Outcomes after the Ross procedure with pulmonary autograft reinforcement by reimplantation

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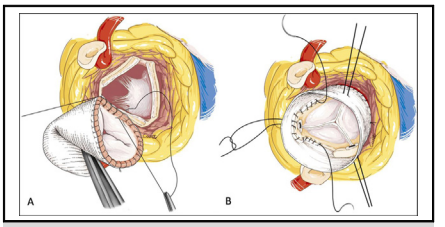
ABSTRACT

Background: Pulmonary autograft reinforcement to prevent dilatation and subsequent neo-aortic valve regurgitation has been reported; however, data on long-term function of the neo-aortic valve after this modified Ross procedure are lacking. Our objective here was to assess long-term outcomes of the modified Ross procedure with autograft reinforcement using the reimplantation technique.

Patients: The outcomes of 61 consecutive patients managed using the Dacron-conduit reinforced Ross procedure between 2009 and 2021 were reviewed. Most patients had a unicuspid or bicuspid aortic valve (n = 52; 85%), predominant aortic valve regurgitation (n = 42; 77%), and >30 mm dilatation of the ascending aorta (n = 33; 54%). A prior aortic valve procedure was noted in 47 patients (77%) patients, including 38 (62%) with surgical repair and 9 (15%) with balloon dilatation. The pulmonary autograft was reimplanted within a Dacron conduit with a median diameter of 25.6 mm (range, 20-30 mm) using the David valve-sparing aortic root replacement technique.

Results: All patients survived. The median age at surgery was 16.8 years (range, 6-38 years). Neo-aortic valve replacement was required in 3 patients (4.9%; 95% CI, 0.34%- 12.7%) because of infective endocarditis, left ventricular false aneurysm, and leaflet perforation, respectively; the repeat procedure was done early in 2 of these patients (2 of 61; 3%). Six patients required right ventricular outflow conduit replacement, 5 by surgery and 1 percutaneously. The median duration of follow-up was 90 months (range, 10-124 months). The 5- and 10-year rates of reintervention-free survival were 84.3% (95% CI, 74%-95%) and 81.6% (95% CI, 72%-93%), respectively, and 5-year survival without aortic reintervention was 94.5% (95% CI, 88%-100%), with little change at 10 years. No patients experienced deterioration of initial neo-aortic valve function (ie, regurgitation or stenosis).

Conclusions: Autograft reinforcement using the reimplantation technique allowed expansion of Ross procedure indications to all patients requiring aortic valve replacement and prevented neo-aortic root dilatation. Failures were uncommon. Long-term follow-up data showed stable neo-aortic valve function. (JTCVS Techniques 2023;17:121-8)



Neo-aortic valve function was stable after the reinforced Ross procedure using reimplantation.

CENTRAL MESSAGE

The reinforced Ross procedure using reimplantation is associated with excellent outcomes, including stable neo-aortic valve function beyond the first decade.

PERSPECTIVE

The reinforced Ross procedure using reimplantation can be considered the procedure of choice for aortic-valve-replacement in adolescents and young adults.

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The management of congenital aortic valve disease in young patients remains controversial. Mechanical prosthetic valve replacement is associated with poor outcomes.[1,2] Despite the current popularity of valve repair, the techniques are not consistently applicable, and the

Abbreviations and Acronyms
CT = computed tomography

long-term outcomes are unpredictable. Although the Ross procedure was described more than 4 decades ago,[3] it is increasingly being considered for a wide spectrum of congenital abnormalities of the left ventricular outflow tract.[4-6] It provides excellent valve hemodynamics with a low risk of endocarditis, no need for anticoagulation, and a potential for growth in small children.[7]

Even if the Ross procedure is a valuable option for aortic valve replacement, it remains controversial, with critics arguing that it may turn a single-valve disease into a disease of both outflow tracts owing to homograft deterioration on the right and dilatation of the neo-aortic root with autograft-valve regurgitation on the left.[8-10] The Ross procedure thus might create a need for further, and increasingly complex, surgery.

