Surgical solutions for complex aortic root pathology

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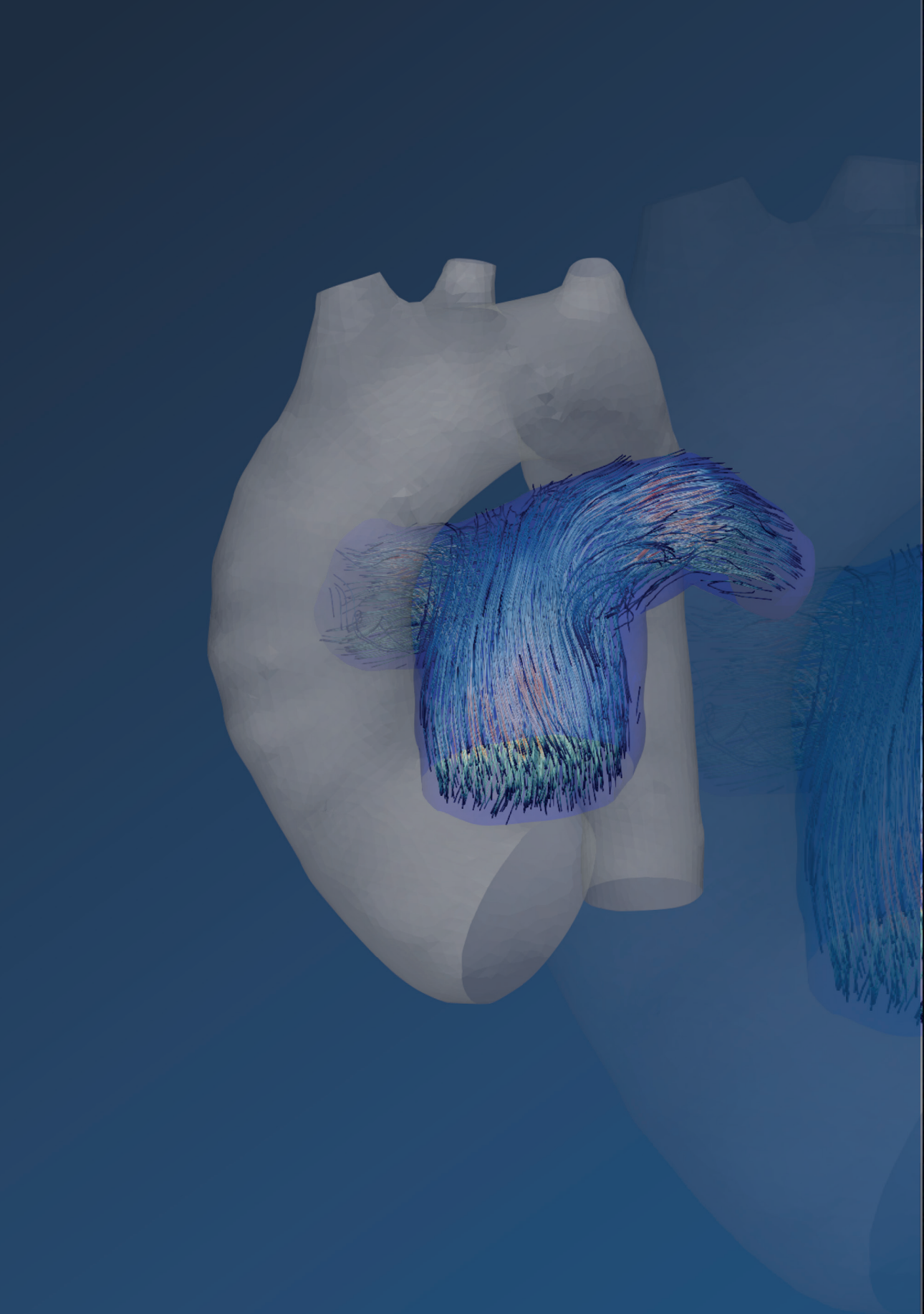

LONG-TERM FOLLOW-UP AFTER THE ROSS PROCEDURE:

A Single Center 22-Year Experience

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CHAPTER 3

ABSTRACT

Background: The aim of this study was to analyze long-term outcomes after the Ross procedure, focusing on autograft function and risk of reoperation in time.

Methods: Between February 1994 and February 2016, 154 patients underwent the Ross (n = 105) and Ross-Konno (n = 49) procedure at our institution and were included in this study. Data were collected retrospectively from patients' medical records or through telephone contact. Competing risks analyses were performed to determine incidences of death and reoperation. A multistate model was constructed to provide insights in the clinical trajectory after operation.

