Journal of the Society for Cardiovascular Angiography & Interventions 1 (2022) 100392

Contents lists available at ScienceDirect

Journal of the Society for Cardiovascular Angiography & Interventions

journal homepage: www.jscai.org

Comprehensive Review

Stenting of the Patent Ductus Arteriosus: A Meta-analysis and Literature Review

Holly Bauser-Heaton, MD, PhD [a,*,†], Katherine Price, BS [b,†], Rachel Weber, MSIE [c], Howaida El-Said, MD, PhD [c]

[a] Department of Pediatrics, Children's Healthcare of Atlanta, Emory University School of Medicine, Atlanta, Georgia; [b] Department of Pediatrics, University of California San Diego School of Medicine, San Diego, California; [c] Division of Pediatric Cardiology, Rady Children's Hospital and University of California San Diego School of Medicine, San Diego, California

ABSTRACT

Background: Patent ductus arteriosus (PDA) stent placement and systemic-pulmonary surgical shunt procedure can both be performed as palliation for infants with duct-dependent pulmonary circulation. The aim of this meta-analysis and literature review was to compare outcomes and study populations between the 2 methods as well as review the technical considerations and complications of PDA stenting.

Methods: A systematic search was conducted using the PubMed database and meta-analysis was performed. Risk ratio and mean difference were used to compare the reported outcomes of studies across patients receiving PDA stent and surgical shunt.

Results: In total, 1094 patients from 8 comparative observational studies were included. The PDA stent group had a lower mortality rate and a shorter hospital length of stay than the systemic-pulmonary surgical shunt group, although at the expense of increased reintervention rates. There were higher proportions of patients with single-ventricle physiology and single-source pulmonary blood flow in the surgical shunt group.

Conclusions: PDA stenting appears to be a noninferior or possibly superior method of palliation for duct-dependent pulmonary circulation compared with systemic-pulmonary surgical shunt, recognizing, however, that patients receiving surgical shunt more often had single-ventricle physiology or single-source pulmonary blood flow in this meta-analysis.

Introduction

Since initial stenting of the patent ductus arteriosus (PDA) was attempted in animal models in the early 1990s,[1] technical advancements have significantly improved outcomes, and this procedure has become an important part of treatment for infants and children with congenital heart disease.[2-5] PDA stenting is emerging as an attractive alternative to first-stage surgical palliation, and the ability of the stent to maintain patency of the duct for several months can offer unique advantages as a less invasive procedure.[6] In this meta-analysis and literature review, we aimed to evaluate clinical outcomes of PDA stents compared with those of surgical systemic-pulmonary shunts in infants with duct-dependent pulmonary circulation as well as describe common technical considerations and complications associated with the stenting procedure.

Duct-dependent pulmonary circulation

Infants with cyanotic congenital heart disease are generally dependent on alternative sources of pulmonary blood flow (PBF), most commonly a PDA. Although prostaglandin E1 can maintain patency in the short term, most patients require a palliative procedure to ensure PBF until definitive surgery can be performed.[6] This has traditionally been accomplished via a surgical systemic-pulmonary shunt, most commonly the modified Blalock–Taussig–Thomas shunt (BTTS).[7] However, the morbidity and mortality rates associated with this procedure, particularly for patients at high surgical risk, prompted the emergence of percutaneous PDA stenting as a less invasive method for palliative maintenance of PBF.[8] Recent studies have suggested that, compared with BTTS, PDA stenting demonstrates comparable or improved mortality, shorter intensive care unit and hospital length of stays, lower complication rates

Abbreviations: BTTS, Blalock–Taussig–Thomas shunt; LOS, length of stay; MD, mean difference; PBF, pulmonary blood flow; PDA, patent ductus arteriosus; RR, risk ratio.

Keywords: congenital heart disease; duct-dependent pulmonary circulation; palliation; patent ductus arteriosus; stent; shunt.

* Corresponding author: bauserh@kidsheart.com (H. Bauser-Heaton).

†Co-first authors.

https://doi.org/10.1016/j.jscai.2022.100392

Received 10 January 2022; Received in revised form 18 April 2022; Accepted 1 June 2022

Available online 7 July 2022

and use of postprocedural extracorporeal membrane oxygenation, and more symmetric pulmonary artery growth, although with increased reintervention rates.[9-11] It has also been shown to incur lower or equivalent costs over the first year compared with BTTS.[12] In fact, some centers have transitioned to exclusive PDA stenting for all infants with duct-dependent pulmonary circulation, including patients with preexisting branch pulmonary artery stenosis, with good outcomes.[13] To further delineate the potential benefits and risks of PDA stenting in palliating duct-dependent cyanotic congenital heart disease, we performed the following meta-analysis of the available literature in this current era from 1991 to 2021.

Meta-analysis: Methods

A literature search was conducted using the PubMed database for studies comparing PDA stents and systemic-pulmonary shunts as palliation for duct-dependent pulmonary circulation from 1991 to 2021. Full-length articles in English were considered, and both retrospective and prospective studies were included. Reference lists of the included studies were manually reviewed for additional studies. Outcomes of interest included mortality, reintervention, hospital length of stay (LOS), and proportions of patients with single-ventricle physiology and single-source PBF.

Risk ratios (RRs) with corresponding 95% CIs were calculated and analyzed for dichotomous variables for each included study as well as all studies combined. Mean difference (MD) with corresponding 95% CI was used to compare hospital LOS. Only studies reporting LOS as mean and SD were included for statistical analysis ($N = 3$). The alpha threshold for statistical significance was 0.05. Analysis was performed in Excel (Microsoft Corporation) and confirmed with MedCalc free statistical calculators (MedCalc Software Ltd) for RR[14] and MD.[15] The majority of studies also reported LOS as median days with IQR from the 25th percentile to the 75th percentile. All reported midpoints (median, but average if median was not provided) as well as ranges (IQR, but ±SD if IQR was not provided) were graphed, including the weighted average of study midpoints to compare PDA stent and surgical shunt.

Results

Of 181 studies initially identified during this time period, 8 studies met the inclusion criteria and were ultimately included in the meta-analysis (Figure 1). Our inclusion criteria were as follows: (1) 2-armed studies comparing PDA stent and surgical systemic-pulmonary shunt as first-stage palliation for infants or neonates with duct-dependent PBF; (2) both retrospective and prospective studies and both multicenter and single-center studies (we excluded single-armed studies, case series, case reports, review articles, letters, and editorials); (3) full-length articles in English; (4) reported at least one of the following outcomes of interest: mortality (all-cause), reintervention, hospital LOS, and proportions of patients with single-ventricle physiology and single-source PBF. Of the 8 studies, 3 were multicenter retrospective cohorts, 4 were single-center retrospective cohorts, and 1 was a single-center prospective cohort (Table 1).[13,16-22]

Mortality

Meta-analysis showed lower mortality rates for the PDA stent group than for the surgical shunt group (RR, 0.58; 95% CI, 0.42-0.81; $P < .05$) (Central Illustration).

Reintervention

Meta-analysis for total reintervention showed higher reintervention rates in the PDA stent group than in the surgical shunt group (RR, 1.35; 95% CI, 1.13-1.61; $P < .05$) (Figure 2). The study by Nasser et al[22] was excluded from the reintervention analysis because the investigators did not perform elective reintervention at their institution, and a large proportion of reintervention procedures were performed on an elective basis during a previously scheduled procedure. We also performed an analysis of reintervention directly related to the stent or shunt, which again demonstrated higher related reintervention rates in the PDA stent group than in the surgical shunt group (RR, 1.63; 95% CI, 1.3-2.06; $P < .05$) (Figure 3).

