Twenty-five years' experience with the arterial switch operation

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Objective: The arterial switch operation was introduced in 1976 to correct transposition of the great arteries and has since replaced atrial palliation. This study examines the long-term outcomes of the arterial switch operation.

Methods: Included in the study were 195 patients who underwent the arterial switch operation from 1977 through June 2000. Patients were evaluated for functional class, pulmonary stenosis, left ventricular function, arrhythmias, aortic sequelae, and coronary disease.

Results: Overall perioperative mortality was 15%, but rates dropped in the last 5 years to 4% for complex transposition and 0% for simple transposition. Of 151 survivors, 2 died late; 1 died of persisting pulmonary hypertension and 1 died of ventricular fibrillation after coronary pathologic changes. At last follow-up, a total of 145 patients were in New York Heart Association functional class I and 4 patients were in class II. The most frequent complication was pulmonary stenosis, necessitating 45 reinterventions in 26 patients. Left ventricular dysfunction was noted in 5 patients. Arrhythmias were seen in 5 patients: 2 patients had ventricular fibrillation (1 died and 1 required a defibrillator implantation), 1 had sick sinus syndrome, 1 had atrial flutter, and 1 had a single attack of supraventricular tachycardia. Aortic valve incompetence was absent or trivial in 146 patients, 3 had mild incompetence, 1 had moderate incompetence, and 1 had severe incompetence. Coronary sequelae were found in 5 of the 61 patients who underwent angiography.

Conclusion: Long-term clinical outcome of the arterial switch operation is good, and perioperative mortality is now low. Morbidity is dominated by pulmonary stenosis and coronary artery disease, with the potential for lethal arrhythmias.

Twenty-five years ago Jatene and colleagues¹ first described the arterial switch operation (ASO) for transposition of the great arteries (TGA). The operation seemed a simple solution for a significant problem. The ASO technique was more complex than its predecessors, the Mustard and Senning procedures,^{2,3} and it required some time before the technique became widely accepted. All the prerequisites for a successful (neonatal) ASO were recognized in time and dealt with,

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TABLE 1. Associated cardiac malformations

Diagnosis	No. of patients	No. of Dutch survivors
Simple TGA	118	100
Complex TGA		
TGA with VSD	63	41
TGA with VSD and coarctation	10	6
TGA with coarctation and intact septum	2	2
TGA with VSD and interrupted aortic arch	1	1
TGA with atrioventricular septal defect and pulmonary venous obstruction (cor triatriatum)	1	1
Total	195	151

The term *VSD* is used to indicate all types of VSD except subpulmonary VSD with overriding pulmonary valve.

which allowed general acceptance of the technique in the 1980s.⁴ Mortality has decreased as expertise has been gained and modifications have been introduced to tackle the problem of supra-valvular pulmonary stenosis.⁵ Twenty-five years have passed since the first ASO was performed in Brazil, and 24 years have passed since the first operation was done in our institution. This study reports on the results and the follow-up to date.

Patients and Methods

From 1977 through June 2000, a total of 195 patients underwent ASOs at the Wilhelmina Children's Hospital in Utrecht, The Netherlands. Associated heart defects are listed in Table 1. Patients from abroad returned home and are unavailable for follow-up.

The 151 Dutch survivors were followed up yearly according to a protocol that included 12-lead and 24-hour electrocardiography (ECG) and detailed echocardiography. Further investigations were performed as indicated. Since 1997, after publications concerning late coronary obstruction,^{6,7} elective coronary angiography was performed in all patients older than 10 years as long as consent of the parents could be obtained.

Pulmonary stenosis suspected on the basis of Doppler echocardiography was always verified by cardiac catheterization (gradient >50 mm Hg or right ventricular pressure >75% of systemic pressure). The aortic root was evaluated by Doppler echocardiography.⁸

Left ventricular dysfunction was defined as a shortening fraction less than 27% on the parasternal long axis. Invasive confirmation was always obtained.

Development of the Switch Technique

Initially, 30 patients underwent a two-stage procedure after pulmonary artery banding. When cyanosis was severe, a 5-mm aortopulmonary shunt was added ($n = 11$ patients). One hundred sixty-four patients underwent primary ASOs. Neonatal switch has been preferred for simple TGA since 1984 and for TGA with ventricular septal defect (VSD) since 1986.