Results: Median age was 12 years, 74% were pediatric patients, and 66% had previous surgical procedures. There were 8 (5%) early deaths, 6 of whom underwent the Ross-Konno procedure, and 10 (7%) late deaths. Survival rates at 15 and 20 years were 86% in the total cohort and 91% in the isolated Ross subgroup. Linearized occurrence rates of endocarditis and valve thrombosis, thromboembolism, and bleeding events combined were 0.30% per patient-year and 0.15% per patient-year, respectively. Cumulative incidences of all-cause reoperation at 15 and 20 years were 35.2% and 45.3%, respectively. Twenty-six patients needed autograft reoperation, 20 due to dilatation. Cumulative incidences of autograft reoperation at 15 and 20 years were 20.1% and 31.1%, respectively. At latest echocardiogram, 4 patients had moderate aortic regurgitation and none had stenosis.

Conclusions: The Ross procedure can be performed safely in young patients with low number of valve-related events. Autograft function remains stable in the first decade after operation, but autograft dilatation in the second decade necessitates reintervention.

INTRODUCTION

Several prostheses are available to replace a dysfunctioning aortic valve. In younger patients, the American and European guidelines currently recommend mechanical prostheses [1, 2]. Their advantage over biological prostheses of longer durability comes at the cost of lifelong anticoagulant treatment.

For young patients in whom a mechanical prosthesis is contraindicated, or who prefer a biological prosthesis, the choice of prosthesis is subject to debate. Several bioprostheses are currently available, but all have relatively short lifetime in younger patients [3]. Alternatively, the pulmonary autograft can be used to replace the diseased aortic valve. This technique has several advantages over other bioprostheses. One of the most important advantages is the growth potential of the pulmonary autograft in children. Furthermore, long-term outcomes might be superior to other biological prostheses [4]. A main disadvantage of the Ross procedure, however, is that a dual valve problem is created for only a single diseased valve. Furthermore, the need for autograft reoperation might impose a problem during late follow-up [4].

Most studies on the Ross procedure have limited follow-up times of about 10 years [5 - 8]. In the present study, we describe our single institution, 22-year experience with the Ross procedure, focusing mainly on autograft function and risk of reoperation in the long-term follow-up.

PATIENTS AND METHODS

Patients and Data Collection

The Ethics Committee of the Leiden University Medical Center approved this retrospective observational study and waived the need for informed consent. All patients who underwent the Ross(-Konno) procedure between February 1994 and February 2016 at the Center for Congenital Heart Disease Amsterdam Leiden, a collaboration between the Leiden University Medical Center, the Academic Medical Center, and the VU Medical Center in the Netherlands, were identified in the center's database and included. Data were collected from patients' medical records or through contact by telephone.

Surgical Technique

After initiation of cardiopulmonary bypass with mild hypothermia and cardiac arrest with cold crystalloid cardioplegia, the aortic valve was inspected. When a repair of the aortic valve did not seem to be durable, the Ross procedure was performed. A subcoronary and root-inclusion technique was used in a small number of patients. In most patients, the autograft was implanted as a neo-root. The pulmonary autograft was placed in the aortic position, generally reinforcing the proximal suture line with a strip of autologous pericardium. In patients with a too narrow aortic annulus or left ventricular outflow tract obstruction, a Konno incision was made to enlarge the aortic annulus [9]. In some fully grown patients, the autograft and ascending aorta were reinforced with a vascular graft above the coronary arteries to prevent autograft dilatation. In others, the autograft was implanted in a Gelweave Valsalva (Vascutek, Renfrewshire, Scotland) vascular prosthesis, starting at the proximal anastomosis. Then, the commissures were fixed into the graft, and the sinuses of Valsalva of the autograft were fully scalloped in a way similar to the valve-sparing root replacement (VSRR) reimplantation technique described by David and Feindel [10]. The distal suture line of the autograft into the vascular graft was made. Finally, an end-to-end anastomosis was made between the vascular graft and native aorta.

Data Reporting

Data are reported according to the 2008 guidelines for reporting mortality and morbidity after cardiac valve interventions [11]. Early mortality was defined as all-cause mortality within 30 days after operation or during the initial hospital admission. Echocardiographic variables were reported according to current guidelines 1, 12. Valve-related events were counted until reoperation on the concerning valve. Data are reported for the total patient cohort and separately for patients who underwent a Ross procedure without the Konno incision (Ross subgroup). The results on most of the patients who underwent a Ross-Konno procedure have been published previously [9]. It was decided to include these patients in the present analysis, because autograft dilatation is one of the most important issues with the Ross(-Konno) procedure and is independent of the Konno incision.

