level of the sub-commisural triangles to that of the intra-operatively measured pulmonary autograft annulus as and when required (Table 1). The entire pulmonary autograft was supported externally by a DVPJ (Fig. 1). The diameter of the DVPJ was calculated from the internal pulmonary autograft annulus diameter, as measured intra-operatively, to which 4 mm were added to compensate for the pulmonary autograft wall thickness (Table 2). The DVPJ was used en bloc to support the neo-AA, neo-SV and the neo-STJ. The pulmonary autograft, together with the DVPJ, was sutured in a horizontal plane immediately proximal to the bottom of the excised aortic valve cusps using isolated, interrupted 4/0 Ethibond sutures (Ethicon, Johnson & Johnson Intl., Belgium). The length of the DVPJ was tailored in a stretched state to match the length of the pulmonary autograft. Two large windows were excised from the DVPJ to allow free passage of the coronary arteries (Fig. 1). The coronary artery anastomoses to the pulmonary autograft were made.

Table 1
Preoperative patient demography, values expressed as median (Q1–Q3).

<table>
<thead>
<tr>
<th></th>
<th>Modified Ross (n = 13)</th>
<th>Conventional Ross (n = 13)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>36 (31–40)</td>
<td>38 (33–41)</td>
<td>0.75</td>
</tr>
<tr>
<td>Males (%)</td>
<td>77</td>
<td>77</td>
<td>1</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>2 (1.9–2.1)</td>
<td>2 (1.9–2.0)</td>
<td>0.52</td>
</tr>
<tr>
<td>NYHA functional class</td>
<td>1 (1–2)</td>
<td>1 (1–2)</td>
<td>0.86</td>
</tr>
<tr>
<td>Left ventricular ejection fraction (%)</td>
<td>59(50–64)</td>
<td>69 (59–72)</td>
<td>0.17</td>
</tr>
<tr>
<td>Indication for Ross operation</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Dominant aortic insufficiency (%)</td>
<td>62</td>
<td>62</td>
<td>1</td>
</tr>
<tr>
<td>Dominant aortic stenosis (%)</td>
<td>38</td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td>Patients with bicuspid aortic valve (%)</td>
<td>77</td>
<td>92</td>
<td>0.59</td>
</tr>
<tr>
<td>Other concomitant diagnoses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ascending aortic aneurysms (%)</td>
<td>23</td>
<td>31</td>
<td>1</td>
</tr>
<tr>
<td>Aortic arch aneurysms (%)</td>
<td>8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Echocardiographic measurements</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Aortic annulus diameter (mm)</td>
<td>25 (24–29)</td>
<td>26 (22–27)</td>
<td>0.81</td>
</tr>
<tr>
<td>Sinus Valsalva diameter (mm)</td>
<td>36 (34–39)</td>
<td>38 (32–40)</td>
<td>0.79</td>
</tr>
<tr>
<td>Sino-tubular junction diameter (mm)</td>
<td>28 (26–34)</td>
<td>32 (29–36)</td>
<td>0.41</td>
</tr>
<tr>
<td>Diameter of the ascending aorta (mm)</td>
<td>34 (30–45)</td>
<td>34 (32–39)</td>
<td>0.93</td>
</tr>
<tr>
<td>Pulmonary valve annulus diameter (mm)</td>
<td>24 (23–27)</td>
<td>24 (23–26)</td>
<td>0.71</td>
</tr>
</tbody>
</table>

The p value calculated using: Exact Wilcoxon Mann—Whitney rank sum test.

* Measured 1 cm above the sino-tubular junction.
separately after punching out holes in the pulmonary autografts at the corresponding sites and without incorporating the DVPJ in the suture lines. Finally, the neo-STJ, together with the DVPJ, was sutured to the distal ascending aorta with a running, monofilament non-absorbable suture. The right ventricular outflow tract was reconstructed with appropriately sized pulmonary homografts in both groups studied.