The Ross procedure can be performed using the subcoronary, inclusion, or root technique. The first 2 techniques are arguably more demanding and rarely suitable for congenital aortic root anomalies,[11-13] which are usually managed using the root technique. The original root technique can be modified by adding fixation of the neo-aortic annulus and/or sinotubular junction to prevent autograft dilatation. Carrel and colleagues in 2008,[8] followed by several other teams, suggested routinely supporting the neo-aortic root by including the entire pulmonary autograft within a Valsalva Dacron conduit.[14-16]

We have modified this supported/reinforced Ross procedure and performed it using a reimplantation technique. The objective of the present study was to describe our experience with this modified technique, its mid-term outcomes, and long-term neo-aortic valve function.

METHODS

We retrospectively reviewed data from 61 consecutive patients who underwent the Ross procedure using our reinforcement/reimplantation technique between 2009 and 2021. All patients provided informed written consent preoperatively, including for publication of their deidentified clinical study data. Age at surgery, sex, initial anatomic diagnosis, prior interventions, indications for the current procedure, cardiopulmonary bypass and myocardial ischemic times, postoperative complications, and mortality were extracted from medical records and surgical databases. Complex left-sided heart disease was defined as multilevel left ventricular obstruction. All patients had preoperative transthoracic echocardiography and perioperative transesophageal echocardiography and then attended regular clinical follow-up visits that included transthoracic echocardiography. Cardiac computed tomography (CT) and/or cardiac catheterization were performed if necessary. The echocardiography findings and long-term follow-up data were recorded from our database and referring physicians.

Baseline Features

Table 1 reports the preoperative patient characteristics. The 43 males (70%) and 18 females (30%) had a median age of 16.8 years (range, 6-38 years). Preoperatively, the New York Heart Association class was I/II in 48 patients and III/IV in 13 patients.

The main reasons for surgery were aortic stenosis (n = 19; 31%), aortic regurgitation (n = 35; 58%), and a combination of the two (n = 7; 11%). Table 2 presents the preoperative echocardiographic and surgical data. The

TABLE 1. Preoperative patient characteristics (N = 61)

Characteristic	Value
Age, y, median (range)	16.8 (6-38)
Weight, kg, median (range)	56.7 (19-106)
Sex ratio, male/female, n	43/18
Etiology, n (%)	
Congenital (including bicuspid)	52 (85)
Endocarditis	1 (2)
Laubri–Pezzi + VSD	5 (8)
LVOT	3 (5)
Previous aortic valve surgery	38 (62)
Previous aortic valve percutaneous dilation	9 (15)
Previous aortic valve replacement	1 (2)
No previous intervention	12 (20)
NYHA class	
I	20 (33)
II	28 (46)
III	9 (14)
IV	4 (7)

VSD, Ventricular septal defect; *LVOT*, left ventricular outflow tract; *NYHA*, New York Heart Association.

TABLE 2. Preoperative echocardiographic and surgical data (N = 61)

Parameter	Value
LVEF, %, median (range)	64.2 (40-82)
Aortic stenosis, mean gradient, mm Hg, median (range)	34.5 (9-85)
Aortic insufficiency, n (%)	56 (92)
Grade 1	8 (14)
Grade 2	8 (14)
Grade 3	28 (50)
Grade 4	12 (21)
Aortic bicuspid or monocuspid valve, n (%)	52 (85)
Aortic annulus diameter, mm, median (range)	22 (12-32)
Valsalva diameter, mm, median (range)	29.5 (15-46)
Sinotubular junction, mm, median (range)	26 (19-43)
Ascending aorta diameter, mm, median (range)	33 (15-51)
Diameter >30 mm, n (%)	33 (54)
Pulmonary insufficiency (<moderate), n (%)	20 (32)
Pulmonary valve diameter, mm, median (range)	23.7 (18-30)
Conduit diameter, mm, median (range)	26 (20-30)
Homograft diameter, mm, median (range)	24 (19-30)
Extracorporeal circulation time, min, median (range)	166 (85-350)
Aortic cross-clamp time, min, median (range)	138 (70-249)

LVEF, Left ventricular ejection fraction.