Follow-Up

Ten patients were lost to follow-up because they returned to their country of origin or emigrated from the Netherlands and were censored from the survival analyses at latest known follow-up. For the remaining 144 patients, clinical follow-up was 100% complete with recent echocardiographic data available for 87% of patients. Median follow-up time for the total patient cohort was 10 years (interquartile range [IQR]: 3 to 19 years) and for the Ross subgroup 17 years (IQR: 4 to 20 years). Total follow-up was 1663 patient-years for the total cohort and 1330 patient-years for the Ross subgroup. Follow-up closed on February 29, 2016.

Statistical Analysis

Continuous variables are expressed as mean ± SD for normally distributed data or as median (interquartile range) for non-normally distributed data. Categorical variables are reported as numbers and percentages. Overall survival was estimated using the Kaplan-Meier method and reported as percentage (95% CI). Differences in overall survival between the Ross and Ross-Konno subgroups were tested using the log-rank test. To avoid informative censoring in the analysis of freedom from reoperation, a competing risks analysis was performed considering death as a competing risk of autograft and all-cause reoperation. Furthermore, to provide more reliable information on reoperation occurrence after surviving the index procedure, early mortality was excluded from the competing risks analysis. The cumulative incidences of death and first autograft reoperation or first all-cause reoperation were estimated using the mstate package version 0.2.8 [13] in R (R version 3.1.2; R Foundation for Statistical Computing, Vienna, Austria) and reported as incidence (95% CI). A multistate model was constructed to estimate the time-dependent probability of being in a specific state, excluding early mortality. Patients started in the event-free state (state 1) and could remain there until censored or pass to one of the following states: right ventricle to pulmonary artery (RV-PA) conduit reoperation (state 2), autograft reoperation (state 3), or death (state 4). Patients who underwent surgical procedures on their RV-PA conduit and autograft simultaneously passed to state 3. Patients in state 2 could either pass to state 3 or state 4. Patients in state 3 could only pass to state 4. Risk factors for autograft reoperation (age, Konno, non-tricuspid valve, and hemodynamics) were analyzed using a Cox proportional hazards model. A p value of less than 0.05 (two-sided) was considered statistically significant.

RESULTS

Of the total of 154 patients who underwent the Ross(-Konno) procedure, 115 patients (75%) were male. The median age at operation was 12 years, ranging from 19 days to 48 years, and 114 patients (74%) were younger than 18 years of age at the time of operation. Two-thirds of the patients had had previous cardiac operations. Most patients had either aortic valve stenosis (46%) or combined stenosis and regurgitation (29%). For the Ross subgroup, the main hemodynamic profiles were mixed (43%) and regurgitant (36%) disease. Most patients (60%) had a bicuspid aortic valve. Patient characteristics are shown in Table 1.

Table 1. Patient Characteristics

Characteristic	Ross (n = 105)	Ross-Konno (n = 49)	Total (n = 154)
Male sex	79 (75)	36 (74)	115 (75)
Age at operation, years	14 (8–25)	1 (0.25–9)	12 (5–19)
Pediatric	66 (63)	48 (98)	114 (74)
Previous operation	58 (55)	44 (90)	102 (66)
Aortic valvulotomy	19 (18)	11 (22)	30 (19)
Trusler plasty	4 (4)	…	4 (3)
Balloon valvuloplasty	25 (24)	20 (41)	45 (29)
Second balloon valvuloplasty	5 (5)	3 (6)	8 (5)
Aortic valve replacement	7 (7)	…	7 (5)
Second aortic valve replacement	2 (2)	…	2 (1)
Hemodynamics			
Stenosis	22 (21)	49 (100)	71 (46)
Regurgitation	38 (36)	…	38 (25)
Mixed	45 (43)	…	45 (29)
Cause			
Degenerative	3 (3)	…	
Rheumatic	7 (7)	…	
Endocarditis	3 (3)	…	
Failed prosthesis	4 (4)	…	
Congenital	80 (76)	49 (100)	
Other	8 (8)	…	

Values are n (%) or median (interquartile range).

