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ORIGINAL RESEARCH

30 Years' Experience in Percutaneous Pulmonary Artery Interventions in Transposition of the Great Arteries

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ABSTRACT

BACKGROUND Pulmonary artery (PA) stenosis is common after arterial switch operation (ASO) for transposition of the great arteries (TGA). Differences between balloon angioplasty (BA) and stents on right ventricular (RV) and PA pressures are not well studied.

OBJECTIVES The purpose of this study was to analyze percutaneous PA interventions' frequency after ASO, complications, and the effects of BA and stents on RV and PA pressures.

METHODS All TGA patients with ASO between 1977 and 2022 in 2 Dutch congenital heart centers were included in this multicenter retrospective study. Peri-operative ASO characteristics and pre-intervention and post-intervention invasive and echocardiographic data were analyzed.

RESULTS ASO was performed in 960 TGA patients, of which 888 survived 30 days and had complete follow-up. Seventy-seven (9%) underwent percutaneous PA interventions. Taussig-Bing anomaly (OR: 2.8; 95% CI: 1.228-6.168; $P = 0.014$), ASO time era 1990 to 1999 (OR: 4.7; 95% CI: 1.762-12.780; $P = 0.002$), and 2000 to 2009 (OR: 4.3; 95% CI: 1.618-11.330; $P = 0.003$) were independently associated with percutaneous PA interventions after ASO. Invasive post-interventional pressures and gradients were lower after stent implantation compared to BA (RV pressure: 47 ± 14 vs 58 ± 11; right PA-PA gradient: 11 ± 11 vs 25 ± 12, $P < 0.05$; RV/left ventricle pressure ratio: 0.4 ± 0.1 vs 0.6 ± 0.2, $P < 0.001$). Of the patients with unilateral PA stenosis (left PA: 41%, right PA: 59%), 77% showed increased RV pressure (>30 mm Hg) and RV/left ventricle pressure ratio improved post-intervention (0.5 ± 0.2 vs 0.6 ± 0.2, $P < 0.05$). Seventeen complications, most minor, were reported (13%). Two post-procedural deaths were reported.

CONCLUSIONS Percutaneous PA interventions are common after ASO and can be performed safely but caution for serious complications is warranted. Unilateral PA stenosis can impact RV pressures. Stents may be more successful at treating PA stenosis compared to BA. (JACC Adv. 2024;3:101327) © 2024 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

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ABBREVIATIONS AND ACRONYMS

ASO = arterial switch operation

BA = balloon angioplasty

LPA = left pulmonary artery

LV = left ventricle

MPA = main pulmonary artery

PA = pulmonary artery

RPA = right pulmonary artery

RV = right ventricular

TGA = transposition of the great arteries

VSD = ventricular septum defect

Transposition of the great arteries (TGA) is a common cyanotic congenital heart defect. The arterial switch operation (ASO) with Lecompte maneuver is the therapy of choice.[1-3] Traction on the pulmonary arteries (PAs) and compression by a dilated neo-aortic root due to the anterior position of the PAs after the Lecompte maneuver might result in branch PA stenosis, which is considered the most common indication for intervention.[4-6] The incidence ranges between 4% and 28% and it is usually treated percutaneously with balloon angioplasty (BA) or stent implantation.[5-9] However, data on the differences in outcome between BA and stent implantation are limited. The aim of this study was: 1) to describe our 30 years' experience in percutaneous PA interventions in TGA patients after ASO; 2) identify indications for PA interventions; and 3) describe the effects of BA and stent implantation on right ventricular (RV) and PA pressures.

METHODS

STUDY POPULATION. All TGA patients who underwent ASO at the University Medical Center Utrecht and Center for Congenital Heart Disease Amsterdam-Leiden, the Netherlands, between 1977 and 2022 were included in this multicenter retrospective cohort study. This included TGA patients with intact ventricular septum, ventricular septum defect (VSD), and double outlet right ventricle with subpulmonary VSD (ie, Taussig-Bing anomaly). TGA patients who underwent percutaneous supravalvular PA interventions were identified from this cohort. This study was approved by the Institutional Ethics Committee of the University Medical Center Utrecht and due to the extensive design of this study, the right of no objection was used.

DATA COLLECTION. Hospital and outpatient records were reviewed to obtain demographics, morphologic and surgical details, and mortality about the entire cohort. In case of missing follow-up 30 days post-ASO, patients were considered lost to follow-up. In TGA patients who underwent percutaneous supravalvular PA interventions, information was collected about catheter interventions including pre-interventional and post-interventional estimated echocardiographic gradients and right-sided surgical interventions.

OUTCOMES. The primary outcome of this study was the presence of percutaneous PA interventions. Percutaneous PA interventions were defined as the first percutaneous procedure for supravalvular PA stenosis after ASO in which a single location (left PA [LPA], right PA [RPA], main PA [MPA]) or multiple locations were treated. Indications were elevated echocardiographic RV pressures or gradients across the pulmonary arteries, reduced exercise capacity, small PA diameter, perfusion mismatch, and non-pulsatile flow or a combination of these factors. Percutaneous PA reinterventions were defined as every additional percutaneous procedure for PA stenosis. The number of percutaneous PA procedures and the number of locations (LPA, RPA, or MPA) treated per procedure were obtained (**Figure 1**, Supplemental Figure 1).