2.1.2. Conventional Ross operation

The surgical technique used in this study has been described earlier [15]. In brief, following excision of the aortic valve, the AA diameter was downsized at the level of the subcommissural triangles to that of the intra-operatively measured pulmonary autograft annulus. The pulmonary autograft was sutured to the AA in a horizontal plane at a level corresponding to the bottom of the excised aortic valve cusps using isolated, interrupted 4/0 Ethibond sutures. The coronary artery anastomoses to the pulmonary autografts were made separately after punching out holes in the pulmonary autografts at the corresponding sites. Distally, the pulmonary autograft was sutured to the distal ascending aorta with a running, monofilament non-absorbable suture. The right ventricular outflow tract was reconstructed with appropriately sized pulmonary homografts in both groups studied.

2.2. Follow-up

All patients were prospectively followed up, for the first time, at our hospital by TTE in a session, at a time period which corresponded to a median follow-up period of 16 months (12–21 months; quartiles-1 (Q1) to quartiles-3 (Q3)) for the modified Ross operation group and 23 months (10–34 months, Q1—Q3) for the conventional Ross operation group. The modified Ross operation group was followed up again, prospectively, after a median 47-month period (40.8–48.6 months; Q1–Q3, maximal: 54 months) with TTE and ergometric evaluation (Fig. 2). Exercise capacity was assessed by bicycle ergometry with gradually increasing resistance and monitoring of heart rate and blood pressure. The results were expressed as percentages of the expected maximum physical work capacity — taking age and gender into account. In accordance with the clinically used cut-off values, exercise capacity ≥80% of the predicted value was considered normal and exercise capacity <80% as sub-normal.

2.3. Echocardiographic studies

All the patients underwent TTE and trans-oesophageal echocardiography (TEE) with a Hewlett-Packard Sonos 5000 (Hewlett-Packard, Andover, MA, USA) with a 2.5- or 3.5-MHz transducer for TTE and a 5-MHz multi-plane transducer for TEE measurements. Preoperative recordings were performed with TTE and TEE. Postoperative and follow-up recordings were performed with TTE. Autograft dimensions were measured at four different levels: (1) AA at the level of leaflet hinges; (2) SV at the largest anteroposterior diameter; (3) STJ at the distal rim of the sinus and (4) proximal ascending aorta, 1 cm above the STJ [18]. All postoperative and follow-up measurements were calculated at end diastole from the parasternal long-axis view of the aortic valve and

![Fig. 2](image-url)

**Fig. 2.** Left ventricular ejection fraction and the exercise capacity following the modified Ross operation after 47-month median follow-up (n = 12). AI: aortic insufficiency, AS: aortic stenosis.
the aorta. The neo-aortic root diameters were measured at the end systole and the end diastole to assess the distensibility of the aortic root. Autograft aortic regurgitation was assessed from multiple echocardiographic windows using multiple techniques: the ratio of jet height/left ventricular outflow diameter, the vena contracta, the pressure half-time of the aortic regurgitant jet and colour Doppler imaging. The degree of aortic regurgitation was graded in four grades: 0 = none; 1 = mild; 2 = moderate and 3 = severe.

Homograft pulmonary regurgitation was assessed from the parasternal short-axis view and graded in the same fashion as aortic regurgitation. Homograft transvalvular gradients were calculated using continuous wave Doppler and graded as follows: mild = peak pressure gradient < 30 mmHg; moderate = peak pressure gradient 30–50 mmHg and severe = peak pressure gradient > 50 mmHg [19]. All follow-up TTE studies in the modified Ross group were analysed for aortic leaflet motion against the neo-SV during systole and for the geometry of the neo-aortic root. The preoperative, post-operative and follow-up echocardiographic studies were analysed by two senior cardiologists (CM and AR) blinded to the type of Ross operation performed.