Hospital LOS

Meta-analysis showed a shorter hospital LOS in the PDA stent group than in the surgical shunt group (MD, −4.20; 95% CI, −6.55 to −1.86; $P < .05$) (Figure 4). MD could not be calculated for studies that did not report SD, although we represented all studies that reported hospital LOS in Figure 5 to illustrate the trend toward shorter hospital LOS for the PDA stent group in all studies.

Single-ventricle physiology

Meta-analysis showed a lower proportion of patients with single-ventricle physiology in the PDA stent group than in the surgical shunt group (RR, 0.74; 95% CI, 0.62-0.88; $P < .05$) (Figure 6).

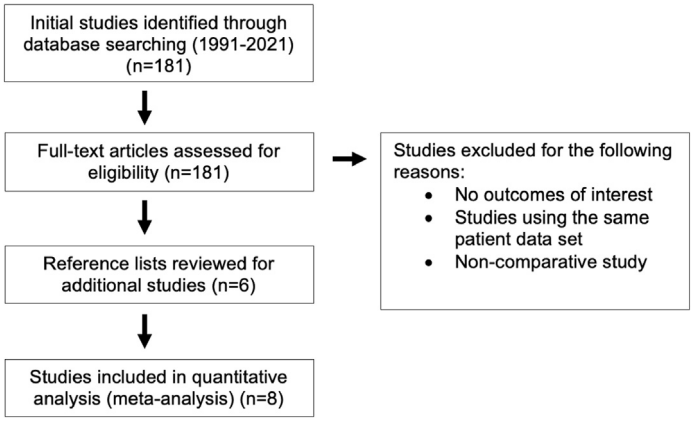


Figure 1. Flow diagram of study selection. Of 181 screened articles, 8 articles were ultimately included in the meta-analysis.

Table 1. Characteristics of included studies.

Reference, year	Study design	Country	Patients receiving PDA stent, *n*	Patients receiving systemic-pulmonary shunt, *n*	Mortality: stent, *n* (%)	Mortality: shunt, *n* (%)	All reinterventions: stent, *n* (%)	All reinterventions: shunt, *n* (%)	Reinterventions: related to stent, *n* (%)	Reinterventions: related to shunt, *n* (%)	Hospital LOS (d): stent	Hospital LOS (d): shunt	Patients with single-ventricle physiology: stent, *n* (%)	Patients with single-ventricle physiology: shunt, *n* (%)	Patients with single-source PBF: stent, *n* (%)	Patients with single-source PBF: shunt, *n* (%)
Amoozgar et al,[16] 2021	Multicenter retrospective cohort	Iran	15	20	3(20%)	6(30%)	N/A	N/A	N/A	N/A	5.5	8.9	6 (40%)	6 (30%)	N/A	N/A
Bentham et al,[17] 2018	Multicenter retrospective cohort	United Kingdom	83	171	15(18%)	61 (35.6%)	33 (39.7%)	41 (23.9%)	14 (16.9%)	25 (14.6%)	14	21	37 (44.6%)	82 (47.9%)	34 (41.0%)	76 (44%)
Glatz et al,[18] 2018	Multicenter retrospective cohort	United States	106	251	7(6%)	26 (10.3%)	50 (47.1%)	56 (22.3%)	50 (47.1%)	43 (17.1%)	10	13	42 (39.6%)	139 (55.3%)	41 (37.6%)	156 (62%)
Lekchuen sakul et al,[19] 2022	Single-center retrospective cohort	Thailand	34	64	4 (11.8%)	15 (23.4%)	15 (44.1%)	53 (82.8%)	15 (44.1%)	35 (54.7%)	12.9	16.9	8 (23.5%)	25 (39.1%)	N/A	N/A
Mallula et al,[20] 2015	Single-center retrospective cohort	United States	13	16	1(7.7%)	2 (12.5%)	7 (53.8%)	5 (31.2%)	7 (53.8%)	5 (31.2%)	10	23	2 (15.4%)	8 (50%)	1 (7.7%)	12 (75%)
McMullan et al,[21] 2014	Single-center retrospective cohort	United States	13	42	2 (15.4%)	5 (11.9%)	3 (23.1%)	14 (33.3%)	3 (23.1%)	11 (26.2%)	N/A	N/A	2 (15.4%)	5 (11.9%)	N/A	N/A
Nasser et al,[22] 2020	Single-center prospective cohort	Saudi Arabia	33	10	4 (12.1%)	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ratnayaka et al,[13] 2021	Single-center retrospective cohort	United States	47	41	3(6.4%)	5 (12.2%)	20 (42.6%)	18 (43.9%)	N/A	N/A	10	29	9 (19.1%)	9 (21.9%)	14 (29.8%)	28 (68.3%)

LOS, length of stay; N/A, not available; PBF, pulmonary blood flow; PDA, patent ductus arteriosus.

Figure 2. Forest plot of total reintervention. Each "event" represents a reintervention. Pooled estimates favor the shunt group (more freedom from reintervention in the shunt group).

Single-source PBF

Meta-analysis showed a lower proportion of patients with single-source PBF in the PDA stent group than in the surgical shunt group (RR, 0.64; 95% CI, 0.53-0.76; $P < .05$) (Figure 6).

Pulmonary artery growth

Meta-analysis of a smaller cohort (based on available data) revealed that the rate of growth, as reported by the change in the Nakata index, favored PDA stenting (79% vs 28%) (Figure 7), with an RR of 0.72 (95% CI, 0.49-1.06) (Figure 8).

Discussion

Meta-analysis showed lower mortality rates and a shorter hospital LOS for patients who received palliation via PDA stent as opposed to systemic-pulmonary surgical shunt, although there was a higher rate of reintervention in the PDA stent group. There were higher proportions of patients with single-ventricle physiology and single-source PBF in the surgical shunt group.

Although initial reports of PDA stenting reported poor mortality and high complication rates,[3,23] technical advancements have significantly improved outcomes.[8] The results of our meta-analysis support offering PDA stenting as the primary palliative intervention for all patients with ductal-dependent pulmonary circulation. Higher reintervention rates in the PDA stent group are not unexpected, as these patients frequently undergo planned interval catheterization and may receive either planned or incidental reintervention during the procedure. This is further suggested by the higher reintervention rates directly related to the primary intervention in the PDA stent group. In fact, stent reintervention may even be considered an advantage because it represents an "adjustable shunt" that can be enlarged, if necessary, with the growth of the child. However, as few studies reported whether each reintervention was performed as a planned procedure or for clinically significant cyanosis, the higher reintervention rates in the PDA stent group should be considered when deciding on a preferred initial palliation strategy. Our data are also supported by a meta-analysis completed previously with additions of pulmonary artery analysis and additional complication data.[10,24]

A possible early reintervention is additional stent implantation due to incomplete ductal coverage by the initial stent.[19] This may be avoided by erring on the side of complete ductal coverage, even at the expense of stent protrusion into the pulmonary artery and the aorta.[25] The most common reinterventions are stent redilation and new stent insertion to address restenosis, although, occasionally, surgical revision or shunt placement may be required if catheter-based reinterventions fail.[17-21,26] In general, reintervention following PDA stenting is usually nonurgent and relatively safe. Risk factors for reintervention include anticipated single-ventricle physiology, increased PDA tortuosity, and lack of prior balloon pulmonary valvuloplasty.[26] As mentioned previously, the use of drug-eluting stents on the basis of reintervention rates is less clear and merits further research.

