Interactive CardioVascular and Thoracic Surgery (2020) 1–8
doi:10.1093/icvts/ivaa034

Cite this article as: Lübe Antunes Pereira F, Nunes Martins C, Lopes RM, Ferber Drummond M, Fantini FA, Correa Vrandecic E *et al*. Impact of pulmonary artery reduction during arterial switch operation: 14 years follow-up. Interact CardioVasc Thorac Surg 2020; doi:10.1093/icvts/ivaa034.

Impact of pulmonary artery reduction during arterial switch operation: 14 years follow-up

Fernanda Lübe Antunes Pereira[a,*], Cristiane Nunes Martins[b], Roberto Max Lopes[b], Matheus Ferber Drummond[a], Fernando Antonio Fantini[a], Erika Correa Vrandecic[c], Mario Oswaldo Vrandecic Peredo[c] and Bayard Gontijo Filho[a]

[a] Department of Cardiovascular Surgery, Biocor Instituto, Belo Horizonte, Brazil
[b] Department of Paediatric Cardiology, Biocor Instituto, Belo Horizonte, Brazil
[c] Department of Cardiology, Biocor Instituto, Belo Horizonte, Brazil

* Corresponding author. Department of Cardiovascular Surgery, Biocor Instituto, Alameda Oscar Niemeyer, 436/506, Vila da Serra, Nova Lima, Belo Horizonte, MG 34006-049, Brazil. Tel: +55-31-997008286; e-mail: nandalube@gmail.com (F. Lübe Antunes Pereira).

Received 1 September 2019; received in revised form 16 January 2020; accepted 10 February 2020

Key question

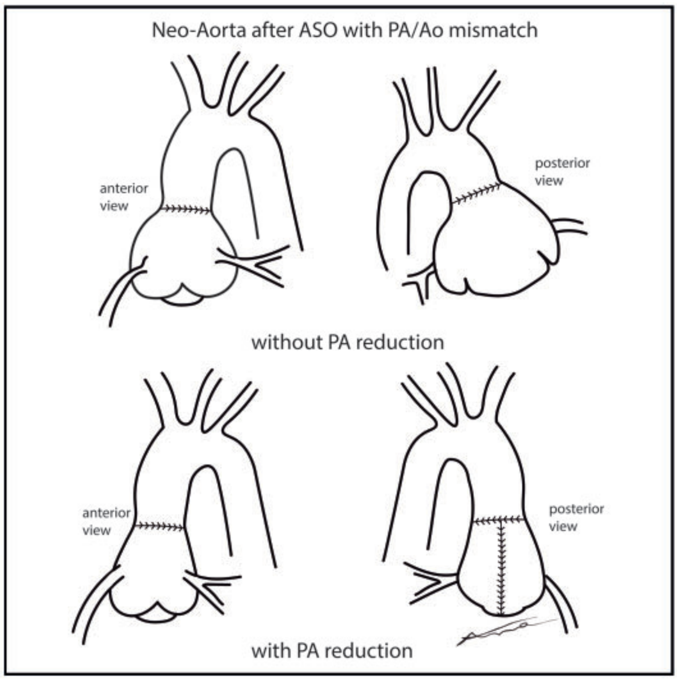
What is the impact of pulmonary artery reduction on the management of mismatch of the great vessels in the arterial switch operation?

Key finding(s)

Stabilization of neo-aortic root dilatation and satisfactory neo-aortic valve performance.

Take-home message

Pulmonary artery reduction proved to be a feasible, low-risk procedure for treating pulmonary artery/aorta mismatch in the arterial switch operation.



Abstract

OBJECTIVES: Pulmonary artery/aorta (PA/Ao) size discrepancy plays an important role in the development of neoaortic root growth and valve regurgitation. Since 2004, we started using PA reduction to manage severe great vessels root mismatch at the time of arterial switch operation. The purpose of this study is to evaluate the impact of this technique in the mid- and long-term follow-up.

METHODS: Patients considered to have severe PA/Ao mismatch (>2:1 ratio) underwent resection of a 3- to 4-mm flap of the posterior PA wall. Patients submitted to this technique were followed up with clinical and image examinations. Echocardiographic findings were reviewed, and *Z*-scores were recorded to evaluate the incidence and progression of neoaortic root dilatation and valve regurgitation.

Presented at the 33rd Annual Meeting of the European Association for Cardio-Thoracic Surgery, Lisbon, Portugal, 3–5 October 2019.

RESULTS: The median (Q1–Q3) follow-up time was 8 years (3–11). Before arterial switch operation, the median (Q1–Q3) *Z*-score of the PA annulus was 2.90 (2.75–3.75). At the latest follow-up, the median *Z*-score of the neoaortic annulus was 1.34 (0.95–1.66). The mean difference between the *Z*-scores of PA annulus and neoaortic annulus was 1.56 ($P < 0.0001$). The mean value of the sinus of Valsalva was +0.29 ± 1, that of sinotubular junction was +0.71 ± 0.6 and that of ascending Ao was +1.09 ± 0.7. There was no severe dilatation of the neoaortic annulus, neoaortic root or ascending Ao during follow-up. Neoaortic valve regurgitation was none or mild in 93% of patients.

CONCLUSIONS: PA reduction proved to be a feasible and low-risk procedure to approach PA/Ao mismatch in arterial switch operation. Mid- and long-term follow-up showed a tendency towards stabilization of the neoaortic root dilatation and satisfactory valve performance after the procedure. Further investigation is required with a larger population and longer-term follow-up.