### 2.4. Statistical analyses

Continuous variables are presented as medians, with Q1 and Q3. Categorical variables are given as percentages and frequencies. The differences observed in the preoperative and intra-operative data in the modified and the conventional Ross groups were tested for significance with the Exact Wilcoxon Mann—Whitney rank sum test (Tables 1 and 2). The differences observed in various echocardiographic variables from discharge to follow-up were analysed for significance separately for the modified and the conventional Ross groups using Exact Wilcoxon signed-rank sum test (Table 3). The echocardiographic variables at discharge and follow-up in the modified Ross group were also compared with similar data from the conventional Ross group and differences observed were analysed for significance using Exact Wilcoxon Mann—Whitney rank sum test (Table 3). In order to minimise the problem with multiple comparisons, the primary aim of the study was chosen to be the differences in the diameter between the two surgical techniques at follow-up. Uncorrected p-values are reported in the article. Data were analysed using R software (R foundation for statistical computing, Vienna, Austria) Version 2.6.2. The level of significance was set at $p < 0.05$.

### 3. Results

The two groups were well matched statistically in all preoperative and intra-operative clinical variables (Tables 1 and 2), apart from AA diameter as measured intra-operatively following excision of the aortic valve ($p = 0.043$; Table 2). The AA was reduced to match the size of the pulmonary autograft in 85% of patients in both groups. The median diameter of the pulmonary autograft annulus was measured directly, intra-operatively—was also similar in the two groups (Table 2). At discharge, all neo-aortic root variables as measured by echocardiography were statistically similar for the two groups (Table 3). One patient from the modified Ross group underwent re-operation for pulmonary autograft endocarditis 7 months postoperatively. During re-operation, this patient suffered from cardioplegia catheter-induced left main coronary artery dissection and left ventricular infarction. Following nearly 1 year of mechanical cardiac support with a Jarvik-2000 left ventricular assist device, this patient was successfully transplanted and is doing well. This patient was therefore excluded from the follow-up analysis. All other patients included in this study are alive and doing well and none has been re-operated. Subsequent to the median follow-up of 16 months, the median diameters of the aortic root in the modified Ross group were as follows: AA = 22 mm (Q1: 21–Q3: 25; $p = 0.63$), SV = 30 mm (Q1: 29–Q3: 32; $p = 0.64$), STJ = 26 mm (Q1: 25–Q3: 28; $p = 0.13$) and the ascending aorta 1 cm above the STJ = 29 mm (Q1: 27–Q3: 32; $p = 0.37$) [17]. These diameters continued to remain unchanged at the second follow-up after a median postoperative interval of 47 months (Table 3). Alternatively, in the conventional Ross operation group, the median diameters of the AA, SV, STJ and 1 cm above the STJ increased significantly from 22 to 23 mm ($p = 0.027$), 31 to 36 mm ($p = 0.0005$), 27 to 31 mm ($p = 0.0097$) and 28 to 31 mm ($p = 0.00097$), respectively, after a median follow-up of

### Table 3

<table>
<thead>
<tr>
<th>Echocardiographic measurements at discharge and follow-up, values expressed as median (Q1—Q3).</th>
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<tbody>
<tr>
<td><strong>Modified Ross</strong></td>
</tr>
<tr>
<td>Discharge</td>
</tr>
<tr>
<td>Aortic annulus diameter (mm)</td>
</tr>
<tr>
<td>Sinus Valsalva diameter (mm)</td>
</tr>
<tr>
<td>STJ diameter (mm)</td>
</tr>
<tr>
<td>Diameter one cm above STJ (mm)</td>
</tr>
<tr>
<td>Aortic insufficiency (grade 0–3)$^a$</td>
</tr>
<tr>
<td>Gradient across aortic valve (mmHg)</td>
</tr>
<tr>
<td>Left ventricular ejection fraction (%)</td>
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</table>