Operative Details

Median cross-clamping time was 134 minutes (range, 65 to 238 minutes). Twenty-nine patients (19%) had concomitant surgical procedure, ranging from bypass surgery to mitral valve replacement. A Konno incision was needed in 49 patients

(32%). In the Ross subgroup, 18 patients (12%) required either small annular extension by incising the annular fibrous ring or annular reduction to make the

Table 2. Operative Details

Operative Details	Ross (n = 105)	Ross-Konno (n = 49)	Total (n = 154)
Cross-clamp time, median (range), minutes	125 (65–238)	150 (80–305)	134 (65–238)
Aortic valve cusps, n (%)			
Unicuspid	2 (2)	…	2 (1)
Bicuspid	65 (62)	27 (55)	92 (60)
Tricuspid	37 (35)	22 (45)	59 (38)
Quadricuspid	1 (1)	…	1 (1)
Implantation technique, n (%)			
Subcoronary	2 (2)	…	2 (1)
Root-inclusion	2 (2)	…	2 (1)
Root replacement	101 (96)	49 (100)	150 (97)
Wrapped pulmonary autograft, n (%)	8 (8)	…	8 (5)
Of which scalloped, n	6	…	6
Additional aortic annulus procedures, n (%)	18 (17)	…	18 (12)
Annular extension	14 (13)	…	14 (9)
Annular reduction	3 (3)	…	3 (2)
Autograft annular reduction, n (%)	1 (1)	…	1 (1)
Right ventricle to pulmonary artery conduit			
Cryopreserved pulmonary homograft	81 (77)	12 (25)	93 (60)
Decellularized pulmonary homograft	2 (2)	…	2 (1)
Cryopreserved aortic homograft	…	4 (8)	4 (3)
Bovine jugular vein graft	22 (21)	33 (67)	55 (36)
Right ventricle to pulmonary artery graft size, mean (SD)	23 (3)	18 (5)	22 (5)
Concomitant procedure, n (%)	19 (18)	10 (20)	29 (19)

pulmonary autograft fit into the aortic annulus. In the later years of our series, the pulmonary autograft was implanted into a vascular tube graft in 8 patients to prevent later dilatation of the autograft. In 6 of these patients, the sinuses of Valsalva were scalloped. Most earlier patients (61%) received a pulmonary homograft to restore the RV-PA connection. Since 2001, a Contegra (Medtronic, Minneapolis,

MN) bovine jugular vein graft was used more often (Table 2). Five patients required postoperative extracorporeal membrane oxygenation for low cardiac output, 7 patients had a postoperative conduction block and required pacemaker implantation.

Survival

Table 3. Causes of Death in the Ross Group

Patient	Age at Operation	Time Between Operation and Death	Year of Operation	Previous Operation	Concomitant Procedures	Cause of Death
1	28 years	0 days	1997	PDA closure	DSAS removal	LV failure, MI due to split-like ostium LCA
2	19 days	57 days	2015	None	None	iCVA after resuscitation
3	31 years	5 months	1995	None	None	End-stage heart failure due to DCM
4	6 months	1 year	2011	Balloon valvuloplasty	None	iCVA after dissection of pulmonary trunk during balloon dilatation RV-PA -> surgical conduit
5	7 years	4 years	1996	Valvuloplasty, PDA + ASD closure	None	Diastolic heart failure due to severe EFE (proved by autopsy)
6	13 years	7 years	2006	None	MVP	Sudden, unexplained
7	35 years	9 years	1995	AVR	None	Sudden, unexplained
8	13 years	9 years	1996	Valvuloplasty, later balloon valvuloplasty	None	Unknown

ASD = atrial septal defect; AVR = aortic valve replacement; DCM = dilated cardiomyopathy; DSAS = discrete subaortic stenosis; EFE = endocardial fibroelastosis; iCVA = ischemic cerebrovascular accident; LCA = left coronary artery; LV = left ventricle; MI = myocardial infarction; MVP = mitral valve plasty; PDA = patent ductus arteriosus; RV-PA = right ventricle to pulmonary artery.

There were 8 early deaths (5%), 6 of whom underwent the Ross-Konno procedure. In total, there were 10 late deaths (7%), 4 of whom underwent the Ross-Konno procedure. A detailed summary of death causes in the Ross subgroup is shown in Table 3. Causes of death in patients who underwent a Ross-Konno procedure have been previously published in detail by our group [9]. For the total study population, 10-, 15-, and 20-year survival rates were 87.0% (95% CI, 81.2% to 93.1%), 85.9% (95% CI, 79.5% to 92.3%), and 85.7% (95% CI, 79.5% to 92.3%),