Keywords: Transposition of the great arteries • Arterial switch operation • Pulmonary artery/aorta mismatch • Pulmonary artery reduction • Neoaortic dilatation • Neoaortic regurgitation

ABBREVIATIONS

Ao	Aorta
ASO	Arterial switch operation
BSA	Body surface area
NYHA	New York Heart Association
PA	Pulmonary artery
SD	Standard deviation
TGA	Transposition of the great arteries
VSD	Ventricular septal defect

INTRODUCTION

The arterial switch operation (ASO) has become the surgical procedure of choice to repair transposition of the great arteries (TGA) in neonates and infants, with excellent early and mid-term results and satisfactory overall survival and functional status [1].

Complications related to the coronary arteries and right ventricular outflow tract are well known, and due to progressive technical refinement and increased surgical experience, its incidence has decreased significantly [2]. On the other hand, reports about progressive neoaortic root dilatation and neoaortic valve regurgitation in the long-term follow-up are raising concern for late reintervention in the patients submitted to ASO [3].

In our experience, and in accordance to other studies, we found that significant pulmonary artery/aorta (PA/Ao) size discrepancy plays an important role in the development of disproportionate neoaortic root growth and neoaortic valve regurgitation after ASO, especially in patients with complex variants of TGA and aortic arch anomalies association [4, 5]. Since 2004, we started using PA reduction to manage severe PA/Ao mismatch at the time of ASO. The purpose of this study is to evaluate the impact of this technique in the mid- and long-term follow-up of these patients.

MATERIALS AND METHODS

Patients

From January 1998 until December 2018, 425 patients underwent ASO in our institute. Since February 2004, 34 patients were submitted to PA reduction during ASO, with 32 hospital survivors. A total of 31 patients were followed up postoperatively with clinical examination and echocardiographic studies until December 2018. One patient, who resided outside of the state, was lost for follow-up examinations and excluded from our study.

Table 1: Patient characteristics

Variables	*n* = 31
Gender, *n* (%)	
Male	16 (51.6)
Female	15 (48.4)
Type of TGA, *n* (%)	
Taussig–Bing	6 (19.4)
TGA + VSD	20 (64.5)
Simple TGA	5 (16.1)
Age at ASO (days), median (Q1–Q3)	26.0 (13.0–73.0)
Associated anomaly, *n* (%)	
None	14 (34.1)
Aortic arch hypoplasia	3 (7.3)
Aortic coarctation	9 (21.9)
Aortic arch interruption	2 (4.9)
Bicuspid pulmonary valve	3 (7.3)
Dextrocardia	2 (4.9)
Juxtaposed atrial appendages	2 (4.9)
Persistent fifth aortic arch	1 (2.4)
Persistent left superior vena cava	1 (2.4)
Ostium secundum atrial septum defect	1 (2.4)
Situs inversus	2 (4.9)
Straddling tricuspid valve	1 (2.4)

ASO: arterial switch operation; TGA: transposition of the great arteries; VSD: ventricular septal defect.

The median (Q1–Q3) age at the time of ASO was 26 (13–73) days. The median (Q1–Q3) age at the last follow-up was 8 years (3–11). Sixteen (51.6%) patients were male, and 15 (48.4%) patients were female. Twenty-six (76.47%) patients had complex TGA [TGA + ventricular septal defect (VSD) or Taussig–Bing anomaly], and 12 (35.29%) patients had associated cardiac anomalies related to the Ao (interrupted aortic arch, coarctation of the Ao or hypoplastic aortic arch) (Table 1). Detailed patients characteristics are available in the Supplementary Material (Table S1).

Surgical technique

The ASO was performed by a single cardiac surgeon, using the usual technique adopted in our institution and previously described [6].

Surgery was performed under standard moderate hypothermic cardiopulmonary bypass, except in cases with aortic arch interruption, where a brief period of total circulatory arrest was necessary for aortic arch reconstruction. Single anterograde infusion of crystalloid cardioplegia was used. Coronary reimplantation

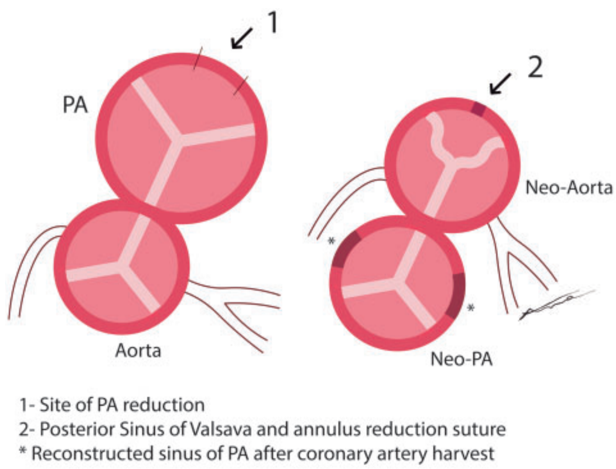


Figure 1: Schematic illustration of great vessels before and after PA reduction during arterial switch operation (ASO). The image on the left shows the position of the great vessels during ASO, PA/aorta mismatch and an indication of pulmonary reduction site. The image on the right shows the aspect of great vessels during ASO, after pulmonary reduction, with posterior sinus of Valsalva reduction suture and leaflets redundancy in the neoaorta as well as reconstruction of sinus of Valsalva in the neopulmonary artery. PA: pulmonary artery.

was performed in the corresponding pulmonary sinus of Valsalva, after marking the anastomosis site with the distended Ao and using a button technique in all patients. The approach for VSD closure (right atrium, PA or Ao) was chosen after transection of the great vessels and coronary mobilization, depending on best site for surgical exposure; LeCompte manoeuvre was used in the great majority of patients (except in patients with side-by-side great vessels relationship); mean ± standard deviation (SD) duration of extracorporeal circulation was 108 ± 11 min, and that of cross-clamping time 75 ± 10 min.