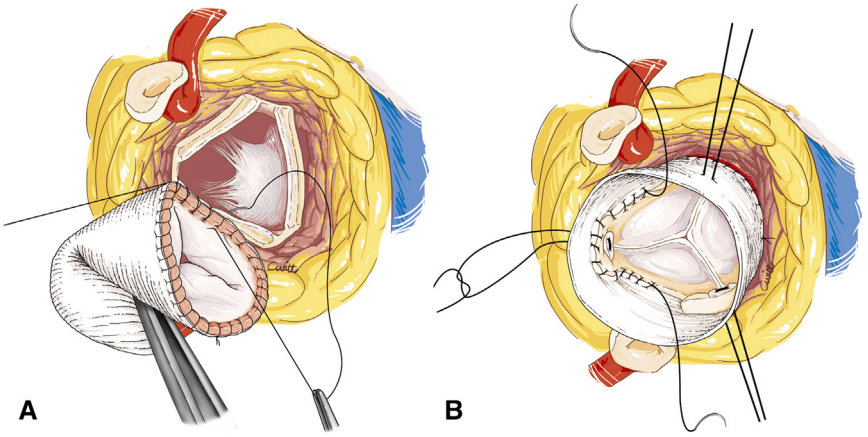

FIGURE 1. A, Anastomosis of the reinforced autograft to the aortic annulus. B, Reimplantation of the autograft inside the conduit.

aortic valve was unicuspid or bicuspid in 52 patients (85%), and 54 patients (33%) had dilation of the ascending aorta >30 mm.

Pulmonary valve insufficiency was mild or minimal in 32% of the patients. The pulmonary autograft was reimplanted within a Dacron conduit with a median diameter of 26 mm (range, 20-30 mm) using the David valve-sparing aortic root replacement technique.

All patients were followed by physical examination, echocardiography, and CT scan. Autograft valve function, homograft or right ventricular conduit valve function, and left ventricular function were assessed by M-mode 2-dimensional echocardiography and color flow Doppler ultrasonography.

Operative Technique

In all patients, we used normothermic cardiopulmonary bypass techniques (aortic and atrial or bicaval cannulation) with intermittent antegrade warm-blood cardioplegia. Aortotomy was performed, and the aortic valve was inspected. In 8 patients, repair was initially attempted, but transesophageal echocardiography then demonstrated suboptimal aortic valve function, necessitating aortic valve replacement.

In our modified reinforced Ross technique, the right and left coronary arteries were harvested with large cuffs and extensively mobilized. The leaflets were removed, along with the aortic root remnant 2 mm above the ventriculoaortic junction. The pulmonary autograft was then harvested using scissors and electrocautery, along with 2 to 3 mm of infundibular muscle. At the septal level, care was taken not to injure the major septal branches of the left coronary artery. Additional fat and fibrous tissue around the autograft were removed to minimize bulk between the autograft and Dacron conduit (Gelweave; Terumo Vascutek). The pulmonary root was tested using Hegar dilators. The appropriate Dacron conduit size was first estimated based on pulmonary annulus size as determined by preoperative echocardiography, CT, and magnetic resonance imaging if available. The final choice was made by adding 2 mm to the largest dilator size that comfortably crossed the sinotubular junction without forcing. The autograft was placed within the straight Dacron conduit, and its proximal end was secured to one end of the conduit using a continuous locking 4/0 or 5/0 polypropylene suture. Paradoxically, in this specific condition, the autograft diameter is usually smaller distally than proximally. The Dacron conduit was then trimmed to 1 cm above the top of the autograft, and the autograft/Dacron composite was then anastomosed to the aortic annulus (left ventricle outflow tract) by a continuous 4/0 polypropylene suture (Figure 1, *A*).