Single-ventricle physiology generally represents a higher-risk group in patients with duct-dependent lesions, and Lekchuensakul et al[19] found that single-ventricle morphology was the major risk factor associated with increased mortality. Our meta-analysis showed that patients with single-ventricle physiology were more likely to receive a surgical shunt. Previous studies have found that among patients with single-ventricle physiology, PDA stenting leads to similar or improved outcomes compared with surgical shunting. For example, among patients with

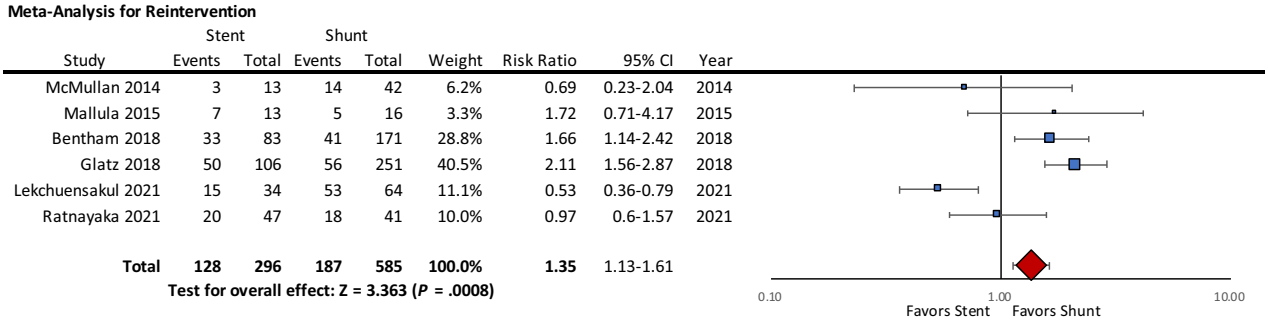


Figure 3. Forest plot of reintervention directly related to the stent or shunt. Each "event" represents a reintervention. Pooled estimates favor the shunt group (more freedom from reintervention in the shunt group).

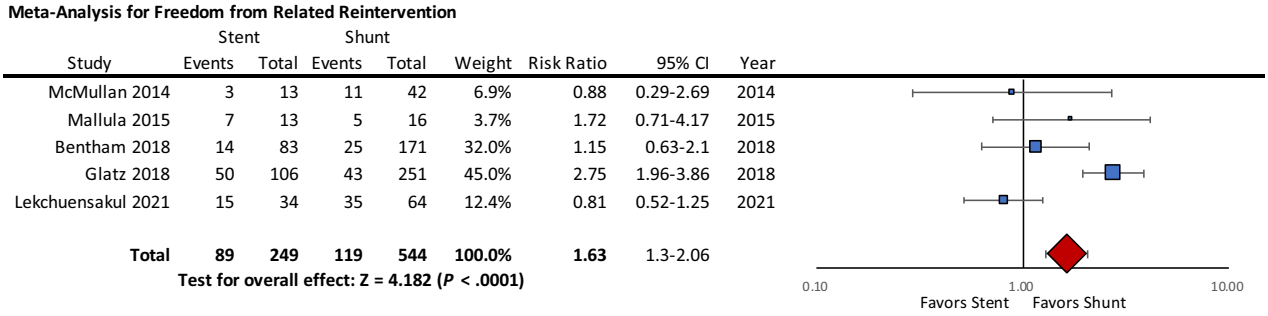


Figure 4. Forest plot of hospital length of stay. Pooled estimates favored the patent ductus arteriosus stent group.

single-ventricle anatomy, Meadows et al[27] demonstrated similar mortality, transplant rates, and pulmonary artery growth between stent and shunt groups, although with higher planned reintervention rates in the stent group. Prabhu et al[28] found that PDA stenting was associated with reduced in-hospital morbidity and increased survival to stage II palliation in patients with single-ventricle physiology compared with surgical shunt. Therefore, it seems that for this group of patients, PDA stenting represents a comparable or even superior palliation strategy to surgical shunting.

Patients with single-source PBF are also typically considered a higher-risk group among those with duct-dependent lesions; hence, the question arises whether stent or shunt would be preferable in these patients compared with those with antegrade PBF. In infants in whom the PDA is the only source of PBF, ductal spasm during the stenting procedure can quickly become a surgical emergency because all blood flow to the lungs ceases.[29] For this reason, single-source PBF is considered a contraindication to PDA stenting by some centers, which is reflected in our meta-analysis that found that a surgical shunt was more commonly employed in patients with single-source PBF. However, Bauser-Heaton et al[29] found that among patients with single-source PBF, PDA stenting was associated with procedural complication rates and mortality that were similar to those of surgical shunt procedure, suggesting that the rarity of ductal spasm still makes stenting an attractive alternative for these patients. However, in that setting, PDA stenting should be considered a relatively high-risk procedure that requires awareness of the cardiac intensive care team and, in some centers, >1 experienced operator and readiness to deploy surgical back up.

Technical considerations

Tortuosity and feasibility

The tortuosity and origin of the PDA have long been considered significant factors in determining the likelihood of successful stenting. For example, a retrospective look at procedure success rates by Roggen et al[30] in 2020 found that stenting was significantly more successful in patients with a straight PDA originating from the descending thoracic aorta than in those with a tortuous PDA arising from the transverse aortic arch (a "vertical" PDA). However, this assumption has been challenged by recent studies that demonstrated successful stenting for a variety of morphologies.[25,31,32] Technical considerations are important in these cases of convoluted ducts or those with difficult origin. Some investigators prefer deploying multiple overlapping stents to ensure full coverage in tackling a tortuous PDA,[31] whereas others prefer to use 1 long stent.[13] However, both stress the importance of covering both ends of the PDA and not leaving a portion unstented. It has also been noted that straightening the PDA by crossing the main pulmonary artery stump and then deflecting it back to the branch pulmonary artery, instead of crossing directly from the PDA to the branch pulmonary artery, can increase the chances of success.[31] Some interventionists have also found it helpful to place a nasogastric tube before stent insertion to aid in the measurement of PDA and serve as a landmark for stent deployment,[32] and others have successfully navigated complex ductal turns using a microcatheter.[8,33]

To standardize terminology and track stenting outcomes according to PDA morphology, Qureshi et al[25] devised a "tortuosity index" using the following classification scheme: type I (straight), type II (1 turn), and type III (multiple turns). A subtype classification was also devised on the basis of the PDA origin. This study found that success rates, procedure time, and need for >1 stent did not significantly differ on the basis of tortuosity index, although a greater index was associated with pulmonary artery jailing, unplanned reintervention, and pulmonary arterioplasty at subsequent surgery.[25]

Vascular approach

The choice of a vascular approach based on origin and morphology also seems to strongly influence the feasibility of stent placement. When the PDA arises from the proximal descending aorta, as is common in pulmonary atresia with intact ventricular septum, critical pulmonary stenosis, and tricuspid atresia, it tends to have a short and straight course. These PDAs can generally be effectively approached via the conventional retrograde femoral artery approach.[34] However, vertical PDAs (those arising from the proximal or middle part of the aortic arch) tend to be both more tortuous and more difficult and time-consuming to approach via the femoral artery, as it is challenging to engage the ampulla, secure a stable guide wire position, and track the stent.[25] Common in tetralogy of Fallot, single-ventricle physiology, and other complex cyanotic heart