TABLE 2. Perioperative mortality (30 patients)

Cause of perioperative mortality	No. of patients
LV failure	21
Imperfect coronary transfer	6
Failure of myocardial protection	2
Loss of LV muscle mass	1
Unknown	12
Pulmonary complications	4
IRDS	1
Pulmonary bleeding	2
Embolism	1
Unrecognized associated defects	4
Subvalvular aortic stenosis	2
Irreversible pulmonary hypertension	1
LV hypoplasia	1
Septicemia	1

LV, Left ventricular; IRDS, idiopathic respiratory distress syndrome.

The ASO was performed according to Jatene and colleagues' original technique, with a conduit when necessary to establish continuity of the pulmonary artery in 9 patients before 1982.⁹ With sufficient length of the pulmonary artery, the gaps left by the coronary arteries were filled with glutaraldehyde-treated pericardium.¹⁰ From 1980 onward, the maneuver described by Lecompte and associates⁵ was performed.

From 1983 to 1991, a total of 9 patients had a button patch in one ostium and a "hemipantaloon" of treated pericardium in the other ostium to overcome traction on the anastomosis. A pantaloony-shaped patch of fresh autologous pericardium was used starting in 1991.¹¹

Statistical Analysis

To investigate survival and time to reintervention or arrhythmia, the Kaplan-Meier method was used with log-rank tests and Cox regression models to test for independence of covariates. Logistic regression was used in the analysis of early mortality. Univariate analyses were performed with the Student *t* test and χ^2 test.

Results

Survival and Current State of Health

We were unable to ascertain the preoperative mortality rate especially in the era before the neonatal ASO. Perioperative mortality was 30 patients (15%). Mortality was 4% for all patients after 1996 and 0% for those with simple TGA. The causes of perioperative mortality are listed in Table 2. Independent predictors were year of surgical experience and balloon atrioseptostomy.¹²

Two patients died late, 1 of whom had TGA and an intact ventricular septum. At the age of 2 months, pulmonary artery banding was performed and a 5-mm aortopulmonary shunt was placed. Despite an ASO at the age of 5 months, this patient died of pulmonary hypertension at the age of 9 years. The second patient had an obstructed left coronary artery, and myocardial infarction developed immediately

TABLE 3. Reinterventions

Cause	No. of procedures	No. of patients
Pulmonary stenosis	42	25
Pulmonary stenosis plus VSD	1	1
Pulmonary stenosis plus moderate supralvalvular aortic stenosis	1	1
Pulmonary stenosis plus pulmonary insufficiency	1	1
Recoarctation	4	3
Diaphragmatic paralysis	3	3
Aortic insufficiency	2	1
VSD	2	2
Supralvalvular aortic stenosis	1	1
Subvalvular aortic stenosis	1	1
Automatic defibrillator implantation	1	1
Pacemaker implantation	1	1

after the ASO. This patient was free of symptoms until she had ventricular fibrillation at the age of 14 years and brain death was diagnosed on her arrival in the hospital.

Most patients (n = 145) are in New York Heart Association (NYHA) functional class I. Four patients are in NYHA functional class II. Among these 4, the first patient had left ventricular dysfunction after an ASO at the age of 1 day. Intensive care course was complicated by junctional ectopic tachycardia with repeated episodes of ventricular fibrillation. The coronary arteries seemed normal, as confirmed by later coronary angiography. This patient had left ventricular dilatation and severe aortic insufficiency. The aortic valve was replaced. The patient still has severe left ventricular dysfunction, has limited exercise capacity, and continues to receive medication. A second patient had an occluded left coronary artery and a myocardial infarct after the operation. Ventricular fibrillation developed at the age of 15 years. An automatic defibrillator was implanted, and he is being treated with β -blockers. The third patient was banded as a neonate but did not undergo the switch before the age of 5 years for reasons related to his status as a child of political refugees. His left ventricle never recovered from loss of muscle mass, and he is dependent on medication. Finally, the fourth patient acquired atrial flutter, for which he receives medication. He is now symptom free with good exercise tolerance.

Reinterventions

Sixty reinterventions were necessary in 35 patients (Table 3). Figure 1 demonstrates freedom from reintervention.

Pulmonary Stenosis

Pulmonary stenosis was the most frequent cause of reintervention, accounting for 45 procedures in 26 patients. Pul-

monary stenosis was subvalvular, valvular, or supralvalvular, depending on associated cardiac malformations and on the method of reconstruction of the pulmonary artery.^{13,14} Stenosis was exclusively in the branches in 5 patients and in the main pulmonary artery in 8. The other 13 patients had combinations of branch and main pulmonary artery stenosis.