The autograft was suspended within the Dacron conduit using 5/0 polypropylene sutures at each commissure, taking care to place the sutures at the same height and at 120 degrees to one another, as usually performed in valve-sparing aortic root replacement procedures. The rigidity of the Dacron conduit allowed fixation of the aortic annulus/left ventricular outflow tract. Thus, resolution of small size discrepancies between the left ventricular outlet and autograft/Dacron composite ring was possible either by appropriate gathering or by a Konno incision (required in 4 of our patients). The pulmonary autograft was then tailored by performing longitudinal incisions in the center of each Valsalva sinus, without removing any autograft tissue. After determination of the optimal coronary reimplantation site, the left coronary artery window was created as distally as possible in the Dacron conduit. The right coronary button was reimplanted in a higher position, closer to the distal end of the conduit. Coronary button reimplantation was done with a continuous 5/0 or 6/0 polypropylene suture. The lower edge of each coronary button to the composite anastomosis was sutured from intima to intima, by passing through all 3 layers (autograft, conduit, and coronary buttons). The aim of this technique was to reduce potential trauma to the free cusp edges from direct contact with the rough Dacron conduit in systole. The lateral and upper edges of the coronary anastomoses involved only the Dacron conduit.

The autograft was then fixed to the Dacron conduit using an in-and-out running suture along the sinuses of Valsalva on either side of the longitudinal incisions described above. This suture line minimized the risk of a dead space allowing hematoma formation between the autograft and conduit (Figure 1, *B*). In our more recent practice after the study cohort, we modified this technique, performing the circular reimplantation sutures before connecting the coronary arteries to the neo-aortic root. The next step of the procedure was testing the neo-aortic valve to check leaflet symmetry and competence (Figure 2).

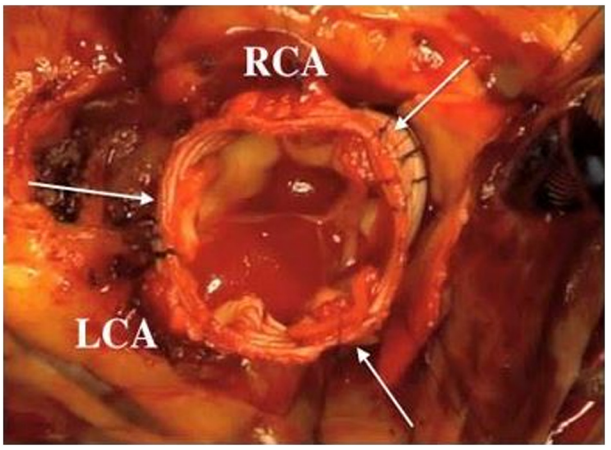

FIGURE 2. Final view of a reinforced pulmonary autograft in the left outflow position. *Arrows* indicate neo-aortic commissures. *RCA*, Right coronary artery button; *LCA*, left coronary artery button.

Next, the right ventricular outflow tract was reconstructed. The distal anastomosis was performed before reestablishing distal aortic continuity, to optimize exposure. All but 2 patients were managed using cryopreserved pulmonary homograft conduits. Finally, the proximal homograft anastomosis was completed by performing a continuous suture. The 2 ventricular cavities were deaired, and the aorta was then unclamped. In 2 of the most recently treated patients, we added a pericardial patch to the median part of the infundibular opening to avoid stress on the suture line and to obtain a more lateral and straightforward allograft conduit position.

Statistics

RStudio was used for the statistical analysis. Continuous variables were described as mean ± SD and discrete variables as median (range). Survival without repeat surgery was assessed using the Kaplan–Meier method.

RESULTS

None of the 61 patients died during a median follow-up of 90 months (range, 10-124 months). The median age at surgery was 16.8 years (range, 6-38 years). The 5- and 10-year survival rates with no repeat procedure were 84.3% (95% CI, 0.74-0.95) and 81.6% (95% CI, 0.72-0.93), respectively. Survival free of aortic reintervention was 94.5% (95% CI, 0.88-1) at 5 years and similar at 10 years (Figure 3).

During follow-up, 8 patients required further open surgery, including mechanical valve replacement in 3 (including 2 Bentall procedures), autograft refixation in 1, and homograft replacement in 4. Two other patients required percutaneous interventions, one for pulmonary valve balloon dilatation and the other for valve replacement.

Ross Failures

The Ross procedure failed in 3 patients, who underwent mechanical valve replacement. In 1 of these patients, the native aortic valve was harvested during the Ross procedure and placed in the pulmonary position. Atrioventricular block necessitated pacemaker implantation after 5 days. At 1 month postoperatively, severe mitral regurgitation due to a tear at the base of the anterior mitral leaflet developed. Patch repair and aortic root reinsertion were successful. One month later, transthoracic echocardiography revealed a left ventricular false aneurysm, seen as a beating image between the aorta and left atrium. A Bentall procedure with a 27-mm mechanical valve was performed. The patient was doing well with no symptoms at the last follow-up 10 years postoperatively.