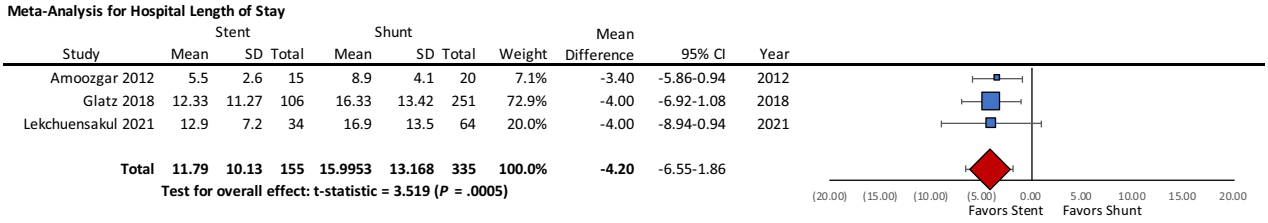
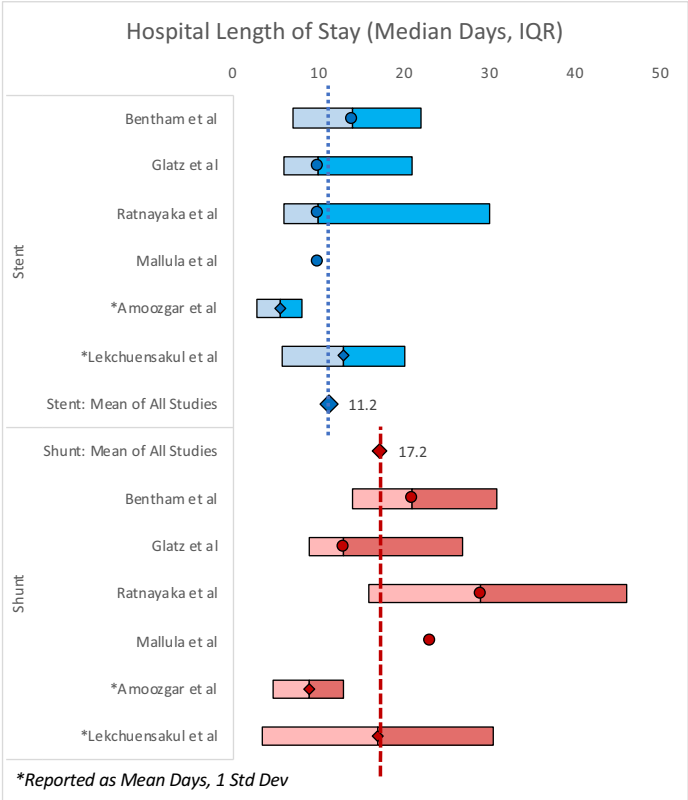


Figure 5. Hospital length of stay showing trend toward shorter length of stay for the patent ductus arteriosus stent group (weighted average of all studies).



PA growth (Nakata index change before vs after)	Weighted average % change	Number of studies	Number of patients
Stent	79%	4	141
Shunt	28%	3	296

Figure 6. Proportions of patients with single-ventricle physiology and single-source pulmonary blood flow in the patent ductus arteriosus stent and surgical shunt groups, showing higher proportions in the shunt group. PBF, pulmonary blood flow.

diseases,[34] these PDAs can occasionally be accessed through the femoral vein via the right ventricle, ventricular septal defect, and ascending aorta.[35] However, as this pathway may be associated with hemodynamic instability in infants (and requires suitable anatomy),[35] nonfemoral approaches have recently gained favor as potentially more efficient approaches for vertical PDAs.

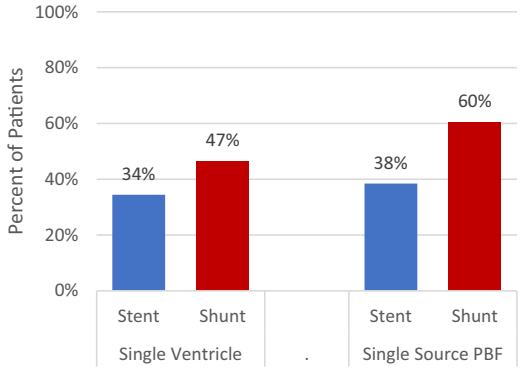


Figure 7. Weighted average change in the Nakata index in patients with stent versus shunt in available studies. PA, pulmonary artery.

Although there is a paucity of large-scale data on vascular access for PDA stenting, multiple smaller observational studies present promising outcomes for the carotid and axillary arteries, particularly for approaching vertical PDAs through the superior aspect of the aortic arch.[25,30,35-41] Bauser-Heaton et al[36] observed that carotid and axillary artery access is more commonly used in highly tortuous PDAs than the femoral artery and that procedural and late complications were similar regardless of the access site. Similarly, Alsawah et al[37] reported that percutaneous carotid access was more commonly used in complex ductal anatomy, and they found that both immediate access-related complications and delayed local complications in these cases were significantly lower than in cases that used the femoral artery. However, the authors also cautioned against potential neurologic complications with carotid access; there was 1 case in the carotid group that resulted in a pseudoaneurysm and acute hemiparesis 3 days after the procedure.[37] Partly in an effort to avoid these potentially devastating neurologic consequences, other interventionists have attempted vertical PDA access through the axillary artery.[38-40,42] Although subclavian artery injury is possible with axillary artery access, for many years, classic Blalock–Taussig shunts have sacrificed the subclavian artery with no significant long-term complications.[43] This likely represents the reason that interventionists such as Lee et al[39] prefer the axillary approach. Breatnach et al[38] described a successful series of PDA stenting via the axillary artery in 20 patients, with 3 access-related complications that were managed conservatively without long-term effects (2 partial dissections to the subclavian artery and a right axillary artery pseudoaneurysm). Polat[40] also noted that for vertical PDAs, the axillary approach was associated with significantly shorter fluoroscopy time and total procedure time than the transvenous approach.

Little is known about the relative benefits and drawbacks of percutaneous carotid access versus surgical cut-down. Sen et al[35] expressed concerns that the direct compression required for hemostasis following percutaneous carotid access could increase the risk of thrombosis, occlusion, or pseudoaneurysm and that it can be difficult to find a balance between anticoagulation for stent patency versus carotid hemostasis. For this reason, their institution prefers surgical cut-down. Others find that increased procedure time for surgical cut-down, as well as the necessity of surgeon availability, makes percutaneous access a more attractive option. Although limited, current data suggest that patency rates following percutaneous access may be similar to those following surgical cut-down.[41,44]

An additional technique that has been found to be helpful for both percutaneous and surgical cut-down carotid access, as well as axillary access, is to "flip" the patient such that the feet are at the head of the table.[42] This position more closely mimics the familiar conventional orientation while approaching from a superior direction, and it allows the operator to have full access to the table for adequately stabilizing the sheath and wire position, which can be paramount while stenting tortuous ducts.[35,36] It may also ease wire and catheter exchanges, which can be critical in cases of hemodynamic instability or other complications.[38] In addition, Bauser-Heaton et al[36] found that the flip technique was associated with shorter procedure times for highly tortuous PDAs, although this did not reach statistical significance. Although the distance to the patient's airway can pose challenges to the anesthesiology team, it does allow for easy access to lower extremity lines, and the benefits of the overall procedure likely outweigh this difficulty.

Type of stent

The choice of bare-metal stent versus drug-eluting stent is generally made by the individual interventionist or institution, as there are limited data comparing their use in neonatal PDA stenting. As neointimal proliferation is a common limiting factor in stent longevity, drug-eluting stents could potentially minimize reinterventions and optimize time before definitive surgery. Therefore, there has been a trend toward the increased use of drug-eluting stents, although many institutions continue

PA Growth (Nakata Index Change Pre vs Post)	Weighted Avg % Change	# Studies	# Patients
Stent	79%	4	141
Shunt	28%	3	296

Figure 8. Analysis of complication data favoring stent in total comparison.

to use bare-metal stents owing to the lack of robust data regarding drug-eluting stent safety.[13,18,20,31,38]

Rapamycin-eluting stents have been shown to prolong ductal patency in piglets, although this effect decreases with time.[39,45] However, some concern remains over the potential immunosuppressive effects of drug-eluting stents. In a study of neonates receiving sirolimus-eluting stents, peak sirolimus levels reached immunosuppressive levels, although no clinically significant adverse outcomes were observed.[46] The level of immunosuppression also correlates with the length and number of stents; Sivakumar et al[47] noted that sirolimus levels did not reach immunosuppressive levels if a single stent of <22 mm was used. Again, however, no clinically significant adverse outcomes were observed for the cases that did reach immunosuppressive levels, and drug levels rapidly decreased within a week.