PA reduction was indicated when PA/Ao ratio was >2:1 and was achieved by the resection of a 3- to 4-mm rectangular fragment from the edge of the posterior wall to within the annulus of the pulmonary valve (Fig. 1), after extensive mobilization of PA and coronary arteries and complete transection of the great vessels. Resection was performed at the posterior sinus of Valsalva (non-coronary sinus) in all but 3 patients with bicuspid pulmonary valve (in these patients, resection was executed in the larger sinus, away from the site of coronary reimplantation). Stay sutures were placed at the edges of the PA walls to allow the perfect alignment of the suture, which was carried out from the annulus to the transected margin of the vessel. Once the flap resection extended down to the valve annulus, meticulous care was taken to avoid distortion of the valve leaflets, keeping the same height of commissures.

Echocardiographic examination

All echocardiographic examinations were performed by the same examiner using Philips HD11 ultrasound system with size appropriated phased-array transducers following the guidelines of the American Society of Echocardiography [7].

Aortic dimensions were measured in triplicate and averaged in the following sites: (i) neoaortic annulus, (ii) maximum diameter of the sinus of Valsalva, (iii) sinotubular junction (transition between sinus of Valsalva and tubular portion of ascending Ao) and (iv) maximum diameter of proximal ascending Ao, using the methods for measurements of the aortic root used in our service and previously described [5].

Data collection and definitions

Medical records were reviewed for echocardiographic preoperative data and *Z*-score for PA, postoperative evaluations including transthoracic echocardiography and current functional status according to the New York Heart Association (NYHA) functional classification.

From October 2018 until December 2018, patients who underwent PA reduction were invited for clinical examination and detailed echocardiography with focus on neoaortic root and neoaortic valve function. Three patients could not attend this last call evaluation, and data of their last routine echocardiography from the years 2013 and 2014 were considered as the latest follow-up.

Angiotomography or angiography was obtained in 26 patients that needed further evaluation of the neoaorta or to study coronary circulation.

Body surface area (BSA) was calculated using the Haycock formula [8]. Aortic measurements were indexed to BSA to calculate *Z*-score using the equations obtained by Pettersen *et al.* [9].

Neoaortic root dilatation was defined as severe (*Z*-score >5), moderate (*Z*-score 3–4.9) and mild (*Z*-score 1–3) at any site of the aortic root [10]. Neoaortic valve regurgitation was assessed using colour Doppler and graded using a jet width/left ventricle outflow tract ratio as mild (R: ≤0.25), moderate (R: 0.25–0.5) and severe (R: >0.5). Pulsed Doppler evidence of holodiastolic flow reversal in the abdominal Ao and the degree of left ventricular dilatation were also used to estimate moderate to important regurgitation [11].

Statistics

Quantitative variables were described as mean ± SD when normally distributed and verified by the Shapiro–Wilk test and median (first quartile–third quartile) when non-normally distributed. Categorical variables were described by absolute frequencies and percentages. Wilcoxon test was used to compare continuous variables (*Z*-score of PA and neoaortic annulus) because these variables were non-normally distributed when verified by Shapiro–Wilk's test. The significance level was 0.05. The statistical analysis was performed using statistical software SPSS version 20.0.

Ethics considerations

This study was approved by the institutional Ethics Committee according to regulations in force for observational studies and in compliance with the Declaration of Helsinki principles.

RESULTS

Operative mortality

In-hospital deaths occurred in 2 (5.88%) patients in the postoperative period. One patient had active bleeding that required haemostasis revision, delayed sternal closure and presented low cardiac output syndrome. The other patient developed

Table 2: Reinterventions

Variables	n = 31
Time after ASO (years), median (Q1–Q3)	2.0 (1.0–7.0)
Reintervention procedure, n (%)	
Angioplasty of recoarctation of the aorta	1 (6.7)
Balloon pulmonary valvuloplasty	2 (13.3)
Bilateral pulmonary branch stenting	1 (6.7)
Epicardial pacemaker implantation	1 (6.7)
Left pulmonary branch stenting	1 (6.7)
Mechanical aortic valve replacement	1 (6.7)
Mechanical pulmonary valve replacement + RVOT augmentation	1 (6.7)
Subaortic stenosis resection + sinus of Valsalva reduction plasty	1 (6.7)
Surgical correction of coarctation of the aorta	4 (26.7)
Surgical correction of pulmonary valve stenosis	1 (6.7)
Surgical correction of pulmonary valve stenosis + RVOT augmentation	1 (6.7)

ASO: arterial switch operation; RVOT: right ventricular outflow tract.

ventilator-associated pneumonia and severe sepsis. No patients died after hospital discharge.