Another patient, managed during the same year as the first, required surgery for mediastinitis 2 weeks after the Ross procedure. One month later, hemodynamic shock necessitated intensive care unit admission. The cause was distal and proximal dehiscence of the reinforced autograft anastomosis with aortic regurgitation. A Bentall procedure was successful.

The third patient had a history of surgical valvotomy at age 2 years, followed 20 years later by repair of the regurgitant bicuspid valve. Early deterioration necessitated a reinforced Ross procedure 1 year later. Aortic valve function was optimal intraoperatively; however, an unplanned postoperative angiography to check coronary artery perfusion was followed by mild aortic regurgitation, which worsened over time. Repeat surgery 2 years later revealed perforation of a leaflet, and the autograft valve was replaced by a mechanical prosthesis.

Right Outflow Complications

Right outflow complications were recorded in 6 patients (9.8%) at 1 to 3 years after the Ross procedure, including homograft stenosis in 5 patients and homograft endocarditis in 1 patient. Open surgery for homograft replacement was performed in 4 of these patients, 2 of whom subsequently required percutaneous dilatation. In another patient, percutaneous pulmonary valve replacement at 6 years after the Ross procedure was successful. Percutaneous balloon dilatation alone provided a good outcome in the remaining patient.

Tricuspid replacement by a mechanical prothesis was required in 1 patient at 6 years after the Ross procedure,

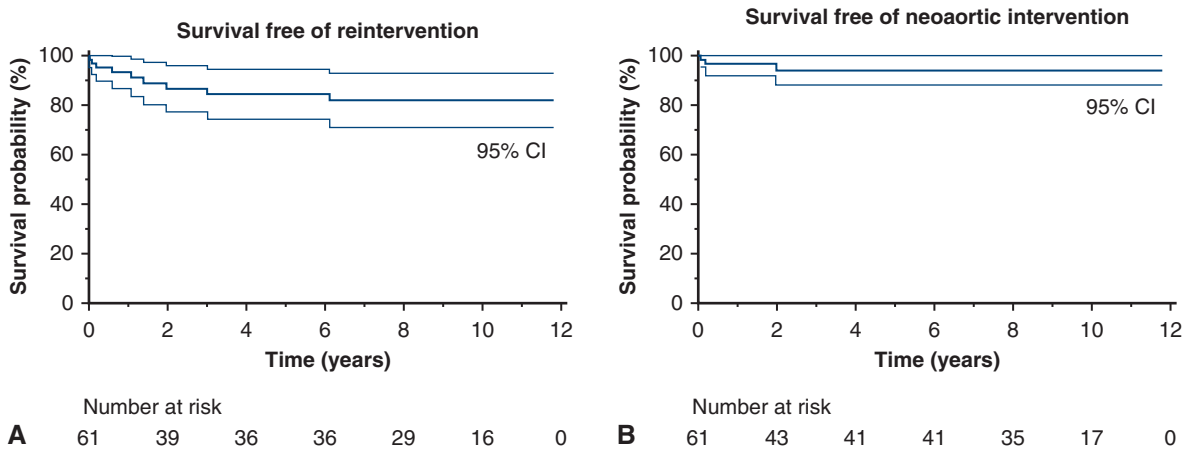

FIGURE 3. Survival curves for free of overall reoperation (A) and free of neoaortic valve reoperation (B). *CI*, Confidence interval.

after 2 conduit exchanges warranted by early deterioration and stenosis and a tricuspid valve repair procedure. The allograft was replaced with a xenograft conduit, and tricuspid valvuloplasty was performed twice. Finally, recurrent severe tricuspid insufficiency due to obstructive right ventricular remodeling was managed by mechanical valve replacement.

At last follow-up, 55 of the 61 patients (90%; 95% CI, 80%-95%) patients had not required pulmonary valve replacement. Table 3 summarizes the outcomes for all patients included in the study.