Secondary outcomes analyzed included: 1) periprocedural and late complications; 2) RV pressures, PA gradients, and the RV:left ventricle (LV) pressure ratio measured during right heart catheterization; and 3) estimated RV pressure and PA gradients and peak velocities measured using transthoracic echocardiography. Periprocedural and late complications were subdivided into major and minor complications. Major complications were defined as an event requiring resuscitation, unplanned surgery, major bleedings including perforations that were treated with a covered stent, device embolization, embolic stroke, air embolus, or an event requiring intubation. Minor complications were defined as all other unplanned events for which no or mild treatment was given including recurrent hemorrhage, vocal cord paresis, and rhythm problems without the need for resuscitation.[10]

SURGERY. Surgical ASO procedure in the cardiac centers has been described before.[11] This includes reconstruction of the neo-PA using a pantaloon-shaped patch of autologous pericardium and the Lecompte maneuver applied whenever possible from 1981 onward, which positions the neo-PA anterior to the neo-aorta.[2] Prior to the Lecompte maneuver, a Jatene procedure was performed which included implantation of a conduit between the RV and PA.[1] In case when a side-to-side anatomy of the great vessels was found, the Lecompte maneuver was not

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The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

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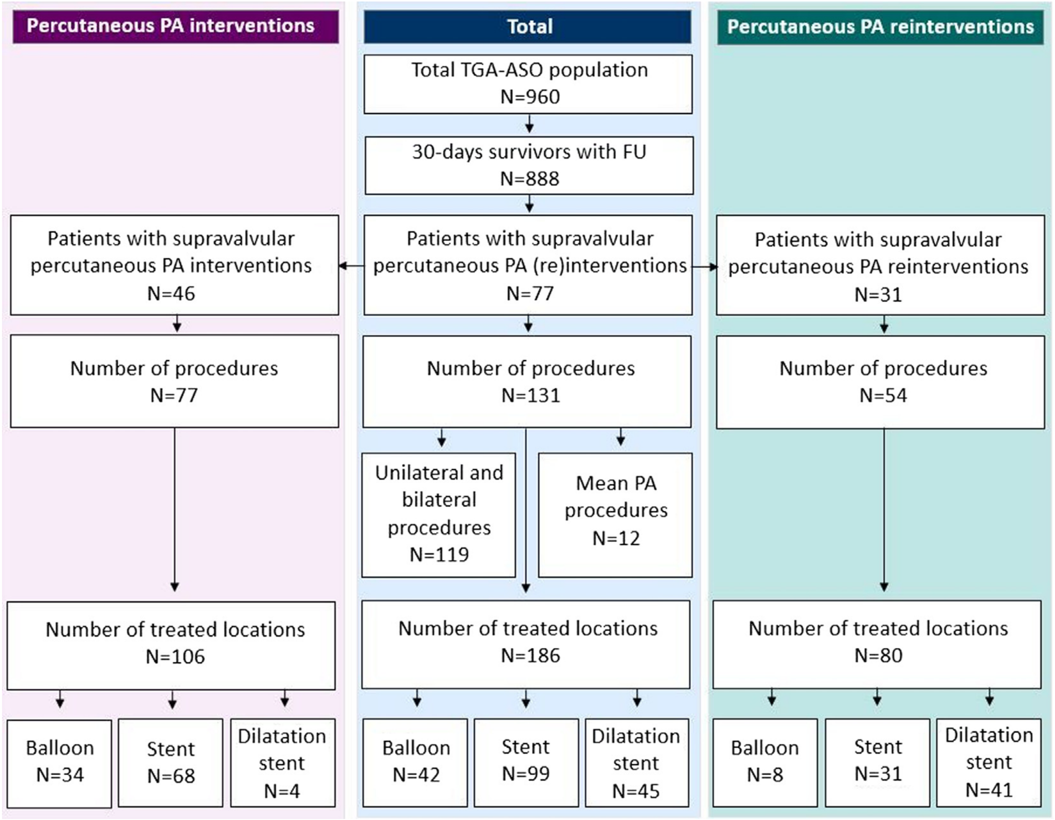
FIGURE 1 Flowchart Percutaneous PA (Re)intervention in TGA Patients After ASO



A flowchart of the number of procedures, the number of locations (LPA, RPA, or MPA) treated per procedure, and the type of procedure (Balloon, stent, dilatation of stent) during percutaneous PA (Re)interventions. ASO = arterial switch operation; FU = follow-up; LPA = left pulmonary artery; MPA = main pulmonary artery; PA = pulmonary artery; RPA = right pulmonary artery; TGA = transposition of the great arteries.

performed to avoid stretching and narrowing of the LPA. In these cases, a direct connection, right-sided to the aorta, will create a tension-free RV to PA connection.

STATISTICAL ANALYSIS. Statistical analysis was performed using IBM SPSS Statistics (SPSS Inc, version, 29.0). Variables were presented as mean ± SD, median (IQR) or frequencies (%) and compared using independent sample *t*-test, paired samples *t*-test, chi-square test, or Fisher's exact test. Correlations were obtained using Pearson correlation coefficient. Possible risk factors for percutaneous PA interventions were identified from literature and assessed using an univariable logistic regression model. In case $P < 0.05$, variables were included in a backward multivariable logistic regression analysis. Results were considered statistically significant at 2-tailed $P < 0.05$.