Reinterventions

Of 31 patients, 11 (35.48%) patients required one or more reinterventions during the follow-up period; these included 10 surgical operations and 5 percutaneous procedures without mortality. Detailed information about reintervention are available in the Supplementary Material (Table S2).

Only 2 (6.45%) patients had reoperations related to left ventricular outflow tract. One patient had aortic mechanical valve replacement (without neoaortic root replacement) and subsequent epicardial pacemaker implantation. The other patient had resection of subaortic stenosis and sinus of Valsalva reduction plasty. In the last case, dilatation occurred on both coronary sinus but was absent on the non-coronary sinus of Valsalva where pulmonary reduction technique was done at the time of ASO.

The remainder of reinterventions were related to right ventricular outflow tract or coarctation of the Ao. All interventions are summarized in Table 2.

Outcomes

Follow-up time: the follow-up time was between 10 and 14 years in 11 patients (35.48%), 5 and 10 years in 9 patients (29.03%) and <5 years in 11 patients (35.48%). The median (Q1–Q3) follow-up time was 8 years (3–11).

Z-score comparison between PA and neoaorta: before ASO, the median (Q1–Q3) *Z*-score of the PA annulus was 2.90 (2.75–3.75). At the latest follow-up, the median (Q1–Q3) *Z*-score of the neoaortic annulus was 1.34 (0.95–1.66). The mean difference between the *Z*-scores of PA annulus and neoaortic annulus was 1.56 ($P < 0.0001$) (Fig. 2). Detailed information about Z-scores are available in the Supplementary Material (Table S3).

A total of 22 (71%) patients presented mild dilatation, and 1 patient showed a *Z*-score of -1.96 of the neoaortic annulus.

Z-score for neoaortic root: the mean ± SD value *Z*-score of the sinus of Valsalva was +0.29 ± 1 and that of sinotubular junction was +0.71 ± 0.6. A total of 16 (51%) patients presented mild dilatation of neoaorta in at least one of these sites. One patient showed a *Z*-score of -2.19 of the sinus of Valsalva.

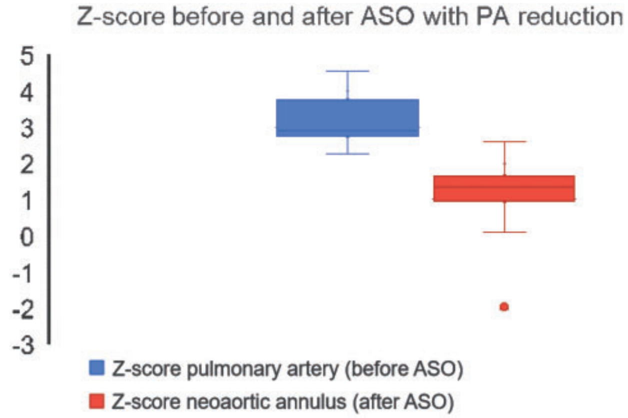


Figure 2: Box-plot *Z*-scores of PA annulus and *Z*-scores of neoaortic annulus. ASO: arterial switch operation; PA: pulmonary artery.

Table 3: *Z*-score values for PA and neoaortic root and neoaortic valve regurgitation

Variables	n = 31
PA *Z*-score, median (Q1–Q3)	2.9 (2.75–3.75)
Neoaortic annulus *Z*-score, median (Q1–Q3)	1.34 (0.95–1.66)
Sinus of Valsalva *Z*-score, mean ± SD	0.29 ± 1.04
Sinotubular junction *Z*-score, mean ± SD	0.72 ± 0.64
Ascending aorta *Z*-score, mean ± SD	1.10 ± 0.74
Neoaortic valve regurgitation, n (%)	
None	14 (41.9)
Mild	16 (51.6)
Moderate	2 (6.5)

PA: pulmonary artery; SD: standard deviation.

Z-score for ascending Ao: the mean ± SD value was +1.09 ± 0.7. A total of 17 (55%) patients presented mild dilatation and 1 patient presented a *Z*-score of -1.13 of the ascending Ao.

There was no severe dilatation of the neoaortic root or ascending Ao during follow-up. One patient presented moderate dilatation of sinus of Valsalva during the follow-up period and was submitted to reduction plasty.

Neoaortic valve regurgitation: regurgitation was none or mild in 29 (93%) patients. Two (6.45%) patients had moderate neoaortic valve regurgitation. One patient was submitted to residual VSD correction and neoaortic valve replacement during the follow-up period, and another one is on watchful observation. There was no severe neoaortic valve regurgitation at the latest follow-up.

Functional status: all 31 patients were in functional class I or II of NYHA at the latest follow-up.

Data are summarized in Table 3.

DISCUSSION

Progressive neoaortic root dilatation and neoaortic valve regurgitation is a recognized time-dependent phenomenon and a long-term complication of ASO [12–14]. It has become the major cause of concern for late reoperations in these patients [15]. Several risk factors for dilatation and regurgitation have been reported, such as presence of VSD, coarctation of the Ao, aortic arch anomalies, prior PA banding, method for the reimplantation of coronary arteries and size discrepancy of the great arteries [10, 12, 16, 17]. The pathophysiological mechanisms for the neoaortic root dilatation and development of moderate-to-severe neoaortic regurgitation are poorly understood and probably multifactorial. Hypotheses have been made about histomorphological differences between the great vessels in TGA, position of the pulmonary valve in systemic circulation, surgical injury to the vasa-vasorum and ischaemic lesions to the arterial wall and geometrical factors of arterial root anastomosis and leaflet coaptation, as well as primary root dilatation followed by somatic growth [18–23].