In 57 of the 61 patients, echocardiography at the last follow-up consistently showed preservation of neo-aortic valve function and left ventricular ejection fraction. None of these patients required cardiac medications. One patient had a moderately diminished ejection fraction due to perioperative ischemic events. At discharge after the Ross procedure, the mean diameters of the autograft annulus and sinotubular junction were 24.8 ± 2.6 mm and 25.3 ± 2.1 mm, respectively. The corresponding values at the last follow-up at a median of 90 months (range, 10-124 months) after the Ross procedure were 25.3 ± 2.1 mm and 25.4 ± 2.7 mm ($P = .06$ and .08, respectively). Aortic insufficiency worse than grade 2 was recorded in a single patient.

DISCUSSION

Congenital bicuspid aortic valve is the most common etiology of aortic valve disease in children, adolescents, and young adults. Conservative repair techniques are improving steadily but continue to show limitations in terms of feasibility and durability.[17] The Ross procedure has gradually become an accepted alternative to mechanical, xenograft, and homograft aortic valve replacement for young patients with aortic valve disease.[18] The subcoronary Ross procedure, which is technically more demanding and has been successfully used in adults, is not optimally suited to congenital anomalies in aortic root morphology. In these conditions, root replacement is therefore the current reference standard.[13] Promising long-term outcomes have been reported in large cohort studies. Nonetheless, reports of delayed complications continue to feed controversy about this procedure. The complication of greatest concern is neo-aortic root dilatation over time with subsequent valve regurgitation.[19]

TABLE 3. Mid-term outcomes (N = 61)

Outcome	Value
Duration of follow-up, mo, median (range)	90 (10-124)
Age at the end of follow-up, y, median (range)	21.7 (6.9-46.5)
Aortic insufficiency grade >2, n	1 (grade 3)
Mean RV-PA gradient, n (%)	
<30 mm Hg	46 (76)
>30 mm Hg	15 (24)
Pulmonary insufficiency, n (%)	5 (8)
Grade 1	1 (2)
Grade 2	2 (4)
Grade 3	2 (4)

RV, Right ventricle; *PA*, pulmonary artery.

In a meta-analysis, the pooled linearized annual rates were 1.15% for autograft deterioration and 0.91% for right ventricular outflow tract conduit deterioration.[20] In another study, dilatation of the neo-aortic valve annulus, Valsalva sinuses, and sinotubular junction occurred after the Ross procedure in at least 20% of patients.[10] Dilatation can occur rapidly, within 10 days after the procedure.[21] Reported risk factors for neo-aortic regurgitation include preoperative aortic regurgitation with aortic annulus dilatation,[21,22] younger age, and male sex.[23] Ross as the primary procedure and older age at the time of the operation independently predicted the development of moderate-severe autograft valve insufficiency in several studies.[24-26] Postoperative autograft valve insufficiency, even when trivial, and the severity of neo-valve regurgitation were proportional to the duration of follow-up. The diameter of the ascending aorta exceeded 30 mm in 33% of our cohort. Owing to the referral pattern at our institution, 71.8% of our patients were age <16 years.

To avoid complications such as root dilatation with or without neo-aortic valve regurgitation, techniques for reinforcing the autograft have been designed. For instance, the autograft can be wrapped in a bovine pericardial patch to prevent dilatation.[26,27] Reinforcing the proximal suture line was associated with a lower 10-year reoperation rate but did not prevent dilatation of the Valsalva sinuses or sinotubular junction.[14,19] An external rigid support for the autograft may be necessary in patients with root aneurysm but not in those with more normal root tissue.[28] No differences in late outcomes were seen between the subcoronary technique and the reinforced root replacement technique.[19] Autograft stabilization using the native ascending aortic wall also has been reported.[29]