RESULTS

PATIENT CHARACTERISTICS. During the study period, 960 patients underwent ASO. Among them, 69 patients (7.2%) died within 30 days after ASO. Additionally, three patients were lost to follow-up. Out of the remaining 888 patients, 77 patients (9%) underwent percutaneous supravalvular PA interventions after ASO. Baseline characteristics are shown in Table 1. Among the 77 patients, 54 patients were male (70%) and morphologic diagnosis was TGA-intact ventricular septum in 45 (58%), TGA-VSD in 23 (30%) and Taussig-Bing anomaly in 9 (12%) patients. Median age at ASO for the PA intervention group was 8 (IQR: 5-19) days and Lecompte maneuver was performed in 96% of the patients. Baseline characteristics of the PA intervention group did not differ from the patient who did not underwent

TABLE 1 Baseline Characteristics

	All ASO Survivors With Follow-Up (n = 888)	No Percutaneous PA Intervention (n = 811)	Percutaneous PA Intervention (n = 77)	*P* Value
Male	615 (69)	561 (69)	54 (70)	0.862
Follow-up post-ASO (y)	17 ± 12	17 ± 12	21 ± 14	**0.007**
Diagnosis				0.064
TGA-IVS	555 (63)	510 (63)	45 (58)	
TGA-VSD	282 (32)	259 (32)	23 (30)	
Taussig-Bing anomaly	51 (6)	42 (5)	9 (12)	
Position great arteries				0.379
Ao anterior	345 (39)	312 (39)	33 (43)	
Ao R anterior to PA	271 (31)	250 (31)	21 (27)	
Ao R side to PA	59 (7)	52 (6)	7 (9)	
Ao L anterior to PA	43 (5)	36 (4)	7 (9)	
Ao R posterior to PA	5 (1)	5 (1)	-	
Unknown	165 (19)	156 (19)	9 (12)	
Age at ASO (d)	9 [6-16]	9 [6-16]	8 [5-19]	0.489
Weight at ASO (kg)	3.8 ± 1.9	3.8 ± 2.0	3.8 ± 1.3	0.853
Time era ASO				**<0.001**
1977-1989	144 (16)	139 (17)	5 (7)	
1990-1999	191 (22)	165 (20)	26 (34)	
2000-2009	240 (27)	209 (26)	31 (40)	
2010-2022	313 (35)	298 (37)	15 (20)	
Lecompte	814 (92)	740 (91)	74 (96)	0.353
2-stage ASO	96 (11)	89 (11)	7 (9)	0.950
Type previous cardiac operation before ASO				0.348
PAB				
Solitary PAB	29 (3)	27 (3)	2 (3)	
PAB and BTT	15 (2)	13 (2)	2 (3)	
PAB and AP shunt	14 (2)	14 (2)	-	
PAB and SAS	7 (1)	7 (1)	-	
PAB, BTT shunt, SAS	7 (1)	6 (1)	1 (1)	
PAB, AP shunt, SAS	4 (0)	4 (1)	-	
PAB and CoA	2 (0)	1 (0)	1 (1)	
PAB and DA stent	2 (0)	1 (0)	1 (1)	
Solitary CoA repair	5 (1)	5 (1)	-	
Solitary BTT shunt	7 (1)	7 (1)	-	
BTT shunt and SAS	3 (0)	3 (0)	-	
Late death	19 (2)	15 (2)	4 (5)	0.074

Values are n (%) or mean ± SD. Bold values indicate $P < 0.05$.

Ao = aorta; AP = aortopulmonary shunt; ASO = arterial switch operation; BTT = Blalock-Thomas-Taussig shunt; CoA = aortic coarctation; DA = ductus arteriosus; FU = follow-up; IVS = intact ventricular septum; R = right; PA = pulmonary artery; PAB = pulmonary artery banding; SAS = surgical atrial septostomy; TGA = transposition of the great arteries; VSD = ventricular septum defect.

percutaneous PA interventions, except for follow-up duration and the ASO time period (era) (Table 1). Average follow-up time was longer in the intervention group compared to the nonintervention group (21 ± 14 years vs 17 ± 12 years, $P = 0.007$). In addition, the majority of ASO procedures in the intervention group were performed during the time eras of 1990 to 1999 and 2000 to 2009. Conversely, in the nonintervention group, the majority occurred during the earliest (1977-1989) and latest (2010-2022) time periods.

RISK FACTORS PERCUTANEOUS PA INTERVENTIONS AFTER ASO. Risk analysis for the need of percutaneous PA interventions is shown in Table 2. TGA morphological subtype (Taussig-Bing anomaly) was found to be an independent risk factor for percutaneous PA interventions (Taussig-Bing anomaly: OR: 2.8; 95% CI: 1.228-6.168; $P = 0.014$). The time era in which ASO was performed (1990-1999 and 2000-2009) was also found to be independently associated with percutaneous PA interventions (ASO time era 1990-1999: OR: 4.7; 95% CI: 1.762-12.780; $P = 0.002$ and ASO time era 2000-2009: OR: 4.3; 95% CI: 1.618-11.330; $P = 0.003$) (Table 2).

PERCUTANEOUS PA (RE)INTERVENTIONS. A total of 131 percutaneous PA procedures (77 interventions and 54 reinterventions) were performed in 77 patients (Figure 1, Supplemental Figure 1). Among these, 119 were performed to address either unilateral or bilateral PA stenosis, while 12 procedures were performed to improve MPA stenosis. During these 131 procedures, 186 locations (LPA, RPA, or MPA) were treated using BA (n = 42), stent implantation (n = 99), and dilatation of an existing stent (n = 45).

PA INTERVENTIONS. Percutaneous PA interventions were performed in 77 patients on average 9 ± 8 years after ASO. The majority was performed within the first 3 years (n = 27, 35%) and during puberty (n = 27, 35%). During 77 procedures, 106 locations (LPA, RPA, or MPA) were treated, most often with stent implantation (n = 68 (64%)). In 20 out of these 68 stent implantations, patients were <5 years old. Thirty-four locations were treated with BA during percutaneous PA interventions. Patients who were treated with BA were significantly younger compared to patients treated with stents (mean age 5 ± 5 years vs mean age 11 ± 8 years; $P < 0.001$). Twenty-two out of 34 BA interventions (65%) ended in stent implantation (n = 17) or surgical correction (n = 5). In addition, three patients received five stents during hybrid stent procedures during reoperations. Four of these stents were necessitated during percutaneous PA interventions (Figure 1, Supplemental Figure 1).