In our experience in the mid- and long-term follow-up, a common finding in patients who developed moderate to important neoaortic root dilatation and neoaortic valve regurgitation was the presence of size discrepancy between the great vessels observed before ASO, especially in patients with complex variants of TGA [5]. Our first series of ASO started in January 1998; since then, 425 patients were operated until December 2018. Initially, anastomosis of the great vessels was accomplished by adjusting the larger diameter of the PA to a much smaller ascending Ao, often requiring trimming of the suture or augmentation of the ascending Ao. This commonly resulted in an initially dilated neoaortic root after ASO.

Pulmonary plasty techniques have been described for the purpose of achieving a better arterial root anastomosis, with good initial results, but lack of long-term period of observation [24–26]. In 2004, we started performing PA reduction by resecting a rectangular flap of the pulmonary arterial wall, reducing the entire pulmonary root including downsizing the valve annulus, achieving a symmetrical total reduction of the neoaortic root and more harmonic anastomosis with the ascending Ao (Fig. 3). Since then, PA reduction was done in 34 patients using essentially the same technique. Only patients with severe PA/Ao mismatch (ratio >2:1) were selected for PA reduction.

Aside from achieving a satisfactory immediate result obtaining a symmetric anastomosis in all patients, observation at mid- and long-term follow-up showed a tendency towards stabilization of the neoaortic dimension as well as a lower incidence of significant neoaortic regurgitation. These results were demonstrated by serial echocardiographic examination in all patients during follow-up and corroborated by angiotomographic or angiographic studies obtained in 26 patients during the same period (Figs 4 and 5).

These observations became more evident when we compared these patients with the group of patients operated before PA reduction was introduced, in 2004. Although there is a difference in follow-up time between the 2 groups of patients, and a reliable and complete database was not available for statistical analysis, the evolution we observed is markedly different. In the first group of patients, there are 3 patients who were submitted to a Bentall procedure.

We believe that PA/Ao size discrepancy plays an important role in the mechanism of neoaortic root dilatation and related valve regurgitation by altering the geometry of the great vessel root and affecting fluid dynamics in this structure, which may lead to changes in the wall shear stress, promoting vascular remodelling and susceptibility to dilatation [27, 28]. Hydraulic *in vitro* studies have shown the occurrence of vortices in dilated

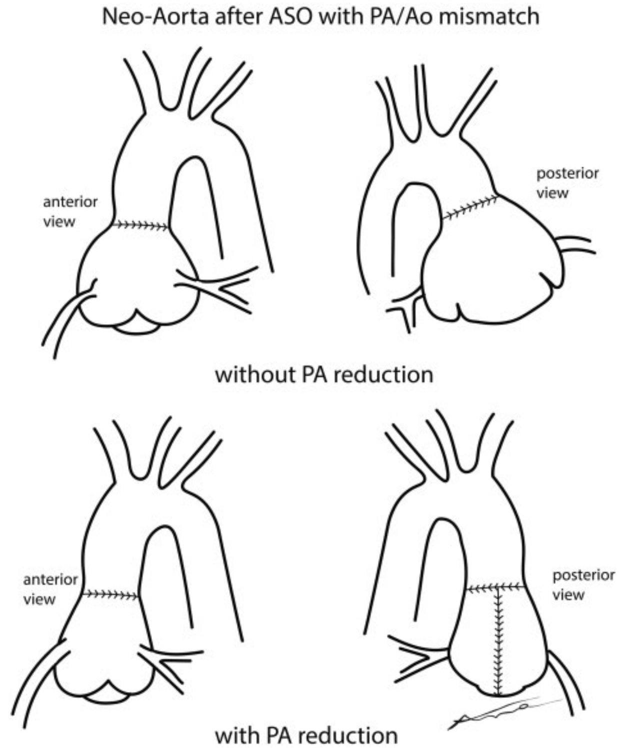


Figure 3: Schematic illustration of the neoaorta after ASO in the presence of preoperative PA/Ao mismatch. Top image shows neoaorta in patients who were not submitted to PA reduction, showing size discrepancy in anastomosis between neoaortic root and ascending aorta. Bottom image shows neoaorta in patients submitted to PA reduction, showing geometric concordance of the anastomosis. Ao: aorta; ASO: arterial switch operation; PA: pulmonary artery.

aortic sinuses that may result in aortic wall thinning and damaging in the regions of haemodynamic jet impact [29].

Preservation of the aortic diameter and valve function with the PA reduction may be explained by (i) reduction of the initial size of the neoaorta that will be followed by an immediate postoperative dilating phase and final normal growth of the vessel with a more uniform development [30] and (ii) geometric concordance between the neoaortic root and ascending Ao anastomosis, avoiding the distortion generated by suture trimming and resulting in a better hydraulic flow pattern, reducing the impact on the arterial wall. This diameter stabilization of the neoaortic root, combined with a wider area of leaflets coaptation obtained with the PA resection, may be the reason for reduced incidence of neoaortic valve regurgitation observed in this patient's evolution.