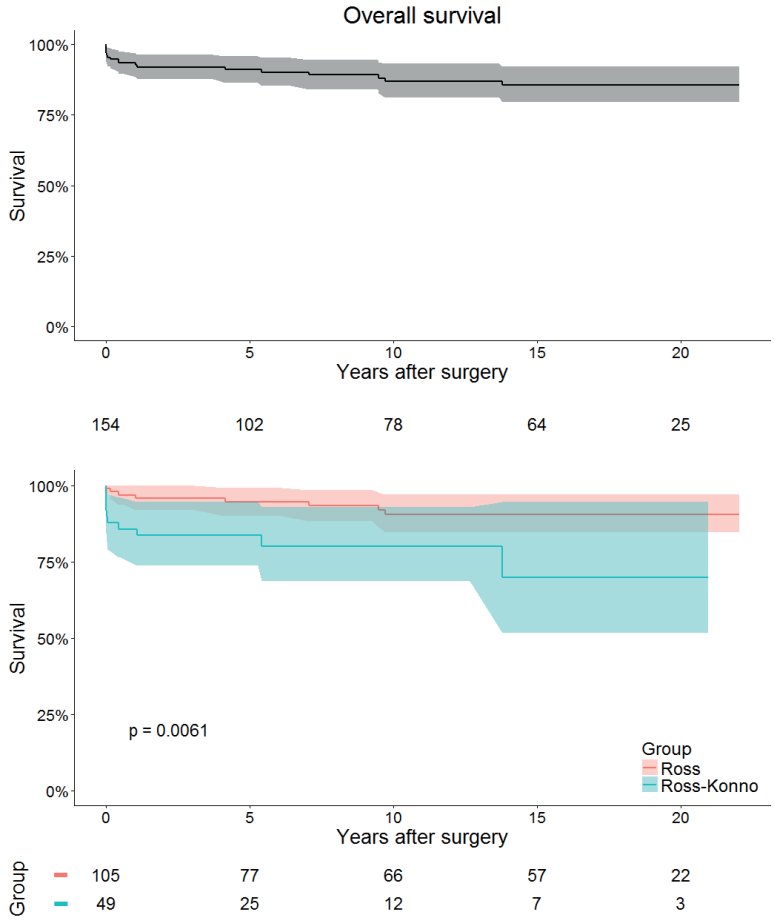

Figure 1. Survival plots for the total study population (top) and subgroups (bottom). Bands denote 95% CIs. Numbers under the curves denote numbers at risk.

respectively. For the Ross subgroup, the 5-year survival rate was 94.6% (95% CI, 90.2% to 99.3%), and 10-, 15-, and 20-year survival rates were 90.7% (95% CI, 84.6% to 97.1%). For the Ross-Konno subgroup, 5- and 10-year survival rates were 83.6% (95% CI, 73.9% to 94.7%) and 80.0% (95% CI, 68.7% to 93.1%), respectively, and the 15- and 20-year survival rates were 70.0% (95% CI, 51.7% to 94.7%). Survival in the Ross subgroup was significantly higher than in the Ross-Konno subgroup (p = 0.006). The linearized occurrence rate (LOR) of late mortality for the total cohort and the Ross subgroup were 0.60% and 0.45% per patient-year, respectively. Survival curves are shown in Figure 1.

Valve-Related Events in the Ross Subgroup

Four patients experienced endocarditis of their pulmonary homograft, 3 of whom needed pulmonary valve replacement. One patient experienced a *Coxiella burnetii* endocarditis but did not need reoperation. The LOR of endocarditis was 0.30% per patient-year. One patient with an impaired left ventricular function and pacemaker experienced a cerebral transient ischemic attack 18 years after Ross procedure, and 1 patient had an idiopathic small pulmonary embolism 6 years postoperatively. No other valve-related events occurred. The LOR of valve thrombosis, thromboembolism, and bleeding events combined was 0.15% per patient-year.

Freedom From Reoperation

The risks of reoperation in hospital survivors using the competing risks model are shown in Table 4. Twenty-six patients (18%) required reoperation on their autograft. Indications for autograft reoperation were autograft dilatation (diameter, >50 to 60 mm; rapid progression; or marked asymmetry of dilatation) in 20 patients, autograft regurgitation in 5 patients, and an iatrogenic perforation of one of the autograft leaflets during Ross procedure in 1 patient. No relationship between age and time to autograft reoperation was found. Fourteen patients received a mechanical prosthesis with (n = 12) or without (n = 2) ascending aorta replacement, 9 patients received a stentless aortic root bioprosthesis (Freestyle, Medtronic, Minneapolis, MN), 2 patients underwent VSRR (reimplantation technique), and 1 patient with an iatrogenic perforation of one of the autograft leaflets had a patch reconstruction of the defect. No risk factors for autograft reoperation were found (Table 5). Thirty-one patients (21%) required reoperation on their RV-PA conduit, some of them several times. The cumulative incidence of