PA REINTERVENTIONS. Percutaneous PA reinterventions were performed in 31 out of 77 patients (40%) on average 4 ± 4 years after the percutaneous PA intervention. The number of percutaneous PA reinterventions per patient were 1 (n = 17), 2 (n = 7), 3 (n = 6), and 4 (n = 1). During 54 procedures, 80 locations (LPA, RPA, or MPA) were treated using BA (n = 8), stent implantation (n = 31), and dilatation of an existing stent (n = 41). Eighty percent of the stents

TABLE 2 Univariable and Multivariable Logistic Regression for Percutaneous PA Interventions After ASO

	Univariable Analysis			Multivariable Analysis[h]		
	OR	**95% CI**	***P* Value**	**OR**	**95% CI**	***P* Value**
Sex						
Male[a]	1.0					
Female	1.0	0.574-1.592	0.862			
Morphological subtype			0.075			0.047
TGA-IVS[b]	1.0			1.0		
TGA-VSD	1.0	0.596-1.700	0.981	1.1	0.632-1.831	0.788
Taussig-Bing anomaly	2.4	1.111-5.307	0.026	**2.8**	**1.228-6.168**	**0.014**
Position great arteries			0.470			
Ao anterior[c]	1.0					
Ao R anterior to PA	0.8	0.448-1.407	0.430			
Ao R side to PA	1.3	0.535-3.028	0.586			
Ao L anterior to PA	1.8	0.758-4.457	0.178			
Center						
UMCU[d]	1.0					
CAHAL	1.4	0.852-2.225	0.191			
Age at ASO (d)	1.0	0.998-1.001	0.505			
Weight at ASO (kg)	1.0	0.899-1.138	0.853			
LeCompte						
No[e]	1.0					
Yes	2.0	0.612-6.534	0.251			
PA banding						
No[f]	1.0					
Yes	1.3	0.571-2.952	0.533			
Time era ASO			<0.001			<0.001
1977-1989[g]	1.0			1.0		
1990-1999	4.4	1.639-11.711	0.003	**4.7**	**1.762-12.780**	**0.002**
2000-2009	4.1	1.565-10.862	0.004	**4.3**	**1.618-11.330**	**0.003**
2010-2022	1.4	0.499-3.927	0.523	1.5	0.521-4.137	0.468

Reference categories of covariate. Bold values indicate $P < 0.05$. [a]Male sex. [b]Morphological subtype "TGA-IVS". [c]Position of the great arteries "Ao anterior". [d]University Medical Center Utrecht. [e]No Lecompte maneuver during ASO. [f]No pulmonary artery banding prior to ASO. [g]Time era in which ASO performed "1977 to 1989". [h]Variables included for multivariable logistic regression: morphological subtype, time era ASO.

CAHAL = Center for Congenital Heart Disease Amsterdam-Leiden; L = left; other abbreviations as in Table 1.

implanted in patients <5 years old required redilatation (n = 12), a new stent (n = 1) or surgical correction (n = 3) at a mean time interval of 7 ± 6 years after initial stent implantation. Indications for percutaneous PA reinterventions were unsuccessful earlier PA intervention, in stent intima proliferation, or somatic growth with stent in situ (**Figure 1**, Supplemental Figure 1).

BALLOONS AND STENTS. Materials used to treat PA stenosis are described in Supplemental Table 2. One cutting balloon was used for a peripheral PA stenosis. Four stents (4%) were implanted in the MPA/right ventricular outflow tract, of which two were part of a Y-stenting procedure. Except for one covered stent to treat a PA vessel tear after BA, only bare metal stents were used. Smaller stent types such as the Cordis Palmaz Genesis stent (Cardinal Health) and Cook Formula stents (Cook Medical) were more often used in smaller patients (≤6 years) while larger stent types such as the CP stent (NuMED) and EV3 IntraStent Mega LD and Max LD (Medtronic) were more often used in larger patients (≥7 years). No self-expandable stents were used.

UNILATERAL VS BILATERAL TREATMENT. From the 131 procedures, 119 procedures were performed for unilateral (n = 68) (LPA 41%, RPA 59%) and bilateral (n = 51) PA stenosis (**Table 3**). Bilateral PA stenosis resulted in significantly higher RV systolic pressures and RV/LV pressure ratios compared to unilateral PA stenosis (RV pressure: 65 ± 18 mm Hg vs 47 ± 15 mm Hg, $P < 0.001$ and RV/LV pressure ratio: 0.7 ± 0.3 vs 0.6 ± 0.2, $P < 0.001$). RV systolic pressure was increased (>30 mm Hg) in 40 out of 51 (78%) bilateral and 52 out of 68 (77%) unilateral procedures. In addition, pre-intervention elevated RV/LV pressure ratio (>0.5) was found in 24 out of 51 (47%) bilateral and 19 out of 68 (28%) unilateral procedures. Overall, RV pressures, the RV/LV pressure ratio and gradients across the stenotic area improved post-procedural (**Table 3**).