Aggarwal et al[48] compared second-generation (fluoropolymer-coated everolimus) drug-eluting stents with bare-metal stents in neonates who underwent PDA stenting for ductal-dependent PBF and found that luminal loss was significantly lower in the drug-eluting stent group (lumen patency of 81% in the drug-eluting stent group vs 50% in the bare-metal stent group). The 2 groups were comparable in pulmonary artery size and symmetry index, hospital LOS, and diuretic usage at discharge. There was a slightly higher rate of bacterial infection in the drug-eluting stent group (used as a surrogate measure of immunosuppression), but this did not reach statistical significance. Additionally, those who received a drug-eluting stent were significantly less likely to need an unplanned reintervention to treat cyanosis (12% vs 28%).[48] However, Shahanavaz et al[26] found that a drug-eluting stent was associated with higher reintervention rates, although the few patients who received a drug-eluting stent in this study were younger and more likely to have single-ventricle physiology than those who received bare-metal stents. These limited observations suggest that a short period of immunosuppression may be tolerated in favor of prolonged stent patency, although further research is needed.

Stent length is generally chosen on the basis of measurement of the PDA by catheter angiography. Although simple if the PDA is straight and short, a long or tortuous PDA can make accurate measurement difficult. Prediction of unfolding of tortuous PDAs is nearly impossible, and the behavior after wire removal is unpredictable. Because ductal constriction of an unstented portion can quickly result in cyanosis, it is considered preferable to choose a stent slightly longer than the measured length, always start at the pulmonary end, and use multiple overlapping stents if necessary to avoid this complication.[6] Although protrusion of a long stent may increase the risk of pulmonary artery jailing, the benefits of avoiding ductal constriction typically outweigh this possibility.[25]

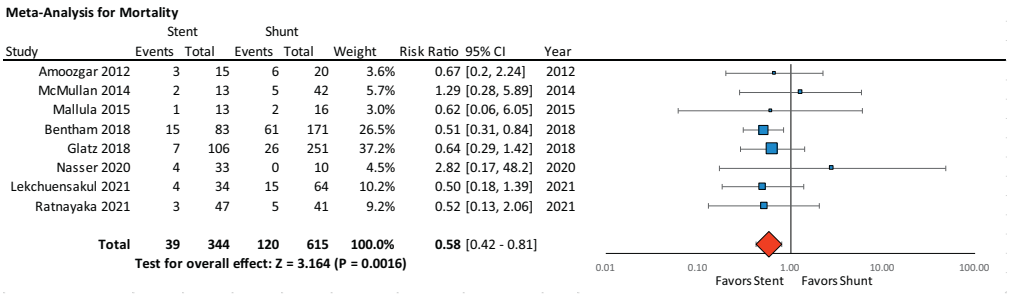
When available, prior computed tomography angiography can also aid in procedure planning by determining which stent lengths may be needed and predicting the best access site and patient orientation, thereby shortening procedure length and decreasing radiation dosage.[49] 3-dimensional modeling in conjunction with computed tomography angiography has also been reported to predict a successful access approach and more accurately estimate PDA length and tortuosity than 2-dimensional angiography.[50]

Although stent diameter can be individualized on the basis of multiple factors (such as expected time to next-stage surgery, PDA length, and antegrade PBF), it is typically chosen on the basis of patient weight: for those weighing <2 kg, a 3-mm stent; for those weighing 2 to 3 kg, a 3.5-mm stent; for those weighing 3 to 4 kg, a 3.5- to 4-mm stent; and for those weighing >4 kg, a 4.5-mm stent.[6,8]

Pulmonary artery jailing and growth

Preexisting branch pulmonary artery stenosis has traditionally been considered a contraindication to PDA stenting because stent protrusion into the pulmonary artery could result in entrapment of pulmonary artery branches and restriction of blood flow (pulmonary artery jailing). This was addressed by the American Heart Association in their 2011 statement "Indications for Cardiac Catheterization and Intervention in Pediatric Cardiac Disease," in which they include a class III recommendation (should not be performed) for PDA stenting in infants with cyanotic congenital heart disease with obvious proximal pulmonary artery stenosis in the vicinity of the ductal insertion (level of evidence: C).[51] Their rationale was that pulmonary artery jailing can potentially lead to hypoxia, stent thrombosis due to sluggish flow, and unilateral pulmonary edema or hemorrhage.[52]

However, recent evidence suggests that branch pulmonary artery stenosis is not a significant risk factor for pulmonary artery jailing, and these patients should not be excluded from PDA stenting.[13,52] Pulmonary artery jailing does tend to be more common with a higher PDA tortuosity index; however, jailed pulmonary arteries do not significantly affect the Nakata index or pulmonary artery symmetry at next-stage surgery compared with nonjailed pulmonary arteries.[25] Additionally, pulmonary artery jailing itself does not increase the ventilation duration, intensive care unit stay, or mortality risk if the jailed pulmonary arteries are recruited immediately.[52] This recruitment can generally be done by catheter-based interventions such as strut dilatation or, if catheter-based interventions fail, by surgery without increased mortality risk.[52] Pulmonary artery arterioplasty is typically required at the time of definitive surgery for those with pulmonary artery jailing, but the benefits of avoiding initial surgery in favor of PDA stenting may outweigh this risk.[25,52] For example, Ganta et al[53] have shown that the Glenn procedure can be successfully performed without the use of cardiopulmonary bypass even if pulmonary artery reconstruction is needed. Although these data reveal reasonable pulmonary artery growth, it should be noted that these numbers are rather small. The jailed pulmonary arteries appear to have higher reintervention rates, and most pulmonary artery sizes are measured with limited reliability via echocardiogram.



Central Illustration. Forest plot of total mortality. Pooled estimates favor the patent ductus arteriosus stent group.

Another outcome of interest in PDA stenting procedures is pulmonary artery growth, particularly relative to growth produced by the conventional systemic-pulmonary surgical shunt. Multiple studies have shown similar or even superior rates of pulmonary artery growth among infants receiving PDA stents compared with those receiving surgical shunts.[9-11,13,16-18,21,24,27] Even among patients with sole-source ductal--dependent PBF[29,54] and hypoplastic pulmonary arteries,[55] PDA stenting provides adequate pulmonary artery growth for definitive surgery. Because the PDA stent allows blood flow to enter the pulmonary arteries centrally (unlike surgical shunts, which are generally placed into one of the branches), it also appears to promote more symmetrical growth.[13,18,24] We included a small meta-analysis from available studies that supports pulmonary artery growth in PDA stenting, although its findings were not significant (Figure 7).[24,27,29,56]

Complications

Although complication rates have decreased dramatically since ductal stenting began, and the procedure is considered safe (procedure-related mortality of <1% in favorable anatomy),[6] consideration should be given to common complications and their management.