RV-PA reoperation for the total group at 10, 15 and 20 years was 10.8% (95% CI, 4.9% to 16.7%), 25.6% (95% CI, 16.6% to 34.7%), and 35.5% (95% CI, 25.2% to 45.8%), respectively. For the Ross subgroup, 10-, 15-, and 20-year cumulative incidence of RV-PA reoperation was 5.8% (95% CI, 0.9% to 10.8%), 20.5% (95% CI, 11.2% to 29.8%), and 30.5% (95% CI, 19.6% to 41.5%), respectively, and for the Ross-Konno subgroup, 10- and 15-year cumulative incidence of RV-PA reoperation was 31.9% (95% CI, 11.0% to 52.9%) and 50.5% (95% CI, 26.1% to 75.0%), respectively.

Table 4. Cumulative Incidences of Reoperation

	Ross	Ross-Konno	Total Group
All-cause reoperation			
5 Years	9.2 (3.1–15.3)	13.9 (2.6–25.2)	10.5 (5.1–16.0)
10 Years	14.4 (6.9–21.9)	37.0 (16.1–57.9)	18.8 (11.5–26.2)
15 Years	30.8 (20.3–41.4)	57.2 (33.4–81.1)	35.2 (25.4–45.1)
20 Years	42.6 (30.8–54.3)		45.3 (34.6–56.0)
Autograft reoperation			
5 Years	3.5 (0–7.4)	0	2.4 (0–5.2)
10 Years	7.4 (1.7–13.0)	4.1 (0–11.9)	6.4 (1.8–11.0)
15 Years	20.0 (10.6–29.5)	26.3 (0.6–52.0)	20.1 (11.4–28.8)
20 Years	30.7 (19.4–42.0)	39.7 (10.8–68.6)	31.1 (20.5–41.7)

Values are incidence (95% CI).

Table 4. Risk factor analyses

Risk factors	Hazard ratio	95%CI	P-value
Autograft reoperation (Univariable Cox regression)			
Age	1.007	0.976–1.039	0.648
Konno	1.543	0.561–4.250	0.401
Non-tricuspid	0.951	0.412–2.192	0.906
Stenosis	0.974	0.432–2.195	0.949
Regurgitation	0.729	0.274–1.937	0.526

Multistate Model

The multistate model (Fig 2) showed a calculated probability of being event free after operation (ie, alive and without reoperation) of 88%, 75%, 58%, and 47%, respectively, at 5, 10, 15, and 20 years after operation. The probability of having had a reoperation on the pulmonary autograft (either combined with RV-PA

conduit reoperation or not) at 5, 10, 15, and 20 years was 3%, 6%, 22%, and 32%, respectively (Table 6).