TABLE 3 Invasive Measurements Unilateral vs Bilateral Percutaneous PA Procedures

	Total Group (N = 119)	Unilateral (n = 68)	Bilateral (n = 51)
Pre-intervention			
RV pressure	54 ± 19	47 ± 15[a]	65 ± 18[a,b]
Elevated RV pressure (>30 mm Hg)	92 (78)	52 (77)	40 (78)
Ratio RV/LV pressure	0.7 ± 0.2	0.6 ± 0.2[a,b]	0.7 ± 0.3[a,b]
Elevated ratio RV/LV pressure (>0.5)	43 (36)	19 (28)[a]	24 (47)[a]
Gradient LPA-PA	28 ± 19	21 ± 16[a,b]	33 ± 20[a,b]
Gradient RPA-PA	32 ± 17	27 ± 14[b]	35 ± 18[b]
Post-intervention			
RV pressure	51 ± 16	49 ± 14	53 ± 18[b]
Elevated RV pressure (>30 mm Hg)	51 (43)	29 (43)	22 (43)
Ratio RV/LV pressure	0.5 ± 0.2	0.5 ± 0.2[b]	0.5 ± 0.2[b]
Elevated ratio RV/LV pressure (>0.5)	13 (11)	7 (10)	6 (12)
Gradient LPA-PA	17 ± 17	13 ± 12[b]	19 ± 20[b]
Gradient RPA-PA	18 ± 16	17 ± 12[b]	19 ± 18[b]

Values are mean ± SD or n (%). [a]$P < 0.05$ between unilateral and bilateral PA interventions. [b]$P < 0.05$ between pre-interventional and post-interventional measurement.

LPA = left pulmonary artery; LV = left ventricle; RPA = right pulmonary artery; RV = right ventricle; other abbreviation as in Table 1.

BA VS STENT IMPLANTATION. Invasive and echocardiography estimated pressures, pressure gradients and ratios were determined before and after percutaneous PA interventions to evaluate treatment effect. Differences in absolute pressures, pressure gradients, and ratios between treatment strategies (BA vs stent implantation) are shown in **Figure 2**, **Table 4**, and Supplemental Table 1. Except for RV/LV pressure ratio, no pre-interventional differences in invasive pressures and gradients were found between BA and stent implantation. After the intervention, invasive RV systolic pressure, RV/LV pressure ratio, and RPA-PA gradient were significantly lower after stent implantation compared to BA (RV pressure: 47 ± 14 vs 58 ± 11 mm Hg; RPA-PA gradient: 11 ± 15 vs 21 ± 8 mm Hg, all $P < 0.005$; RV/LV pressure ratio: 0.4 ± 0.1 vs 0.6 ± 0.2, $P < 0.001$). In addition, echocardiography estimated LPA and RPA gradients and peak velocities are significantly lower after stent implantation compared to BA (LPA gradient: 31 ± 19 mm Hg vs 43 ± 23 mm Hg; Vmax LPA: 2.7 ± 0.8 m/s vs 3.2 ± 0.9 m/s; Vmax RPA: 2.8 ± 0.9 m/s vs 3.4 ± 1.2 m/s, all $P < 0.05$; RPA gradient: 34 ± 19 mm Hg vs 52 ± 26 mm Hg, $P < 0.001$) (**Figure 2**, **Table 4**, Supplemental Table 1).

INVASIVE VS ECHOCARDIOGRAPHY ESTIMATED PRESSURES AND GRADIENTS. PA pressures correlated moderately to good between invasive and echocardiography estimated measurements (pre-interventional: LPA: $R = 0.75$, $P < 0.001$; RPA: $R = 0.43$, $P = 0.016$; post-interventional: LPA: $R = 0.59$, $P = 0.008$; RPA: $R = 0.62$, $P = 0.001$). Pre-interventional elevated RV pressure (>30 mm Hg) was found in 146 out of 186 (79%) locations for PA stenosis using invasive measurements, compared to 58 out of 186 (31%) locations using echocardiography (**Table 4**, Supplemental Table 1).

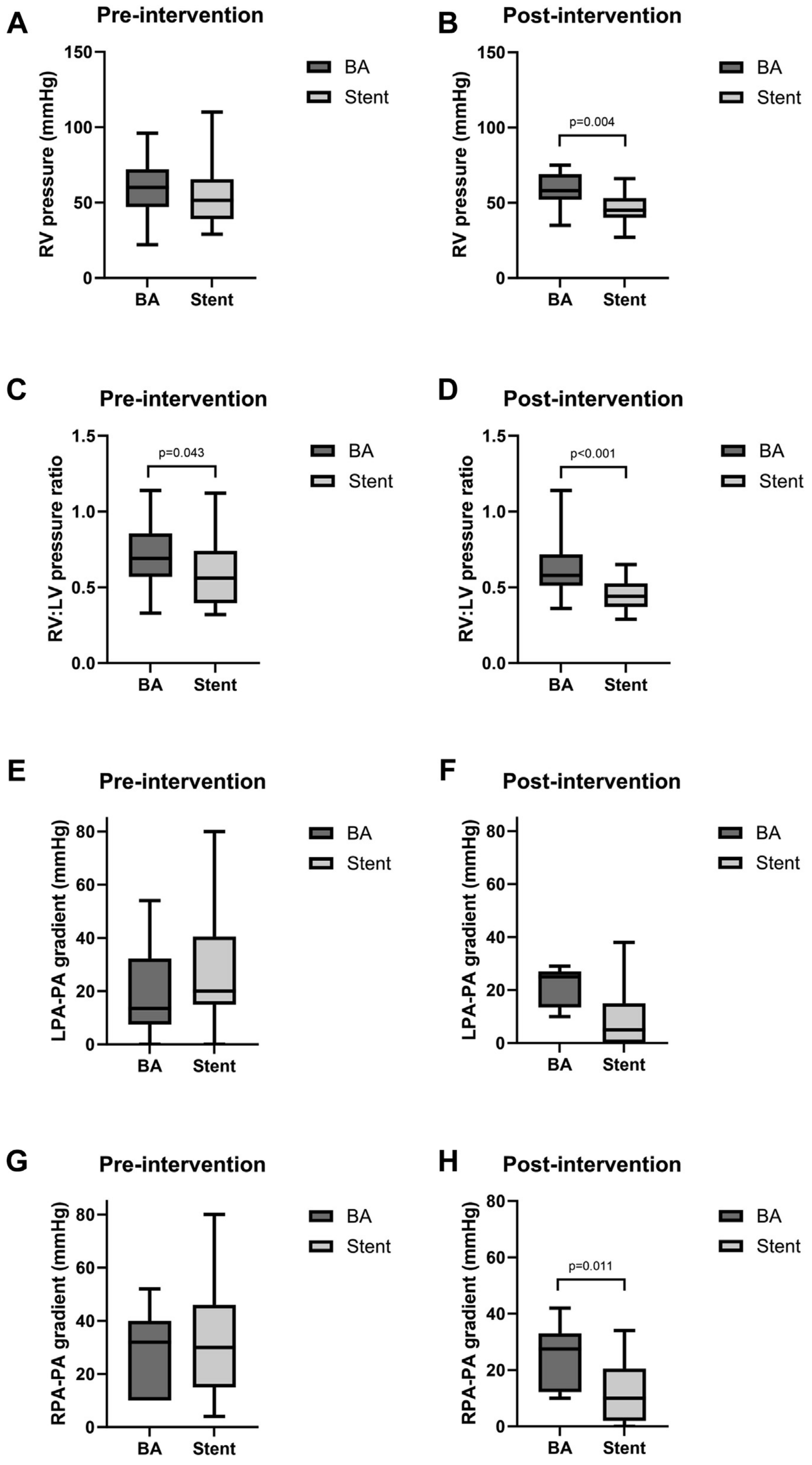
COMPLICATIONS. In total, 17 complications (13%) (PA interventions, n = 13; PA reinterventions, n = 4) in 15 patients occurred periprocedural (n = 15) or after (n = 2) the procedure (**Table 5**). From the periprocedural complications, 4 out of 15 (27%) were major and 11 out of 15 (73%) were minor. Major complications consisted of stent dislocation (necessitating surgical removal) (n = 1), a PA vessel tear treated with a covered stent (n = 1), an iatrogenic aortopulmonary communication during the procedure resulting in mortality (n = 1, age 27 years) and acute cardiac failure after PA embolism of a calcified in-stent vegetation by catheter intervention during the procedure resulting in mortality (n = 1, age 19 years). Minor complications consisted of recurrent hemorrhage (n = 1), rhythm problems without resuscitation (n = 2), and other unplanned events with no or mild treatment (n = 8). All post-procedural complications were minor (n = 2) (**Table 5**).