$^a$Exact Wilcoxon signed rank test.
$^b$Comparing echocardiographic variables of the two groups at discharge using Exact Wilcoxon Mann—Whitney rank sum test.
$^c$Comparing echocardiographic variables of the two groups at follow-up using Exact Wilcoxon Mann—Whitney rank sum test.
$^d$Grade 0 = none, grade 1 = mild, grade 2 = moderate, grade 3 = severe.
of just 23 months (Table 3). No patient had significant aortic insufficiency at the follow-up in both the groups and all patients showed significant improvement in the left ventricular function (Table 3). The geometry of the aortic root was normal in the modified Ross operation group patients and these patients could not be differentiated visually from those in the conventional Ross operation group by the investigators. Moreover, the neo-aortic valve cusps did not hit the neo-aortic sinus wall during cardiac systole in any patient in the modified Ross operation group. The neo-aortic root showed minimal change (1 mm) in the diameters during cardiac cycle. At the 47-month median follow-up, the median exercise capacity of the patients who had undergone the modified Ross operation was 102% of the expected normal (Fig. 2). Only one patient had exercise capacity <70% of the expected normal. This patient suffered from severe aortic insufficiency preoperatively and had the lowest ejection fraction (36%) in this study. At the latest follow-up, this patient’s ejection fraction had improved to 40%.

4. Discussion

We reported the present modification in the Ross operation in this journal in the year 2002. Since then, two more scientific publications have discussed modification of the Ross operation along lines similar to ours using vascular prostheses to support the pulmonary autograft [20–21]. The present study reports the fate of the tubular DVPJ following 4.5 years of follow-up with special reference to (a) the pulmonary autograft and DVPJ dilatation (b) the impact of using DVPJ on the neo-aortic root geometry (c) the impact of DVPJ on neo-aortic valve function and (d) the impact of DVPJ on the coronary artery reserve.

In addition to the above modifications in the Ross operation where a Dacron graft is used, there is also a clinical study published in the medical literature by Skillington et al. in which the patient’s native aorta has been wrapped around the pulmonary autograft to prevent the dilatation of the entire pulmonary autograft early following a Ross operation [22]. However, this method has certain theoretical disadvantages. The aortic root is significantly large in patients with bicuspid aortic valve and aortic insufficiency than in a normal population matched for sex and body surface area [15]. Wrapping of the pulmonary autograft with an already dilated native aortic root may, therefore, not provide adequate protection against autograft dilatation at mid- or long-term follow-up. Furthermore, the aortic root tends to be small in patients with bicuspid aortic valve disease with aortic stenosis [15]. Therefore, wrapping a larger pulmonary autograft with a relatively small native aortic root in this subset of the population may distort the pulmonary autograft geometry and function. These apprehensions encouraged us to look for alternative modifications that could provide external support of the entire neo-aortic root and, at the same time, preserve the normal geometry of the aortic root and the aortic valve function.

The tailor-made DVPJ significantly prevented dilatation of the neo-AA, neo-SV, neo-STJ and ascending aorta 1 cm above the STJ in the modified Ross operation group following a median follow-up of 47 months (Table 3). This impact was already noted at the first major follow-up subsequent to a median period of 16 months and the results continued to remain stable at the recent follow-up of 4 years. Moreover, the geometry of the aortic root — as assessed subjectively on TTE — was not affected with the use of the DVPJ. The identical median diameters of the neo-AA (23 mm), neo-SV (30 mm) and neo-STJ (25 mm) both at discharge and at the 47-month median follow-up confirm, objectively, as well that the use of cylindrical DVPJ does not affect the normal geometry of the neo-aortic root. Further, the DVPJ did not affect the function of the neo-aortic valve following a median follow-up of 47 months (Table 3) and the neo-aortic valve cusps did not hit the neo-aortic sinus wall during cardiac systole in any patient.