Even though the results obtained with PA reduction are encouraging, we have to consider some drawbacks in our technique: (i) suture malalignment of the valve leaflets during PA closure may result in neoaortic valve regurgitation; (ii) neoaortic valve configuration after PA resection with redundancy of posterior valve leaflet may affect its performance in a longer-term; (iii) the PA reduction adds more suture lines to the surgical technique and special attention to haemostasis should be paid; and (iv) indication to resect and the amount of resection are a surgeon's on-the-spot decision. Although we did not have complications related to neoaortic stenosis, we have recorded neoaortic root *Z*-scores below -1, which may indicate excessive resection of PA.

The main points that should be observed when performing the technique are (i) patient selection (severe mismatch between the great vessels, ratio > 2:1); (ii) site of resection (always on the non-

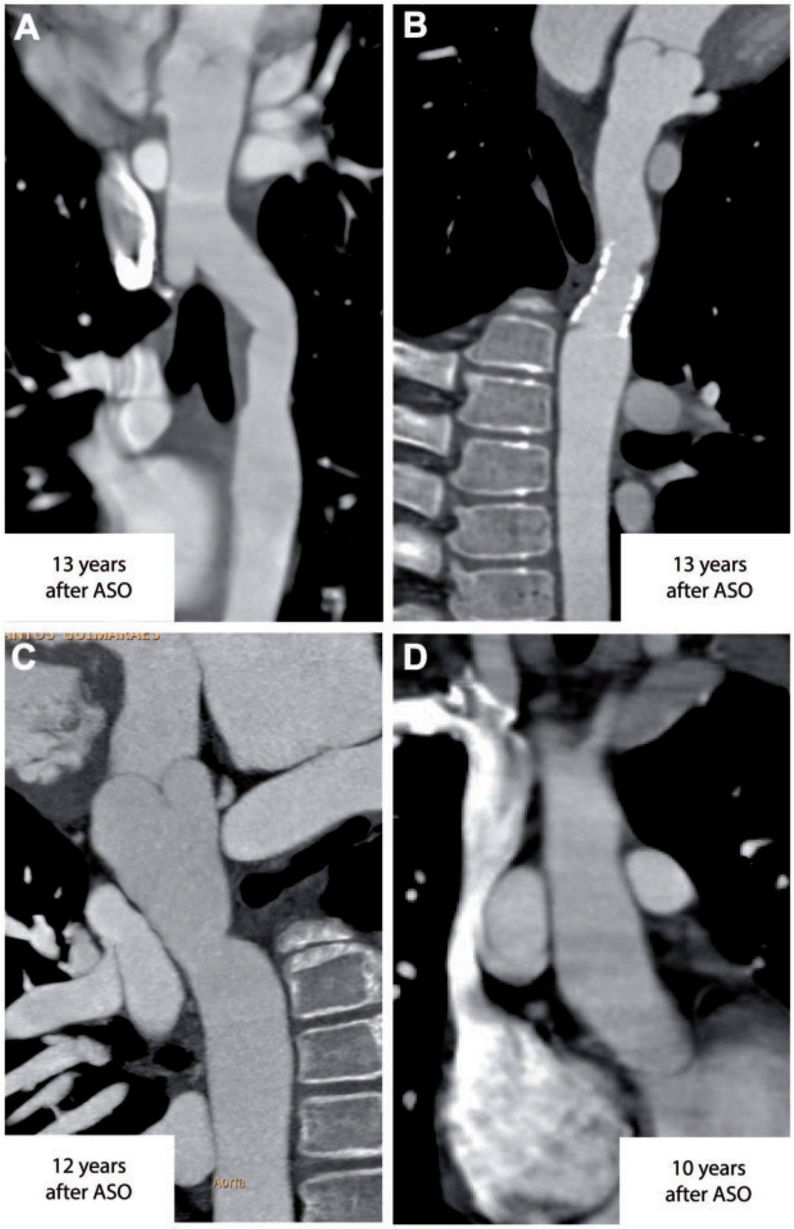


Figure 4: Angiotomographic images of neoaorta of 4 different patients (**A**, **B**, **C** and **D**) submitted to pulmonary artery reduction in the long-term follow-up after ASO. Patient B had angioplasty correction of recoarctation of the aorta. Patient C had interruption of aortic arch associated with the transposition of the great arteries before ASO. ASO: arterial switch operation.

coronary sinus of Valsalva, regardless of coronary anatomy); (iii) resection of a 3- to 4-mm fragment of PA (about one-third of the sinus diameter); and (iv) alignment of the suture (it is essential to use 1 stay suture on the superior edges of transected PA to align the flaps and start the suture from the root to the top of PA to avoid leaflet malalignment).

We also believe that PA reduction will not be effective in all patients with PA/Ao mismatch. Patients who show extreme dilatation of pulmonary sinuses of Valsalva before ASO will probably maintain the progressive dilatation in spite of the reduction, as we observed in one of our patients. Since more important neoaortic root dilatation and need for replacement have been described occurring after 15–20 years of follow-up, our present findings may change as our observation period continues.

Limitations

This study has several limitations, including its single institution, retrospective nature and the wide range of follow-up time. The morphometric study may have been influenced by non-blinded measurements. Lack of available normalized aortic root diameter in Brazilian paediatric population may have affected our findings. Other interesting variables were not included in this study for insufficient reliable statistical information. Comparison with the first group of patients, not submitted to pulmonary reduction, would be significant for the evaluation of our technique. Mechanisms for neoaortic root enlargement and neoaortic valve regurgitation and the effects of the technique described are speculative and require further investigation.