DISCUSSION

To the best of our knowledge, this is the most extensive study describing percutaneous PA interventions in TGA patients after ASO. We found that: 1) percutaneous PA interventions are common after ASO and are independently associated with morphological subtype (Taussig-Bing anomaly) and ASO time era (1990-1999 and 2000-2009); 2) unilateral PA stenosis can already impact RV pressures; 3) stent implantation seems more successful in reducing pressure gradients compared to BA; and 4) complications of PA interventions are rare but may be life-threatening if not recognized in time (eg, iatrogenic aortopulmonary communication) (**Central Illustration**).

TOTAL ASO COHORT AND PREDICTORS OF PERCUTANEOUS PA INTERVENTIONS. Over the 45-year interval of this study, 960 patients underwent ASO, of which 888 patients survived 30 days post-ASO and had complete follow-up. Our incidence rate of 9% for percutaneous PA interventions is relatively low compared to 4% to 28% in literature, which vary due to differences in patient complexity, indications for PA interventions and follow-up duration.[5-9] Sex, age, and weight at ASO were not associated with the need for percutaneous PA interventions, which is in accordance with other

FIGURE 2 **Invasive Measurements All Location Specific Percutaneous PA (Re)interventions**



Graphs show difference in invasive pre-interventional and post-interventional RV pressure (A and B), RV/LV pressure ratio (C and D), LPA-PA gradient (E and F), and RPA-PA gradient (G and H) between balloon angioplasty and stent implantation. BA = balloon angioplasty; LV = left ventricle; RV = right ventricle; other abbreviations as in Figure 1.

TABLE 4 **Pre-interventional and Post-interventional Invasive Measurements All Percutaneous Location Specific PA Interventions**

	Total Group (N = 186)	Native Balloon Angioplasty (n = 42)	Stent Implantation (n = 99)	Dilatation Prior Stent (n = 45)
Age at percutaneous (re)intervention (y)	10 ± 8	5 ± 5[a]	12 ± 9[a]	10 ± 8
Pre-intervention				
RV pressure	58 ± 19	59 ± 17	56 ± 19	63 ± 19
RV pressure >30 mm Hg	146 (79)	27 (64)	82 (83)	37 (82)
Ratio RV/LV pressure	0.7 ± 0.2	0.7 ± 0.2[a]	0.6 ± 0.2[a]	0.7 ± 0.3
Gradient LPA-PA	29 ± 19	19 ± 17	29 ± 19	34 ± 22
Gradient RPA-PA	33 ± 16	31 ± 16	32 ± 16	36 ± 18
Post-intervention				
RV pressure	51 ± 16	58 ± 11[a]	47 ± 14[a]	56 ± 19
RV pressure >30 mm Hg	84 (45)	16 (38)	44 (44)	24 (53)
Ratio RV/LV pressure	0.5 ± 0.2	0.6 ± 0.2[b]	0.4 ± 0.1[b]	0.6 ± 0.3
Gradient LPA-PA	17 ± 17	21 ± 8	11 ± 15	28 ± 22
Gradient RPA-PA	19 ± 16	25 ± 12[a]	11 ± 11[a]	28 ± 19

Values are mean ± SD or n (%). [a]$P < 0.05$ between native balloon angioplasty and stent implantation. [b]$P < 0.001$ between native balloon angioplasty and stent implantation.