Acute complications

The most commonly reported acute complication is vessel occlusion or injury related to vascular access, which can generally be managed with heparin infusion.[6,8,13,18,24,27,29] Vascular access can also occasionally result in local infection.[6,57]

Acute stent thrombosis is a rare (2%-3%) but life-threatening complication and usually presents as a precipitous drop in oxygen saturation in the minutes or hours following stent placement.[16.34] If this occurs while the guide wire is still across the ductus, the balloon should be inflated (multiple times if necessary) to break up the thrombus. If the guide wire has been removed, a stiff coronary wire can be inserted and used to drill through the thrombus, and then a balloon can be used to disrupt the clot.[6,8,16,34] For this reason, it is recommended to leave the guide wire across the stent for 15 minutes after expansion.[16,34,58] Interventionists also reported the use of thrombolytic therapy for acute stent thrombosis; however, this can lead to severe and possibly fatal bleeding, particularly if surgical shunt placement is required.[6,58]

Ductal spasm is similarly life-threatening if not aggressively addressed. It typically results from guide wire manipulation across the PDA and causes sudden desaturation.[34] If the guide wire is adequately positioned, an immediately placed stent can relieve spasm and restore PBF.[6,8,16,34] If immediate stent expansion is not possible, the wire should be removed, prostaglandin E1 should be restarted, blood pressure should be optimized to ease blood flow through the PDA, and the procedure can be reattempted after patient stabilization.[8,34] If spasm recurs, extracorporeal membrane oxygenation and surgical shunt placement should be pursued as necessary.[8,20,34]

Stent malposition or migration can also complicate the procedure, particularly if the pulmonary end of the PDA is >2.5 mm.[6,18,19,34] If this occurs, the interventionist can attempt to reposition the stent or secure it in place with a second stent.[8,24,59] Other alternatives include pushing and expanding the stent in a peripheral pulmonary branch or leaving it in place to be removed at next-stage surgery.[6,8,27,34] However, if this is not possible, the patient may require surgical stent retrieval and construction of a surgical shunt.[6,8,34,55]

Late complications

A common complication following PDA stenting, particularly in cases of a large stent to a single lung, is mild heart failure resulting from pulmonary overflow. This can potentially lead to pulmonary hypertension and steal from the systemic circulation, although it is usually effectively managed with diuretics.[6,34,60] If believed to be due to a large stent, the interventionist could also attempt to implant additional stents to reduce the stent diameter and effective PBF.[6,34]

Bronchial compression by a stented duct has also been considered a theoretical complication, especially if the patient has evidence of preexisting bronchial compression from a large and ectatic PDA.[61,62] However, stenting may actually improve bronchial compression by leading to PDA shrinkage, straightening, and lateralization[63]; therefore, bronchial compression should not necessarily be considered a contraindication to stenting.[13]

One of the most common late complications, and a significant driver behind reintervention rates, is neointimal proliferation and resulting stenosis of the stent. Endothelialization of the stent can occur as early as 1 month after insertion,[23] and many will require reintervention to address a clinically significant closure after approximately 4 months.[3,57,64] Although larger stents typically have also increased longevity, an appropriately sized stent should be chosen in the newborn to avoid overcirculation. Time to definitive surgery typically depends on individual patient anatomy; those with single-source PBF or univentricular anatomy generally require earlier surgical palliation than patients with antegrade PBF or biventricular anatomy.[65] Although individual institutions likely vary on preferred age and weight for second-stage palliation, Ganta et al[53] reported successful Glenn operation at a median age of 4.9 months and weight of 5.7 kg after PDA stenting in infants with duct-dependent PBF, suggesting that PDA stent duration may be sufficient to avoid reintervention until surgery can be performed. However, patients with dual-source PBF, comorbidities, or complex repairs in which later surgery is desired should have an intense outpatient follow-up, and reintervention will likely need to be planned closer to 3 to 4 months of age to prolong the life of the stent.

Limitations

As PDA stenting is still a relatively recent innovation in treating duct-dependent lesions, there was an imbalance in sample size in this meta-analysis (shunt, $n = 615$; stent, $n = 344$), which may reduce the ability to detect significant differences between the 2 groups. Furthermore, all studies included were observational studies and, therefore, prone to confounding and selection bias. There were likely multiple factors influencing whether a patient received a PDA stent or a surgical shunt, as demonstrated by the finding that those with single-ventricle physiology and single-source PBF were more likely to undergo surgical shunt placement. Other factors may include PDA anatomy and overall patient stability, which we were unable to quantify in this meta-analysis but may have influenced outcomes.

Individual institutions are also likely to exhibit heterogeneity in the reintervention strategies and reporting. For example, we excluded Nasser et al[22] from the reintervention analysis because they did not perform elective reintervention at their center and, in most centers, a large proportion of reintervention procedures were performed on an elective basis (although few studies reported whether reintervention was performed as a planned procedure). Individual studies likely also vary in reintervention reporting; to homogenize this, we attempted to analyze both total reported reinterventions and those directly related to the stent or shunt. However, individual reasons were not always given for reintervention; occasionally, it was unclear whether a reintervention was necessary because of the original procedure or for an unrelated reason.

In addition, Bentham et al[17] and Ratnayaka et al[13] used an intention-to-treat model; they reported group size and outcomes according to the originally planned procedure, regardless of whether it was successful. The remaining 6 studies reported numbers for only patients who successfully received a PDA stent or surgical shunt.

Therefore, we were unable to correct for potential crossover patients in Bentham et al[17] or Ratnayaka et al[13] or unsuccessful procedures in the remaining studies.

In addition, each of the included studies defined mortality differently from 6 months after the procedure and as long as 7 years. This makes the analysis more difficult; although other articles report on this topic, mortality was defined as the initial hospital admission and thus these articles were excluded from our mortality analysis.

Conclusion

PDA stenting as palliation for duct-dependent pulmonary circulation has lower mortality rates and a shorter hospital LOS than systemic-pulmonary surgical shunt procedure, although at the expense of increased reintervention rates. There were higher proportions of patients with single-ventricle physiology and single-source PBF in the surgical shunt group. Technical advances such as alternative access routes and drug-eluting stents have improved the success of PDA stenting in the current era. Results have also shown that increased tortuosity and preexisting branch artery stenosis should not necessarily be considered contraindications to stenting, as these PDAs can be successfully stented with good outcomes.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethics statement

This research adheres to relevent ethical guidelines.