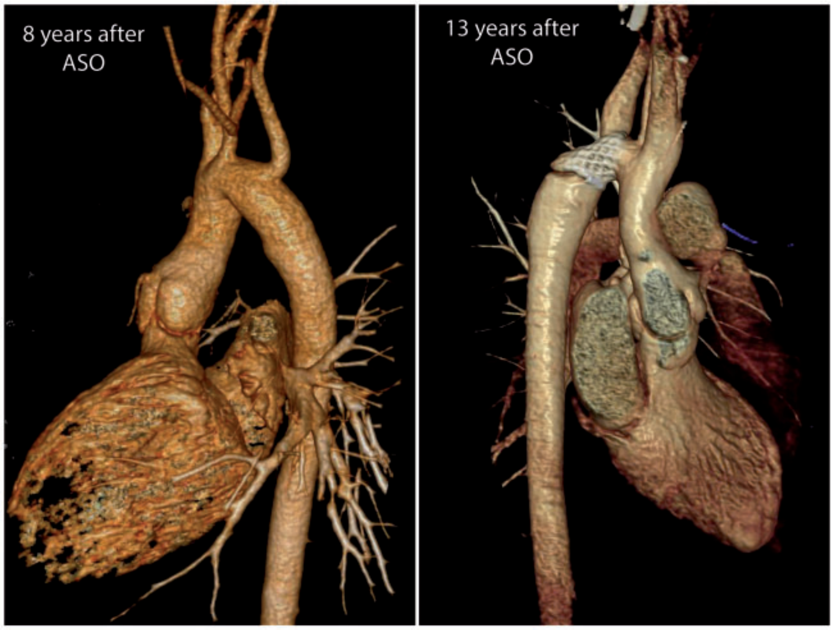


Figure 5: Three-dimensional angiotomography reconstruction of neoaorta in different patients submitted to pulmonary artery reduction after ASO. Patient on the right had angioplasty correction of recoarctation of the aorta. ASO: arterial switch operation.

CONCLUSION

In conclusion, PA reduction during ASO proved to be a feasible, reproducible and low-risk procedure to approach PA/Ao mismatch. Mid- and long-term follow-up showed a consistent tendency towards stabilization of the neoaortic root dilatation and satisfactory neoaortic valve performance after the procedure. Nevertheless, further investigation is required with a larger population, control group and longer-term follow-up.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

Conflict of interest: none declared.

Author contributions

Fernanda Lübe Antunes Pereira: Conceptualization; Data curation; Formal analysis; Project administration; Resources; Visualization; Writing—original draft; Writing—review & editing. **Cristiane Nunes Martins:** Investigation; Methodology; Supervision; Validation; Visualization. **Roberto Max Lopes:** Formal analysis; Validation; Visualization. **Matheus Ferber Drummond:** Formal analysis; Supervision; Validation; Visualization. **Fernando Antonio Fantini:** Formal analysis; Supervision; Validation; Visualization. **Erika Correa Vrandecic:** Methodology; Supervision; Validation; Visualization. **Mario Oswaldo Vrandecic Peredo:** Supervision; Visualization. **Bayard Gontijo Filho:** Conceptualization; Formal analysis; Investigation; Project administration; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing.

ACKNOWLEDGEMENTS

The authors thank Ana Luiza Lübe Antunes Pereira for the illustrations.

REFERENCES

[1] Villafañe J, Regina Lantin-Hermoso M, Bhatt AB, Tweddell JS, Geva T, Nathan M *et al.* D-Transposition of the great arteries. J Am Coll Cardiol 2014;64:498–511.
[2] Losay J, Touchot A, Serraf A, Litvinova A, Lambert V, Piot JD *et al.* Late outcome after arterial switch operation for transposition of the great arteries. Circulation 2001;104:I-121–6.
[3] Vargo P, Mavroudis C, Stewart RD, Backer CL. Late complications following the arterial switch operation. World J Pediatr Congenit Heart Surg 2011;2:37–42.
[4] Prifti E. Early and long term outcome of the arterial switch operation for transposition of the great arteries: predictors and functional evaluation. Eur J Cardiothorac Surg 2002;22:864–73.
[5] Martins CN, Filho BG, Lopes RM, das Chagas Lima F. Mid- and longterm neo-aortic valve regurgitation after Jatene surgery: prevalence and risk factors. Arq Bras Cardiol 2018;111:21–8.
[6] Filho BG, Fantini FA, Lora HM, Martins C, Lopes RM, Hayden E *et al.* Reconstrução da artéria pulmonar na operação de Jatene. Rev Bras Cir Cardiovasc 2001;16:236–43.
[7] Lopez L, Colan SD, Frommelt PC, Ensing GJ, Kendall K, Younoszai AK *et al.* Recomendações para os médicos de quantificação durante a realização do ecocardiograma pediátrico: relatório escrito pelo grupo da Sociedade Americana de Ecocardiografia e do Conselho em Cardiopatias Congênitas. ABC Imagem Cardiovasc 2014;27:151–83.
[8] Haycock GB, Schwartz GJ, Wisotsky DH. Geometric method for measuring body surface area: a height-weight formula validated in infants, children, and adults. J Pediatr 1978;93:62–6.
[9] Pettersen MD, Du W, Skeens ME, Humes RA. Regression equations for calculation of z scores of cardiac structures in a large cohort of healthy infants, children, and adolescents: an echocardiographic study. J Am Soc Echocardiogr 2008;21:922–34.
[10] McMahon CJ, Ravekes WJ, O'Brian Smith E, Denfield SW, Pignatelli RH, Altman CA *et al.* Risk factors for neo-aortic root enlargement and aortic regurgitation following arterial switch operation. Pediatr Cardiol 2004; 25:329–35.
[11] Tani LY, Minich LL, Day RW, Orsmond GS, Shaddy RE. Doppler evaluation of aortic regurgitation in children. Am J Cardiol 1997;80:927–31.
[12] Lange R, Cleuziou J, Hörer J, Holper K, Vogt M, Tassani-Prell P *et al.* Risk factors for aortic insufficiency and aortic valve replacement after the arterial switch operation. Eur J Cardiothorac Surg 2008;34:711–17.
[13] van der Bom T, van der Bom T, van der Palen RLF, Bouma BJ, van Veldhuisen SL, Vliegen HW *et al.* Persistent neo-aortic growth during