Among the 125 patients who did not have a reintervention to relieve pulmonary stenosis, the highest flow velocity on Doppler echocardiography in the main pulmonary artery or the branches was 2.3 ± 0.6 m/s (calculated gradient 23 ± 12 mm Hg) at the latest follow-up.

The pulmonary artery was reconstructed with a conduit in 5 patients, with two separate button patches in 62, and with a pantaloony-shaped patch in 85. The Lecompte maneuver was used in 131 patients.

In the Cox regression model, the method of pulmonary reconstruction was the only independent predictor of pulmonary stenosis necessitating reintervention (Figure 2, $P = .011$). On further analysis, use of a conduit was the determining factor. In a model without the patients who had conduits, it was the material of the patch (glutaraldehyde-treated pericardium or fresh pericardium, $P = .02$), rather than the shape (buttons or pantaloony), that was the determining factor ($P = .84$).

Univariate statistical analysis demonstrates that a conduit increased main pulmonary artery stenosis ($P < .001$). Button patches increased both main pulmonary artery ($P = .016$) and branch stenosis ($P = .001$). The pantaloony patch decreased both main pulmonary artery ($P < .001$) and branch stenosis ($P = .001$). The Lecompte maneuver decreased main pulmonary artery stenosis ($P = .037$) and had no statistically significant influence on branch pulmonary stenosis ($P > .999$). Previous pulmonary artery banding raised the risk of both branch ($P = .022$) and main pulmonary artery stenosis ($P = .002$). Older patients (operated on earlier in the experience) were more likely to have branch or main pulmonary artery stenosis ($P < .001$ for both).

Sixteen patients needed a single reintervention for pulmonary stenosis; this intervention was surgical in 9 cases and by balloon angioplasty in 7. Six patients required two procedures (catheterization followed by an operation in 3 cases, two catheterizations in 2 cases, and two operations in 1 case). In 4 patients three or more procedures were necessary, starting with surgical intervention in all cases. In cases of valvular or subvalvular stenosis, catheter interventions were unsuccessful. Stenosis in the distal main pulmonary artery and in the branches is more amenable to balloon angioplasty, although some of our patients will need stent implantation in the future. Surgery consisted of patch angioplasty of the main pulmonary artery or the branches in 13 procedures. A transannular patch was necessary in 8 pa-

Figure 1. Kaplan-Meier curve demonstrating freedom of reintervention (*solid line*) with 95% confidence interval (*dotted lines*). Numbers represent numbers of patients at risk at 2, 5, 10, 15, and 20 years of follow-up.

Figure 2. Kaplan-Meier curves demonstrating freedom of reintervention for pulmonary stenosis in relation to method used to reconstruct pulmonary artery. *Straight line* represents pantaloons patch of fresh autologous pericardium; *dashed line* represents two button patches of glutaraldehyde-treated pericardium; *dotted line* represents conduit (Dacron polyester fabric or dura mater). Difference between lines is significant according to log-rank test ($P = .0011$). Numbers represent numbers of patients at risk in each group at 2, 5, 10, 15, and 20 years of follow-up.

Figure 3. Kaplan-Meier curves demonstrating freedom of symptomatic arrhythmias (solid line) with 95% confidence interval (dotted lines). Numbers represent numbers of patients at risk at 2, 5, 10, 15, and 20 years of follow-up.

tients, and 2 patients underwent homograft replacement of the pulmonary valve.

Arrhythmias

Five patients had arrhythmias develop during follow-up (Figure 3). Two had ventricular fibrillation, and 1 of these died. In the other patient a defibrillator was implanted at the age of 15 years. Both patients had perioperative myocardial infarctions and left coronary obstruction. A third patient had sick sinus syndrome without adequate ventricular escape. He had TGA with VSD and underwent the switch at the age of 57 days (after a Rashkind procedure) and received a pacemaker at the age of 12 years. The fourth patient had a single attack of supraventricular tachycardia at the age of 11 years. No medication was prescribed. The fifth patient had severe pulmonary stenosis with tricuspid insufficiency. He withdrew from follow-up for 6 years and subsequently underwent reoperation. Three years later he had atrial flutter. He underwent cardioversion and is maintained with medication pending ablation of the flutter circuit.

Aortic Root Pathology

Aortic insufficiency was absent in 107 cases, trivial in 39, grade 2/4 in 3, and grade 3/4 in 1. One patient required valve replacement for grade 4/4 insufficiency. Three of the 5 patients with significant insufficiency had Taussig-Bing anomaly, and 1 patient had pulmonary artery banding and a second-stage ASO.