References

1. Moore JW, Kirby WC, Lovett EJ, O'Neill JT. Use of an intravascular endoprosthesis (stent) to establish and maintain short-term patency of the ductus arteriosus in newborn lambs. *Cardiovasc Intervent Radiol*. 1991;14(5):299–301.
2. Gibbs JL, Wren C, Watterson KG, Hunter S, Hamilton JR. Stenting of the arterial duct combined with banding of the pulmonary arteries and atrial septectomy or septostomy: a new approach to palliation for the hypoplastic left heart syndrome. *Br Heart J*. 1993;69(6):551–555.
3. Gibbs JL, Rothman MT, Rees MR, Parsons JM, Blackburn ME, Ruiz CE. Stenting of the arterial duct: a new approach to palliation for pulmonary atresia. *Br Heart J*. 1992;67(3):240–245.
4. Ruiz CE, Zhang HP, Larsen RL. The role of interventional cardiology in pediatric heart transplantation. *J Heart Lung Transplant*. 1993;12(6 Pt 2):S164–S167.
5. Alwi M, Choo KK, Latiff HA, Kandavello G, Samion H, Mulyadi MD. Initial results and medium-term follow-up of stent implantation of patent ductus arteriosus in duct-dependent pulmonary circulation. *J Am Coll Cardiol*. 2004;44(2):438–445.
6. Valdeomillos E, Jalal Z, Boudjemline Y, Thambo JB. Filiale de cardiologie pédiatrique et congénitale de la Société française de cardiologie. Transcatheter ductus arteriosus stenting in paediatric cardiology: indications, results and perspectives. *Arch Cardiovasc Dis*. 2020;113(2):129–141.
7. Boucek DM, Qureshi AM, Goldstein BH, Petit CJ, Glatz AC. Blalock-Taussig shunt versus patent ductus arteriosus stent as first palliation for ductal-dependent pulmonary circulation lesions: a review of the literature. *Congenit Heart Dis*. 2019;14(1):105–109.
8. Aggarwal V, Petit CJ, Glatz AC, Goldstein BH, Qureshi AM. Stenting of the ductus arteriosus for ductal-dependent pulmonary blood flow-current techniques and procedural considerations. *Congenit Heart Dis*. 2019;14(1):110–115.
9. Alsagheir A, Koziarz A, Makhdoum A, et al. Duct stenting versus modified Blalock-Taussig shunt in neonates and infants with duct-dependent pulmonary blood flow: a systematic review and meta-analysis. *J Thorac Cardiovasc Surg*. 2021;161(2):379–390.e8.
10. Fakhry Abdelmassih A, Menshawey R, Menshawey E, et al. Blalock-Taussig shunt versus ductal stent in the palliation of duct dependent pulmonary circulation; a systematic review and metanalysis. *Curr Probl Cardiol*. Published online May 8, 2021. https://doi.org/10.1016/j.cpcardiol.2021.100885
11. Li D, Zhou X, Li M. Arterial duct stent versus surgical shunt for patients with duct-dependent pulmonary circulation: a meta-analysis. *BMC Cardiovasc Disord*. 2021;21(1):9.
12. Goldstein BH, O'Byrne ML, Petit CJ, et al. Differences in cost of care by palliation strategy for infants with ductal-dependent pulmonary blood flow. *Circ Cardiovasc Interv*. 2019;12(4):e007232.
13. Ratnayaka K, Nageotte SJ, Moore JW, et al. Patent ductus arteriosus stenting for all ductal-dependent cyanotic infants: waning use of Blalock-Taussig shunts. *Circ Cardiovasc Interv*. 2021;14(3):e009520.
14. Relative risk calculator. MedCalc Software Ltd. https://www.medcalc.org/calc/relative_risk.php. Accessed April 4, 2022.
15. Comparison of means (t-test). MedCalc Software Ltd. https://www.medcalc.org/manual/comparison-of-means-t-test.php. Accessed April 4, 2022.
16. Amoozgar H, Edraki MR, Naghshzan A, et al. Midterm follow up of transcatheter closure of coronary artery fistula with Nit-Occlud(R) patent ductus arteriosus coil. *BMC Cardiovasc Disord*. 2021;21(1):192.
17. Bentham JR, Zava NK, Harrison WJ, et al. Duct stenting versus modified Blalock-Taussig shunt in neonates with duct-dependent pulmonary blood flow: associations with clinical outcomes in a multicenter national study. *Circulation*. 2018;137(6):581–588.
18. Glatz AC, Petit CJ, Goldstein BH, et al. Comparison between patent ductus arteriosus stent and modified Blalock-Taussig shunt as palliation for infants with ductal-dependent pulmonary blood flow: insights from the congenital catheterization research collaborative. *Circulation*. 2018;137(6):589–601.
19. Lekchuensakul S, Somanandana R, Namchaisiri J, Benjacholamas V, Lertsapcharoen P. Outcomes of duct stenting and modified Blalock-Taussig shunt in cyanotic congenital heart disease with duct-dependent pulmonary circulation. *Heart Vessels*. 2022;37(5):875–883.
20. Mallula K, Vaughn G, El-Said H, Lamberti JJ, Moore JW. Comparison of ductal stenting versus surgical shunts for palliation of patients with pulmonary atresia and intact ventricular septum. *Catheter Cardiovasc Interv*. 2015;85(7):1196–1202.
21. McMullan DM, Permut LC, Jones TK, Johnston TA, Rubio AE. Modified Blalock-Taussig shunt versus ductal stenting for palliation of cardiac lesions with inadequate pulmonary blood flow. *J Thorac Cardiovasc Surg*. 2014;147(1):397–401.
22. Nasser BA, Abdulrahman M, Qwaee AAL, Alakfash A, Mohamad T, Kabbani MS. Impact of stent of ductus arteriosus and modified Blalock-Taussig shunt on pulmonary arteries growth and second-stage surgery in infants with ductus-dependent pulmonary circulation. *J Saudi Heart Assoc*. 2020;32(1):86–92.
23. Gibbs JL, Uzun O, Blackburn ME, Wren C, Hamilton JR, Watterson KG. Fate of the stented arterial duct. *Circulation*. 1999;99(20):2621–2625.
24. Santoro G, Capozzi G, Caianiello G, et al. Pulmonary artery growth after palliation of congenital heart disease with duct-dependent pulmonary circulation: arterial duct stenting versus surgical shunt. *J Am Coll Cardiol*. 2009;54(23):2180–2186.
25. Qureshi AM, Goldstein BH, Glatz AC, et al. Classification scheme for ductal morphology in cyanotic patients with ductal dependent pulmonary blood flow and association with outcomes of patent ductus arteriosus stenting. *Catheter Cardiovasc Interv*. 2019;93(5):933–943.
26. Shahanavaz S, Qureshi AM, Petit CJ, et al. Factors influencing reintervention following ductal artery stent implantation for ductal-dependent pulmonary blood flow: results from the congenital cardiac research collaborative. *Circ Cardiovasc Interv*. 2021;14(12):e010086.
27. Meadows JJ, Qureshi AM, Goldstein BH, et al. Comparison of outcomes at time of superior cavopulmonary connection between single ventricle patients with ductal-dependent pulmonary blood flow initially palliated with either Blalock-Taussig shunt or ductus arteriosus stent: results from the congenital catheterization research collaborative. *Circ Cardiovasc Interv*. 2019;12(10):e008110.
28. Prabhu NK, Zhu A, Meza JM, et al. Transition to ductal stenting for single ventricle patients led to improved survival: an institutional case series. *World J Pediatr Congenit Heart Surg*. 2021;12(4):518–526.
29. Bauser-Heaton H, Qureshi AM, Goldstein BH, et al. Comparison of patent ductus arteriosus stent and Blalock-Taussig shunt as palliation for neonates with sole source ductal-dependent pulmonary blood flow: results from the congenital catheterization research collaborative. *Pediatr Cardiol*. 2022;43(1):121–131.
30. Roggen M, Cools B, Brown S, et al. Can ductus arteriosus morphology influence technique/outcome of stent treatment? *Catheter Cardiovasc Interv*. 2020;95(6):1149–1157.
31. Bahaidarah S, Al-Ata J, Alkhushi N, et al. Outcome of ductus arteriosus stenting including vertical tubular and convoluted tortuous ducts with emphasis on technical considerations. *Egypt Heart J*. 2021;73(1):83.
32. Recto MR, Doyle S, Guerra VC, Yang SG, Yeh Jr T. Morphology of the patent ductus arteriosus does not preclude successful patent ductus arteriosus stent implantation in high-risk patients undergoing hybrid stage I palliation: recommendations to optimize ductal stent positioning. *Catheter Cardiovasc Interv*. 2013;82(4):519–525.
33. Haas NA, Fernandez-Rodriguez S, Dalla Pozza R, et al. Microcatheter-assisted stenting of the tortuous vertical ductus arteriosus via femoral access in a duct-dependent pulmonary circulation. *Int J Cardiol*. 2019;285:103–107.
34. Alwi M. Stenting the ductus arteriosus: case selection, technique and possible complications. *Ann Pediatr Cardiol*. 2008;1(1):38–45.
35. Sen S, Pradhan P, Jain S, Trivedi D, Kaushik P. Hybrid stenting of the arterial duct with carotid cutdown and flip technique: immediate and early results. *Cardiol Young*. Published online October 11, 2021. https://doi.org/10.1017/S1047951121004017
36. Bauser-Heaton H, Qureshi AM, Goldstein BH, et al. Use of carotid and axillary artery approach for stenting the patent ductus arteriosus in infants with ductal-dependent pulmonary blood flow: a multicenter study from the congenital catheterization research collaborative. *Catheter Cardiovasc Interv*. 2020;95(4):726–733.