Abbreviations as in Tables 1 and 3.

studies.[9,12] Taussig-Bing anomaly and the middle ASO time eras (1990-1999 and 2000-2009) were independently associated with percutaneous PA interventions. This might be explained due to the lack of stents in the early ASO time era (1977-1989) percutaneous treatment of PA stenosis was restricted to BA introduced in the 1980s. The higher incidents of residual stenosis after BA might have led to a higher rate of corrective surgery. Moreover, the need for percutaneous PA interventions declined in the last era (2010-2022), possibly due to improved surgical techniques or increased restraint due to complications after percutaneous PA interventions. The finding that Taussig-Bing anomaly is an independent risk factor for percutaneous PA interventions is in contrast to the literature but might be explained because results are often limited to less complex types of TGA and because side-by-side great arteries occur more frequently in these patients.[7,9] In contrast, we found that the performance of a Lecompte maneuver during ASO, great vessel anatomy, and PA banding prior to ASO were not related to the need for PA intervention.[2,6] This might partly be explained by the predominant use of one-stage ASO including Lecompte maneuver in our cohort and missing data.

TABLE 5 **Complications All Percutaneous PA Procedures (N = 131)**

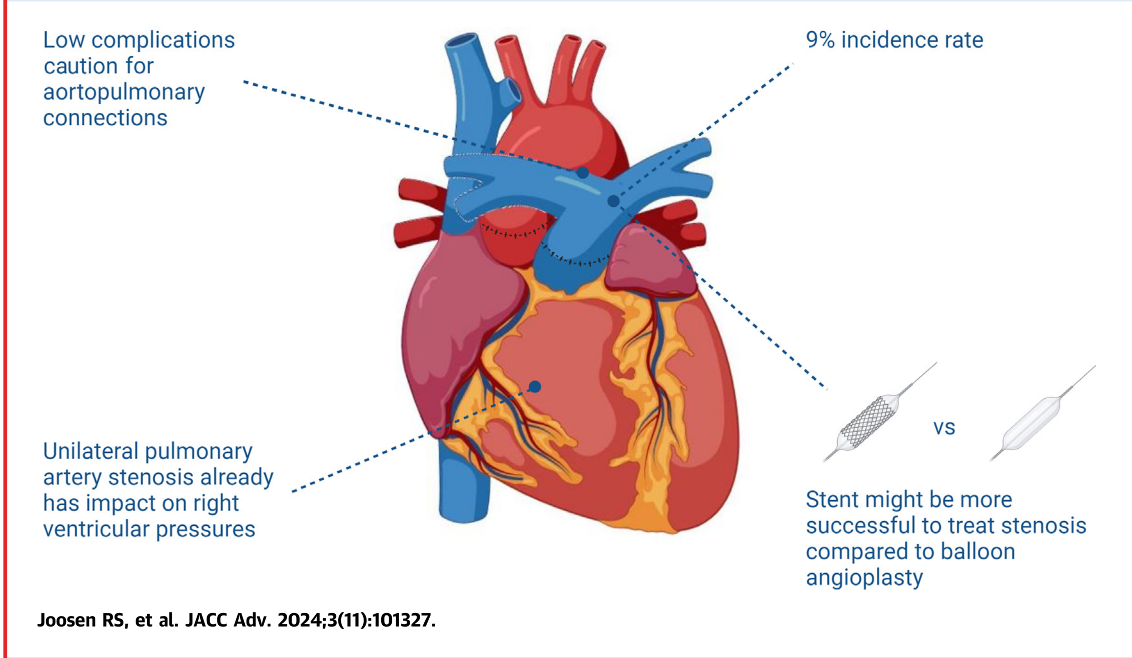
Complications	17 (13)
Complications during	15 (88)
Major complications	4 (27)
Stent dislocation necessitating surgical removal	1 (25)
Pulmonary artery vessel tear treated with a covered stent	1 (25)
Iatrogenic aortopulmonary communication resulting in mortality	1 (25)
Acute cardiac failure after pulmonary artery embolism of a calcified in-stent vegetation by catheter intervention resulting in mortality	1 (25)
Minor complications	11 (73)
Recurrent hemorrhage	1 (9)
Rhythm problems without resuscitation	2 (18)
Other unplanned events with no or mild treatment	8 (73)
Complications after	2 (12)
Minor complications	2 (100)
Recurrent hemorrhage	2 (100)

Abbreviation as in Table 1.

PA (RE)INTERVENTIONS. PA stenosis is the most common indication for catheter intervention and reoperation after ASO in mid-term follow-up studies.[8,9] Most PA interventions were performed within the first 3 years after ASO with a second peak around puberty. This is in accordance with previous literature and might be explained because rapid growth during the early childhood and adolescence might drive the development of PA stenosis.[7,8] We also found that percutaneous PA interventions typically entail multiple procedures rather than just one, often necessitating additional percutaneous or surgical reinterventions. This can be attributed to residual stenosis following BA and relative stenosis after stenting, which may require adjustments to the stent diameter to accommodate growth.[7,8] Performance of percutaneous PA interventions during the pediatric age sets challenges due to the growing child, the need for reinterventions during life and procedural risks. Patients in our cohort underwent BA for all levels of supravalvular PA stenosis (MPA and branch PA) and were significantly younger compared to those who underwent stent implantation. BA is often considered for younger children because stents require serial dilation to adult size to accommodate for somatic growth. In addition, stent implantation in small children was long time limited by solely availability of closed cell design stents. Stents from earlier decades were limited in use by insufficient final diameter for adults.[13] However, modern stents (ie, Cook Formula 535, EV3 Mega LD) became available during the last decades and allowed for implantation in small children with sequential expansion to adult size.