However, the diameters at the level of the AA, SV, the STJ and the ascending aorta 1 cm above the STJ increased significantly in the conventional Ross operation group at the median follow-up of just 23 months (Table 3). It occurred despite the fact that 85% of patients in this group underwent native AA reduction by suture obliteration of one or more sub-commissural triangles to match pulmonary autograft–annulus size. In addition, 54% patients in this group had the proximal AA suture line supported externally with a strip of Dacron or Teflon. This may, on the other hand, explain why the median AA diameter in the conventional Ross group did not show any significant difference from that of the modified Ross group — both at discharge and at follow-up (Table 3).

The use of DVPJ in the modified Ross operation did not prolong the aortic occlusion time, cardio-pulmonary bypass time, time on ventilator and the stay in the intensive care when compared with the conventional Ross operation group (Table 2). The modified Ross operation was performed with equal ease in patients with aortic stenosis and aortic insufficiency and irrespective of the preoperative size of the native aortic root. Perioperative bleeding and the need for blood transfusions were comparable in the two groups. The perioperative morbidity and mortality and the mid-term survival in the modified Ross operation group also compared well with the studied outcome of the matched conventional Ross operation group. It has also been shown, in this study, that the DVPJ does not negatively affect either the left ventricular function (Table 3) or the coronary artery reserve at mid-term follow-up (Fig. 2). The exercise capacity was within normal range in 11 out of 12 (90%) patients and the only patient with sub-normal exercise capacity suffered from severe aortic insufficiency and had the lowest left ventricular ejection fraction (36%) preoperatively.

The long-term fate of woven Dacron vascular prosthetic grafts is known and these prostheses have been used extensively over prolonged periods of time for aortic and aortic valve reconstructions [23]. The Vascutek vascular prostheses dilate by 5.7% directly following their exposure to systemic arterial blood pressure and, thereafter, by another 1.3% at the 2-year follow-up [24]. These observations correlate well with our 16- and 47-month follow-up data from the modified Ross operation group that showed no significant dilatation of the aortic root dimensions following discharge (Table 3). Slater et al. and Thierry et al. have also described modifications of the Ross operation on similar lines using tubular and Valsalva vascular prostheses, respectively. However, these modifications — including ours — differ from...
each other on numerous technical details [20,21]. If the Ross operation has to remain a viable alternative to mechanical aortic valve replacement in young people, a technically easy and safe modification of the conventional Ross operation is necessary to prevent continued attrition of pulmonary autografts over time on account of dilatation and neo-aortic valve insufficiency. At the 4.5-year follow-up, the modified Ross operation technique described in this article has shown promising results in this context. However, these results need to be confirmed again at long-term follow-up (>10 years). Based on the present mid-term promising results, we would not hesitate recommending the use of the modified Ross operation in all young adult patients undergoing Ross operation for bicuspid aortic valve disease. This modification may be particularly indicated in patients with a preoperative diagnosis of bicuspid aortic valve insufficiency in whom freedom from pulmonary autograft re-operation, aortic insufficiency (non-endocarditis) and valve-related death, all combined, at 13 years is only 53% [25].

The modified Ross operation discussed in this article does not address the potential problem of dysfunction in the pulmonary homograft that is used to reconstruct the right ventricular outflow tract. The latest advent of the minimally invasive, percutaneous trans-venous placement technique of biological pulmonary valves in the right ventricular outflow tract — together with a possible long-term durable pulmonary auto- graft afforded by the modified Ross operation technique described here — should make the Ross operation an attractive option in the treatment of aortic valve disease in young adults. This modification does not allow the autograft growth and, therefore, is not a suitable option for the growing paediatric patient in whom the AA has not acquired the minimal adult size in relation to the body surface area.

In conclusion, the use of an external DVPJ support in conjunction with the conventional free-standing pulmonary autograft Ross operation prevents the dilatation of the entire neo-aortic root after a median follow-up of 47 months and a maximum follow-up of up to 4.5 years.

In addition, the DVPJ does not affect the normal geometry of the aortic root. Further, the modified Ross technique preserves the normal systolic excursion of the neo-aortic valve and maintains the coronary artery reserve within normal range at the 4.5-year follow-up.

References