adulthood in patients after an arterial switch operation. Heart 2014;100: 1360–5.

[14] Marino BS, Wernovsky G, McElhinney DB, Jawad A, Kreb DL, Mantel SF *et al*. Neo-aortic valvar function after the arterial switch. Cardiol Young 2006;16:481–9.

[15] Koolbergen DR, Manshanden JSJ, Yazdanbakhsh AP, Bouma BJ, Blom NA, de Mol B *et al*. Reoperation for neoaortic root pathology after the arterial switch operation. Eur J Cardiothorac Surg 2014;46:474–9; discussion 479.

[16] Hwang HY, Kim W-H, Kwak JG, Lee JR, Kim YJ, Rho JR *et al*. Mid-term follow-up of neoaortic regurgitation after the arterial switch operation for transposition of the great arteries. Eur J Cardiothorac Surg 2006;29: 162–7.

[17] Talwar S, Gupta A, Sreenivas V, Choudhary SK, Airan B. Fate of neoaortic valve in patients undergoing arterial switch operation for transposition of great arteries. Am J Cardiovasc Thorac Surg 2017;2:1–6.

[18] Lalezari S, Mahtab EAF, Bartelings MM, Wisse LJ, Hazekamp MG, Gittenberger-de Groot AC. The outflow tract in transposition of the great arteries: an anatomic and morphologic study. Ann Thorac Surg 2009;88: 1300–5.

[19] Cohen MS, Marino BS, McElhinney DB, Robbers-Visser D, W van der W, Gaynor JW *et al*. Neo-aortic root dilation and valve regurgitation up to 21 years after staged reconstruction for hypoplastic left heart syndrome. J Am Coll Cardiol 2003;42:533–40.

[20] Grotenhuis HB, Ottenkamp J, Fontein D, Vliegen HW, Westenberg JJM, Kroft LJM *et al*. Aortic elasticity and left ventricular function after arterial switch operation: MR imaging—initial experience. Radiology 2008;249: 801–9.

[21] Murakami T, Nakazawa M, Momma K, Imai Y. Impaired distensibility of neoaorta after arterial switch procedure. Ann Thorac Surg 2000;70: 1907–10.

[22] Formigari R, Toscano A, Giardini A, Gargiulo G, Di Donato R, Picchio FM *et al*. Prevalence and predictors of neoaortic regurgitation after arterial switch operation for transposition of the great arteries. J Thorac Cardiovasc Surg 2003;126:1753–9.

[23] Michalak KW, Moll JA, Moll M, Młudzik K, Moll JJ. Neoaortic valve function 10 to 18 years after arterial switch operation. World J Pediatr Congenit Heart Surg 2010;1:51–8.

[24] Arcieri L, Cantinotti M, Pak V, Bernabei M, Assanta N, Murzi B. The V-shape reduction plasty to reduce the neoaortic root-ascending aorta discrepancy in children undergoing arterial switch operation. J Card Surg 2014;29:410–12.

[25] Ma K, Li S, Hu S, Hua Z, Yang K, Yan J *et al*. Neoaortic valve regurgitation after arterial switch: ten years outcomes from a single center. Ann Thorac Surg 2016;102:636–42.

[26] Mohammadi S, Serraf A, Belli E, Aupecle B, Capderou A, Lacour-Gayet F *et al*. Left-sided lesions after anatomic repair of transposition of the great arteries, ventricular septal defect, and coarctation: surgical factors. J Thorac Cardiovasc Surg 2004;128:44–52.

[27] den Reijer PM, den Reijer PM, Sallee D, van der Velden P, Zaaijer ER, James Parks W *et al*. Hemodynamic predictors of aortic dilatation in bicuspid aortic valve by velocity-encoded cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2010;12:4.

[28] Cecchi E, Giglioli C, Valente S, Lazzeri C, Gensini GF, Abbate R *et al*. Role of hemodynamic shear stress in cardiovascular disease. Atherosclerosis 2011;214:249–56.

[29] Querzoli G, Fortini S, Espa S, Costantini M, Sorgini F. Fluid dynamics of aortic root dilation in Marfan syndrome. J Biomech 2014;47:3120–8.

[30] Hutter PA, Thomeer BJ, Jansen P, Hitchcock JF, Faber JA, Meijboom EJ *et al*. Fate of the aortic root after arterial switch operation. Eur J Cardiothorac Surg 2001;20:82–8.