The flow velocity measured by Doppler echocardiogra-

phy in the ascending aorta was a mean of 1.32 m/s, without a significant increase with time ($P = .14$). At the latest follow-up, aortic flow velocity was less than 2 m/s (<16 mm Hg) in 137 patients, 2 to 3 m/s (16–36 mm Hg) in 13 patients, and 3.2 m/s (41 mm Hg) in 1 patient. Stenosis of the aortic valve or anastomosis leading to left ventricular hypertrophy on ECG or echocardiography did not occur. One patient had mild stenosis develop at the aortic anastomosis, without left ventricular hypertrophy. He required reintervention for pulmonary stenosis, and patch angioplasty of the aorta was performed during this procedure. One patient had TGA with subpulmonary VSD and left ventricular outflow tract stenosis, thought to be caused by bulging of the septum because of the higher right ventricular pressure. After ASO, however, the stenosis increased, necessitating reoperation half a year later. The patient with interrupted aortic arch had severe stenosis develop at the site of aortic cannulation; this necessitated reoperation within the first postoperative week.

Coronary Arteries

To date, cardiac catheterization has been performed in 61 patients who were not selected for symptoms or abnormal findings on ECG or echocardiography. Coronary sequelae were found in 5 patients. There was no relationship to the initial coronary anatomy.¹² Two patients had an occluded left coronary artery (Figure 4); both had ventricular fibrillation develop as described previously. Whether an attempt

Figure 4. Aortogram (right oblique view) of patient with perioperative myocardial infarction, demonstrating large right coronary artery and absent left coronary artery.

should be made to reperfuse the occluded coronary artery in the surviving patient is still under debate.

The third patient has an occluded right coronary artery in an originally complex coronary anatomy with circumflex branches from both ostia. Retrograde collateral flow was noted to perfuse the area of flow of the right coronary artery, and perfusion scintigraphy was normal. This patient is currently completely free of symptoms.

Asymptomatic stenosis of the right coronary ostium was documented in a fourth patient, and a fifth patient has multiple tortuous collaterals without evidence of obstruction of a major coronary branch. These last 2 patients have normal 12-lead and 24-hour ECGs, normal left ventricular function, and normal scintiscans.

Left Ventricular Dysfunction

Left ventricular dysfunction was encountered in 5 patients. Two patients had occluded left coronaries as described previously. In another patient the left ventricular dysfunction was attributed to failure of myocardial protection during the switch. The fourth patient had loss of left ventricular mass related to a very late ASO, despite pulmonary artery banding as a neonate. This patient had a protracted postoperative course and still requires medication. Finally, 1 patient had enlargement of the left ventricle with suboptimal contractility, without coronary artery abnormalities. This patient had Taussig-Bing anomaly and had undergone coarctectomy and banding of the pulmonary artery as a neonate. An ASO was performed at the age of 1.4 years. Loss

TABLE 4. Complications in patients with primary arterial switch and with second-stage switch

Complication	Primary	2nd-stage	P value
No complications	100	8	<.001
Pulmonary stenosis	17	9	.003
Other reinterventions	8	1	.42
Symptomatic arrhythmias	2	3	.02
Aortic insufficiency	4	1	.616
Left ventricular dysfunction	1	4	.001
Coronary sequelae	2	3	.13
Suboptimal functional class	1	3	.007
Late death	0	2	.019
Total surviving patients	129	22	

Figures represent numbers of patients.

of muscle mass before the switch is a possible factor, although his postoperative course was uneventful.

Two-Stage Switch

A two-stage ASO was performed in 31 cases. Thirty patients underwent banding, combined with a shunt in 11 cases. One patient underwent a shunt without banding because of hypoplastic pulmonary branches.

Early mortality in this group was 9 patients (29%). In univariate analysis, banding was a risk factor for early death ($P = .025$), but in the multivariate analysis surgical experience rather than banding was the significant factor.

In the group of patients with late complications, many had previous banding; only 8 of 22 patients surviving this two-stage procedure did not have any complications (Table 4). In Cox regression analysis, banding ($P = .05$) and shunt ($P = .02$) were independent predictors for one or more postoperative complications.

Discussion

The initial enthusiasm for the ASO was tempered by the high mortality during the early years.¹⁵ Although the long-term quality of life for the patients was expected to be better, the short-term survival rates associated with the Mustard and Senning procedures compared favorably with those associated with the ASO.