The majority of the patients who underwent BA in our cohort ended up with stent implantation or surgical relief of PA stenosis during follow-up. This suggests that BA is not sufficient for a long-term treatment of PA stenosis in these patients. Post-interventional invasive and echocardiography estimated RV and PA pressures and gradients were

CENTRAL ILLUSTRATION Pulmonary Artery Stenosis in Transposition of the Great Arteries



Joosen RS, et al. JACC Adv. 2024;3(11):101327.

Created in BioRender. Joosen, R. (2023) BioRender.com/j13u676. Abbreviations as in **Figure 1**.

significantly lower after stent implantation compared to BA. The greater success of stents for treating PA stenosis in these patients is confirmed by other studies, reporting success rates between 53% to 74% for BA and 75% to 86% for stents.[14-16] This might be explained by differences in etiology of the PA stenosis. BA might be more effective in non-compliant lesions (eg, stenosis due to scarring at anastomosis or shunt sites) by tearing the intima or media that allows vascular remodeling and healing at a larger diameter.[17] Restenosis after initial successful BA is due to fibrosis and elastic recoil of the vessels.[18] In contrast, stents are particularly effective for vessels compressed by adjacent structures (compliant stenosis), as is often the case in TGA patients after ASO.[15,19] The Lecompte maneuver during the ASO procedure enhances neo-aortic root dilatation and makes the PA vulnerable for elongation and geometrical distortion.[7,20] Reinterventions after successful stent implantation are indicated due to intima proliferation or adaptation to growth.[18] Long-term data confirm that stents maintain their safety and efficacy over the long term and dilation of stented vessel to adult size can be performed successfully.[21]

UNILATERAL PA STENOSIS. Most patients were treated for unilateral PA stenosis. Seventy-seven percent showed increased RV systolic pressure (>30 mm Hg) and 28% an increased RV/LV pressure ratio (>0.5), which improved post-intervention. Compromised PA distension due to a fixed PA stenosis might lead to reduced PA compliance, resulting in increased afterload and RV pressure.[22] The severity of unilateral PA stenosis is often underestimated on transthoracic echocardiography and results in false “normal” RV pressures.[23] Little is known about RV function and adaptation in case of unilateral PA stenosis. Luo et al showed that most TGA patients had normal RV systolic function after PA interventions during follow-up, but patients with early PA interventions after ASO (concomitant revision or interventions during the intensive care unit stay) showed worse RV systolic function at discharge.[7] Animal studies showed that PA interventions do not completely restore RV contractility and no hypertrophy is observed, suggesting limited RV adaptation to increased afterload.[22,24] In addition, unilateral PA stenosis might result in subclinical RV dysfunction in TGA patients after ASO, while not yet present on cardiac magnetic resonance imaging.[25] Future larger studies are needed to provide insight into RV function and adaptation to unilateral PA stenosis.

COMPLICATIONS. Our incidence of complications is lower compared to literature.[26] Four major complications were periprocedural. Two periprocedural-related major complications (vessel tear and stent dislocation) could be resolved. Two patients died related to major complications because of acute cardiac failure after PA embolism of a calcified in-stent vegetation (in the era before the presence of extracorporal membrane oxygenation) and an iatrogenic aortapulmonary communication. Patients who underwent Lecompte maneuver are at risk for iatrogenic aortopulmonary communications following stent implantation in PAs. This may be associated with the weak tissue properties of the PA and ascending neoaorta, even decades after ASO.[26] Moreover, insufficient tissue strength could be explained by the presence of a denuded tissue plane or the lack of a tissue plane in some instances.[27] Previous reports on bilateral PA stenting suggest reduced compliance of the PAs to accommodate the aorta.[26] Aortopulmonary communications represent a rare but potentially life-threatening complication and only 12 cases of aortopulmonary communications are reported.[27] Signs and symptoms as systemic hypotension and hypovolemic shock due to severe left to right aorta-PA shunting may be misinterpreted. Pulmonary hypertension might occur in case of a large aortopulmonary communication. Awareness among operators is crucial and sealing of the “AP window” using a covered stent should be taken into account. Post-procedural aortic angiography is crucial since PA angiography is unlikely to reveal contrast flow due to pressure differential.[27] Pre-procedural imaging like computed tomography angiography, cardiac magnetic resonance, or periprocedural 3D rotational angiography enables to determine the geometry of the PA stenosis, choose the best stent-geometry, and offer advanced risk assessment of the planned procedure.

STUDY LIMITATIONS. This study is subject to the limitations inherent to the retrospective design. The relatively small sample size may be insufficient for detecting differences between subgroups and should be considered when interpreting the findings of this study. In addition, patients were referred from different institutions which resulted in differences in clinical work-up and nonuniformly reporting of information.

CONCLUSIONS

Percutaneous interventions for PA stenosis are common in TGA patients after ASO and can be performed safely but caution for serious complications is warranted. Unilateral PA stenosis can already impact RV pressures. Stents might be more successful to treat PA stenosis compared to BA.

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PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: PA stenosis is the most common indication for intervention in TGA patients after ASO and is usually treated percutaneously with BA or stent implantation. However, data on the differences in outcome between BA and stent implantation are limited.

COMPETENCY IN PATIENT CARE AND PROCEDURAL SKILLS: Percutaneous interventions for PA stenosis are common in TGA patients after ASO and stents might be more successful in treating PA stenosis compared to BA. PA interventions can be performed safely but rare serious complications such as aortopulmonary communications can occur. We observed that the majority of patients with unilateral PA stenosis already have increased RV pressures.

TRANSLATIONAL OUTLOOK: As techniques such as self-expanding covered stents and 3D road mapping during interventions continue to improve, we anticipate that branch PA stenting will be performed with lower thresholds. Given this trend, it is crucial to evaluate the long-term effects of these interventions on RV function and patient outcomes, making this an important focus for future research.

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APPENDIX For supplemental tables and a figure, please see the online version of this paper.