Autograft reinforcement by inclusion within a conduit has grown in popularity as a method both for stabilizing the neo-aortic root and for preventing dilatation of the ascending aorta.[7,13,21,23,30] We initially used this technique to support the pulmonary autograft; however, we noted short-term adverse events in 2 patients. In 1 patient, the very large dead space between the autograft and conduit layers allowed blood accumulation by seepage through the multiple suture lines, with hematoma formation and subsequent autograft valve dysfunction; in the other, autograft invagination into the holes created for coronary button reimplantation on the Dacron conduit caused asymmetric dilatation of the supported neo-aortic root (Figure 4). Therefore, we promptly changed our reimplantation technique to a probably safer, albeit more time-consuming, alternative. The reinforced reimplantation Ross technique allowed us

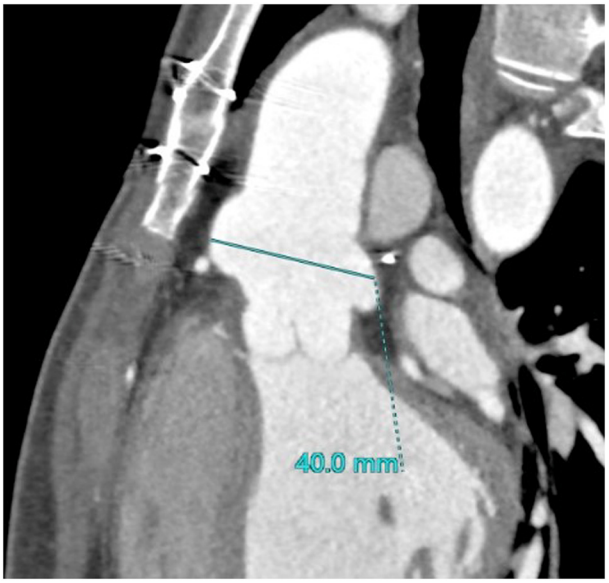

FIGURE 4. Postoperative (6 months) computed tomography scan of the neo-aortic root of an early patient operated on with a conventional reinforcement (before a switch to reimplantation) technique. The autograft wall appears to bulge through the coronary artery reimplantation holes.

to widen the spectrum of indications to all patients age <40 years (patients are referred to adult cardiac units) with valve stenosis or regurgitation, including those with unfavorable root morphology and/or size discrepancy between the aortic and pulmonary roots.

The possibility that the absence of Valsalva-shaped sinuses may adversely affect autograft durability has been suggested.[14] We do not use this type of conduit, because its specific design for annuloaortic ectasia makes it unsuitable for pulmonary autograft morphology, in which the largest segment is the right ventricular muscle ridge and suture tension at the Valsalva sinus and commissural levels is a concern.[14,31]

Despite evidence that valve-sparing aortic root replacement using the reimplantation technique can produce favorable outcomes in aortic root disease, its use for pulmonary autografts in adolescents and young adults was not an obvious choice. However, valve function remained stable over time in all patients, including the youngest ones with a strong growth potential. When present, residual regurgitation was trivial or mild and did not increase during follow-up. The smallest conduit size, 20 mm, was used in a 12-year-old boy with Laubry–Pezzi syndrome due to an infundibular ventricular septal defect and failure of primary valve repair performed 1 year earlier. The Ross procedure is challenging in this situation but is made possible by the reimplantation technique. Neo-aortic valve function was normal 12 years later. The youngest patient was 6 years old and had undergone neonatal aortic valvotomy, ventricular septal defect closure, and coarctation repair. A