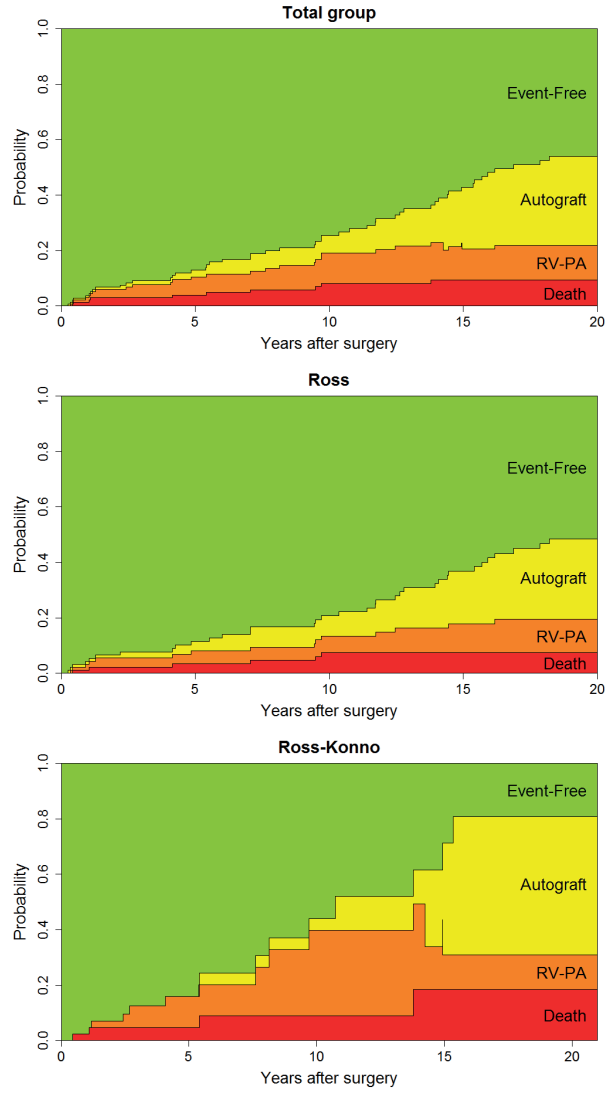

Fig 2. Multistate models of the states "event-free", right ventricle to pulmonary artery (RV-PA) reoperation ("RV-PA"), autograft with or without RV-PA reoperation ("autograft") and "death", excluding early mortality. This model follows each patient during follow-up and shows the proportion of patients in each state at any time. Multiple transitions per patient are possible. Patients started in the event-free state and could go to all other states. Patients within the RV-PA state could go to the autograft or death state, and patients in the autograft state could go to the death state.

Table 6. Multi state model estimates (all numbers are percentages, numbers between parentheses denote 95% confidence interval)

Total group	Event free	RV-PA reoperation	Autograft reoperation	Death
5 year	88.0 (82.2–93.6)	5.6 (1.7–9.6)	2.5 (0–5.2)	3.9 (0.6–7.2)
10 year	75.3 (67.0–83.5)	10.1 (4.4–15.7)	6.4 (1.8–11.1)	8.2 (3.1–13.3)
15 year	57.8 (47.6–67.9)	10.5 (3.6–17.6)	22.2 (13.1–31.4)	9.5 (3.8–15.1)
20 year	46.5 (35.7–57.2)	11.9 (4.6–19.2)	32.2 (21.6–42.7)	9.5 (3.8–15.1)
Ross group	**Event Free**	**RV-PA reoperation**	**Autograft reoperation**	**Death**
5year	89.7 (83.3–96.0)	3.4 (0–6.9)	3.5 (0–7.4)	3.4 (0–7.1)
10 year	80.3 (71.7–89.0)	4.7 (0.3–9.2)	7.4 (1.7–13.1)	7.5 (1.8–13.2)
15 year	64.0 (53.0–74.9)	9.2 (2.8–15.6)	19.3 (10.2–28.4)	7.5 (1.8–13.2)
20 year	52.2 (40.4–64.1)	10.9 (3.8–17.9)	29.4 (18.5–40.2)	7.5 (1.8–13.2)
Ross-Konno group	**Event Free**	**RV-PA reoperation**	**Autograft reoperation**	**Death**
5 year	84.0 (72.2–95.8)	11.3 (0.9–21.7)	0	4.7 (0–11.0)
10 year	56.0 (34.6–77.4)	30.9 (10.7–51.1)	4.2 (0–12.0)	8.9 (0–18.8)
15 year	19.2 (0–38.8)	12.5 (0–29.2)	40.2 (16.6–63.7)	18.5 (0.5–36.5)
20 year	19.2 (0–38.8)	12.5 (0–29.2)	49.8 (25.6–73.9)	18.5 (0.5–36.5)

Echocardiographic Follow-Up

Recent echocardiographic follow-up was available for 109 of 126 surviving patients with a median time to echocardiogram of 9 years (IQR, 3 to 17 years). Left ventricular function was good in all but 16 patients, of whom 13 had mild impairment and 3 had moderate impairment of left ventricular function. Right ventricular function was mildly impaired in 10 patients. Of patients who did not undergo reoperation on their autograft, 27 patients had mild aortic regurgitation (AR) and 4 patients had moderate AR. All had normal gradients (<20 mm Hg) over their autograft. Mean sinus of Valsalva diameter was 38 ± 7 mm, and 5 patients had sinus dilatation more than 45 mm in diameter, without more than mild AR.

Comment

Choosing an aortic valve substitute in children and young adults imposes some difficult decisions. The ideal prosthesis has a growing capacity in children, does not need anticoagulant treatment, and has a long durability. Mechanical

prostheses do have a long durability but need anticoagulant treatment. Of the available biological valve substitutes, limited durability was described 3, 14. The pulmonary autograft lacks the need of anticoagulant treatment and has a growing potential in children, but it comes at the cost of creating a double valve problem for a single valve disease. Its technical difficulty might impose a limitation for its use. In our series, early mortality was 5% for the total study population. However, if we only consider our straightforward Ross patients, that is, excluding the much more complex Ross-Konno patient group, early mortality was only 1.7%, which is lower than the pooled percentage in a meta-analysis [4]. Furthermore, one of the two early deaths in our Ross subgroup was due to a technical problem in the earlier years of our experience. Therefore, in experienced hands, early mortality approaches the postulated upper limit of operative mortality for elective aortic valve replacement of about 1%. Our 15- and 20-year survival rate of 91% in the Ross subgroup is comparable with that of other recent reports 5, 6, 7, 8.