In our study population, the initial perioperative mortality was as high as 60%, leading to discussions about whether to continue implementing this technique.¹⁶ Gradually, improving results of the neonatal ASO provided the support necessary for us to persevere. Like other groups, we are now able to report acceptable mortalities.¹⁷⁻¹⁹

Late mortality has been limited to 2 patients. One patient with simple TGA died of irreversible pulmonary hypertension, even though he had never been exposed to elevated pulmonary arterial pressures. The development of pulmonary vascular disease is well documented in patients with TGA and VSD but less well known in patients with simple

TGA. In 1998, Rivenes and Grifka²⁰ reported on a small group of patients who, despite adequate and timely intervention, had pulmonary vascular occlusive disease develop. This spontaneous development of pulmonary vascular disease in TGA, although rare, remains a significant unsolved problem.

The other late death was that of a patient with postoperative coronary pathologic changes. Perioperative left ventricular ischemia and dysfunction was the main cause of early mortality in our series. Postoperative coronary pathologic changes may be seen late, without perioperative complications, as reported by Bonhoeffer and coworkers,⁶ by Tanel and associates,⁷ and by our group.¹² The percentage of patients with such changes is small, but the implications are serious. Pathologic changes can be seen late, with ventricular arrhythmia or sudden death after a long silent interval of many years. As Bonhoeffer and coworkers⁶ advocated, we have adopted a policy to perform coronary angiography in the follow-up of all ASOs, currently at the age of 10 years. Whether patients are at increased risk for ischemic heart disease later in life remains to be determined.

Arrhythmias are related in part to imperfections in the ASO: coronary occlusion with infarction or long-standing right ventricular pressure overload from pulmonary stenosis. The precise causes of the binodal disease (sick sinus syndrome without ventricular escape) and of the single episode of supraventricular tachycardia are unclear, and these conditions are not necessarily attributable to the surgery. In a comparison of the incidence of supraventricular arrhythmias after switch operations with the incidence after atrial baffle procedures, the advantage of the ASO is overwhelmingly clear.²¹

A two-stage ASO was the norm during the early experience. Some lessons can be learned concerning retraining the left ventricle for a late ASO in the current era. Loss of left ventricular muscle mass may lead to higher perioperative mortality risk, even if the pulmonary band seems adequate. Persistent left ventricular dysfunction and late arrhythmias should be anticipated.

Significant aortic insufficiency is rare and related to the original anatomy, especially subpulmonary VSDs. Lack of support of the overriding pulmonary (neo-aortic) valve may be an important factor. Size difference between the great arteries, often more pronounced in this type of VSD, is another possible cause. As we have previously reported elsewhere, progressive dilatation of the neo-aortic root did not seem to be a factor.⁸ A significant relationship with pulmonary artery banding, as was previously found by others,²² was not encountered.

Stenosis of the aortic anastomosis is seldom seen after the arterial switch because, unlike with the pulmonary anastomosis, there is no traction. Also, a pulmonary (neo-aortic) valve of insufficient size will preclude an ASO, whereas

stenosis of the right ventricular outflow tract is no contraindication.

Most surviving patients did not have problems and are in NYHA class I, not unlike the experience that Kirklin and colleagues²³ reported in 1992. Four of our patients are in NYHA class II, with left ventricular dysfunction, arrhythmias, or both.

Pulmonary stenosis remains the most frequent complication and the most frequent cause of reintervention. The continuous modifications of ASO have decreased the incidence of pulmonary stenosis. However, insufficient follow-up duration does preclude interpretation of improvement through use of the pantaloon patch. Currently, the pulmonary branches are dissected down to the hilum, and an ample pantaloon patch is used to elongate the main pulmonary artery. The incidence of pulmonary stenosis is with this technique expected to drop well below 10%. Some pulmonary stenosis will remain in patients with unfavorable anatomy, such as our patient with hypoplastic pulmonary branches.

The overall outcome of this group of patients is promising and supports the decision to abandon the atrial switch procedure. However, an in-depth study of quality of life and school and professional careers, like those that have been performed for patients after Mustard and Senning operations,²⁴ has not yet been performed for patients after the ASO. To complete the long-term evaluation of the ASO, such a study seems imperative.

Conclusion

After 25 years, the ASO has been established as the operation of choice for TGA. The current results are excellent, and operative mortality has dropped to 4% even for the complex forms of TGA. In long-term follow-up, the patients remain in good condition and are able to lead normal lives. Pulmonary stenosis remains the most frequent cause of reintervention, although modifications in surgical technique have reduced this problem. Late coronary pathologic changes are rare but carry serious, life-threatening consequences. Patients and doctors can be completely unaware of such changes unless angiography is performed.

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