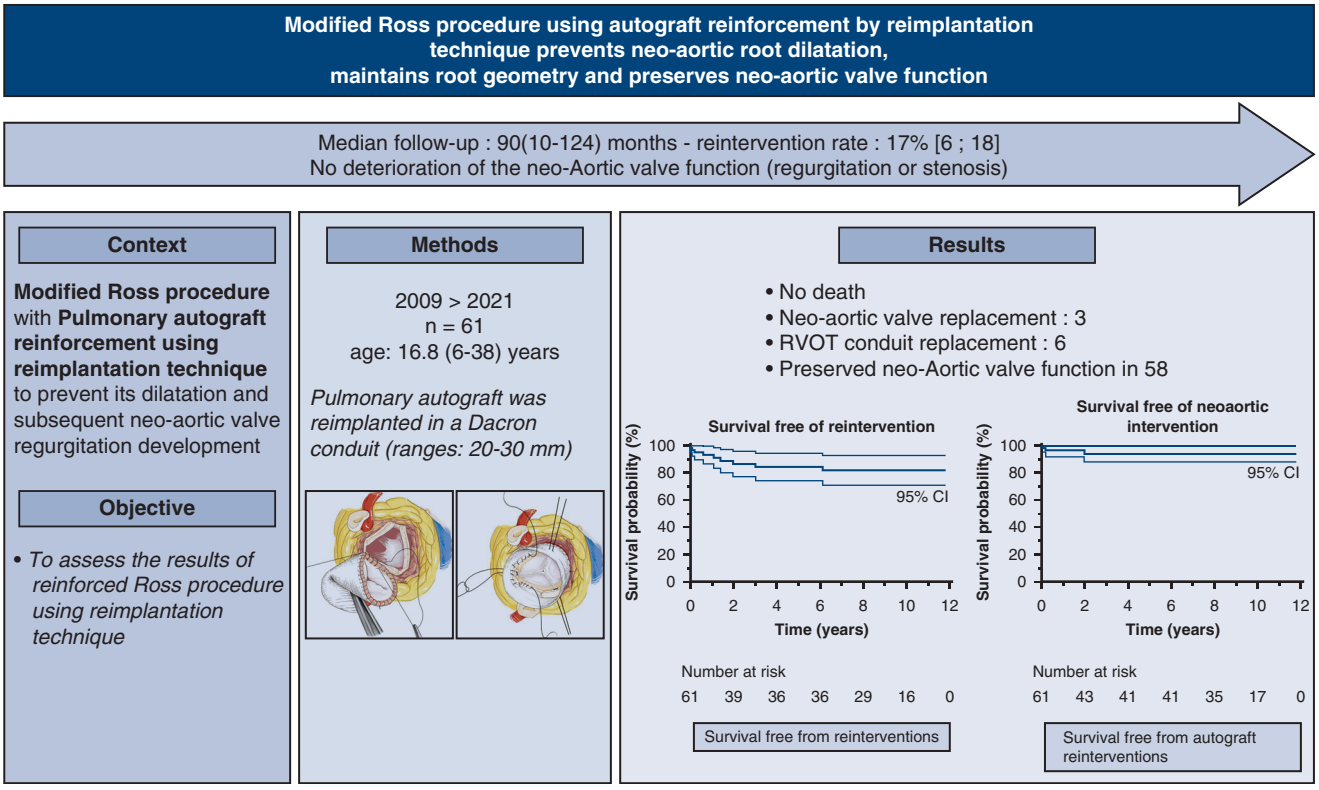

FIGURE 5. Graphical abstract summarizing the content of our study in a single image. *RVOT*, Right ventricular outflow tract.

24-mm conduit was used. Neo-aortic valve function was favorable during follow-up, although allograft endocarditis required repeat surgery.

Pulmonary root replacement by the native aortic root instead of a homograft has been suggested.[32] The single patient in our experience managed using this used approach developed postoperative atrioventricular block, a tear in the base of the anterior mitral valve requiring repair, and a subsequent left ventricular false aneurysm requiring a Bentall procedure (Figure 4). We did not use this technique again. In our assessment, neither this nor the other 2 failures that resulted in mechanical valve replacement were related to the reinforcement procedure.

Early degeneration and stenosis of the pulmonary allograft is rare but of concern. In addition, in 3 of our patients, high gradients across the pulmonary allograft developed within 6 months, requiring further surgery earlier than expected.

Video Abstract and Figure 5 summarize the messages of our study.

CONCLUSIONS

Pulmonary autograft reinforcement using the reimplantation technique may be a valuable option with several advantages and low risks in young patients needing aortic valve replacement across the spectrum of aortic root morphologies. Our technical modification consisting of the reimplantation technique provided excellent clinical outcomes with stable aortic valve function after approximately a decade. These findings provide hope that the outcomes will remain favorable over the subsequent decades in our patients.

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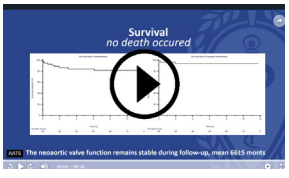

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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