Only 4 patients (0.3% per patient-year) experienced an endocarditis of the RV-PA conduit, of whom 3 needed reoperation, and none of the pulmonary autograft. This is lower compared with the 20% reported by Charitos and colleagues [15] and the pooled percentage reported by Takkenberg in a meta-analysis [4]. The low number of valve-related events seen in this present and other studies advocates the use of the Ross procedure.

After 20 years, cumulative incidence of reoperation was 45%, and cumulative incidence of autograft reintervention was 31%. This is also comparable with other recent reports 5, 6, 7, 8 and is better than expected from other conventional bioprostheses, especially considering the young age of the patient group. We could not identify risk factors for autograft reoperation. Most autograft reoperations consisted of either mechanical or biological valve and root replacement. We only performed two VSRR procedures. A recent article by Mookhoek and colleagues [16] showed a freedom from pulmonary autograft reoperation after VSRR of only 76% at 8 years. In our opinion, this rate does not justify the use of this technique. Furthermore, in our experience, at reoperation, autograft valve leaflets were very thin and often showed large fenestrations and low cuspal heights, which may limit the durability of VSRR in these patients. Hence, this technique should be reserved for either young patients with a shorter expected durability of a conventional prosthesis or patients with a strict contraindication for a mechanical prosthesis.

The German Ross Registry report [6] shows a higher freedom from autograft reoperation in subcoronary implanted autografts compared with root replacements. Because our series shows that most of the indications for autograft reoperation were due to dilatation of the autograft, this higher freedom from reoperation may be expected when the native aortic wall tissue is preserved [17]. The thinner autograft wall is more prone to dilate in the high-pressure systemic circulation. Several techniques of root reinforcement are available [18, 19]. Wrapping the autograft in a vascular tube graft has shown promising results in the mid-term [18]. We have adapted a technique in which we implant the pulmonary autograft in a vascular tube graft, removing the sinuses of Valsalva in a way similar to VSRR. Although we have no long-term outcomes of this procedure, we believe this might postpone autograft reoperation in this group of patients. The diameter of the vascular prosthesis should not interfere with somatic growth. Hence, the technique is limited to teenagers and adults. A potential downside to this technique is the more complex nature of the operation, reserving it to experienced centers only.

In our series, reoperations on the RV-PA conduit occurred earlier than reoperation on the autograft. This difference was the largest in the Ross-Konno patients, as expected because of the much younger patient group and growth of the child. Postponing autograft reoperation even more by recent wrapping techniques, RV-PA reoperation may become the real burden after the Ross procedure. However, in experienced hands, RV-PA reoperation has a lower operative risk and can even be performed with the use of transcatheter valve replacement. In our series, 7 patients received a transcatheter pulmonary valve. Recent developments with decellularized homografts [20] and tissue-engineered heart valves may also reduce the need for reoperation on the RV-PA conduit. Although no reoperation whatsoever after the Ross procedure will probably remain an utopia, providing a durable solution until the age in which conventional (biological) valve prostheses are accepted treatment options pleads in favor of the use of the Ross operation in young patients.

Mechanical prostheses are an alternative for the Ross procedure. A recent meta-analysis by Etnel and colleagues [21] comparing the Ross-procedure with, among others, mechanical aortic valve replacement in children, showed that the rate of reoperations was higher in the Ross group, mainly because of right-

sided reinterventions in growing children. Furthermore, endocarditis rates were comparable between both groups, but the Ross procedure was associated with significantly less thromboembolic events, and there was a trend toward lower bleeding rates in the Ross group. Risks and benefits of both type of interventions should be discussed with patients, their parents, or both.

The retrospective nature of this study comes with its accompanying limitations. This report describes an extensive study period in which surgical and perioperative treatment has changed and may have improved in time. The completeness and very long nature of follow-up provides valuable insights in the functioning of the pulmonary autograft and RV-PA conduits in time.

In conclusion, the Ross procedure can be performed safely in young patients in need of aortic valve replacement with very low number of valve-related events during a considerable long-term follow-up. Autograft function remains stable during the first decade after operation, but autograft dilatation in the second decade necessitates reintervention. New techniques that prevent dilatation of the pulmonary autograft will delay the need for autograft reoperation. Recent developments in less-invasive valve replacement techniques lower the reoperation risk, thus lowering the disadvantage of creating a double valve problem for single valve disease.

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