37. Alsawah GA, Elmarsafawy H, Hafez M, Rakha S. Evaluation of carotid artery access in comparison with femoral artery access in neonatal percutaneous stenting of ductus arteriosus. *Cardiol Young*. 2021;31(9):1465–1471.
38. Breatnach CR, Aggarwal V, Al-Alawi K, et al. Percutaneous axillary artery approach for ductal stenting in critical right ventricular outflow tract lesions in the neonatal period. *Catheter Cardiovasc Interv*. 2019;93(7):1329–1335.
39. Lee J, Ratnayaka K, Moore J, El-Said H. Stenting the vertical neonatal ductus arteriosus via the percutaneous axillary approach. *Congenit Heart Dis*. 2019;14(5):791–796.
40. Polat TB. Stenting the vertical ductus arteriosus via axillary artery access using "wire-target" technique. *Congenit Heart Dis*. 2017;12(6):800–807.
41. Justino H, Petit CJ. Percutaneous common carotid artery access for pediatric interventional cardiac catheterization. *Circ Cardiovasc Interv*. 2016;9(4):e003003.
42. Bauser-Heaton H, Qureshi AM, Goldstein BH, Glatz AC, Petit CJ. Use of novel "flip technique" aids in percutaneous carotid artery approach in neonates. *JACC Cardiovasc Interv*. 2019;12(16):1630–1631.
43. Moulton AL, Brenner JI, Ringel R, et al. Classic versus modified Blalock-Taussig shunts in neonates and infants. *Circulation*. 1985;72(3 Pt 2):II35–II44.
44. Choudhry S, Balzer D, Murphy J, Nicolas R, Shahanavaz S. Percutaneous carotid artery access in infants < 3 months of age. *Catheter Cardiovasc Interv*. 2016;87(4):757–761.
45. Lee KJ, Hinek A, Chaturvedi RR, et al. Rapamycin-eluting stents in the arterial duct: experimental observations in the pig model. *Circulation*. 2009;119(15):2078–2085.
46. Lee KJ, Seto W, Benson L, Chaturvedi RR. Pharmacokinetics of sirolimus-eluting stents implanted in the neonatal arterial duct. *Circ Cardiovasc Interv*. 2015;8(5):e002233.
47. Sivakumar K, Pavithran S, Sonawane B, Rajendran M, Ramasamy R. Serum sirolimus levels after implantation of third generation drug eluting cobalt chromium coronary stent in ductus arteriosus in neonates with duct-dependent pulmonary circulation. *Pediatr Cardiol*. 2020;41(7):1354–1362.
48. Aggarwal V, Dhillon GS, Penny DJ, Gowda ST, Qureshi AM. Drug-eluting stents compared with bare metal stents for stenting the ductus arteriosus in infants with ductal-dependent pulmonary blood flow. *Am J Cardiol*. 2019;124(6):952–959.
49. Jadhav SP, Aggarwal V, Masand PM, Diaz E, Zhang W, Qureshi AM. Correlation of ductus arteriosus length and morphology between computed tomographic angiography and catheter angiography and their relation to ductal stent length. *Pediatr Radiol*. 2020;50(6):800–809.
50. Chamberlain RC, Ezekian JE, Sturgeon GM, Barker PCA, Hill KD, Fleming GA. Preprocedural three-dimensional planning aids in transcatheter ductal stent placement: a single-center experience. *Catheter Cardiovasc Interv*. 2020;95(6):1141–1148.
51. Feltes TF, Bacha E, Beekman RH, et al. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. *Circulation*. 2011;123(22):2607–2652.
52. Prabhu S, Joshi A, Mehra S, et al. Branch pulmonary artery jailing during patent ductus arteriosus stenting: recruitment and immediate outcomes. *World J Pediatr Congenit Heart Surg*. 2021;12(3):320–330.
53. Ganta S, Artrip J, Haley, et al. Stage 2 palliation after ductal stenting for ductal dependent pulmonary blood flow. Paper presented at: Congenital Scientific Sessions, American Association for Thoracic Surgery 101st Annual Meeting; May 2, 2021; Seattle, WA.
54. Santoro G, Capozzi G, Capogrosso C, et al. Pulmonary artery growth after arterial duct stenting in completely duct-dependent pulmonary circulation. *Heart*. 2016;102(6):459–464.
55. Santoro G, Gaio G, Capozzi G, et al. Fate of hypoplastic pulmonary arteries after arterial duct stenting in congenital heart disease with duct-dependent pulmonary circulation. *JACC Cardiovasc Interv*. 2015;8(12):1626–1632.
56. Elmarsafawy H, Elasfar A, Taha FA. Evaluation of the growth of central pulmonary arteries following patent ductus arteriosus stenting in patients with duct dependent pulmonary circulation. *Pediatr Cardiol*. 2020;41(8):1667–1674.
57. Santoro G, Gaio G, Palladino MT, et al. Stenting of the arterial duct in newborns with duct-dependent pulmonary circulation. *Heart*. 2008;94(7):925–929.
58. Alwi M, Mood MC. Stenting of lesions in patent ductus arteriosus with duct-dependent pulmonary blood flow: focus on case selection, techniques and outcome. *Interv Cardiol Clin*. 2013;2(1):93–113.
59. Schranz D, Michel-Behnke I, Heyer R, et al. Stent implantation of the arterial duct in newborns with a truly duct-dependent pulmonary circulation: a single-center experience with emphasis on aspects of the interventional technique. *J Interv Cardiol*. 2010;23(6):581–588.
60. Raval A, Thakkar B, Madan T, et al. Ductus arteriosus stenting: a promising percutaneous palliation in patients with duct-dependent pulmonary circulation. *Rev Port Cardiol*. 2016;35(11):583–592.
61. Hahn E, Vincent JA, Kadenhe-Chiweshe A, Ratner V, Krishnamurthy G. Emergent transcatheter relief of bronchus compression by an ectatic ductus arteriosus in a premature neonate: a case report. *J Neonatal Perinatal Med*. 2013;6(4):349–353.
62. Smith CL, Saul D, Goldfarb SB, Biko DM, O'Byrne ML. Compression of the left mainstem bronchus by patent ductus arteriosus in neonates under consideration for ductal stenting. *Catheter Cardiovasc Interv*. 2020;95(6):1158–1162.
63. Zayed WM, Bhandari K, Guyon PW, et al. Bronchus compression relieved by patent ductus arteriosus stenting. *Catheter Cardiovasc Interv*. 2020;96(7):1434–1438.
64. Matter M, Almarsafawey H, Hafez M, Attia G, Abuelkheir MM. Patent ductus arteriosus stenting in complex congenital heart disease: early and midterm results for a single-center experience at children hospital, Mansoura, Egypt. *Pediatr Cardiol*. 2013;34(5):1100–1106.
65. Sivakumar K, Bhagyavathy A, Coelho R, Satish R, Krishnan P. Longevity of neonatal ductal stenting for congenital heart diseases with duct-dependent pulmonary circulation. *Congenit Heart Dis*. 2012;7(6):526–533.