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# Advancements in Transcatheter Interventions for Cyanotic Patients with Duct-Dependent and MBT Shunt-Dependent Pulmonary Circulation

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3) **Mini N,** Zartner PA and Schneider MBE (2024) Transcatheter dilation and stenting of the modified Blalock-Taussig shunt in cyanotic heart diseases: points to consider. A single-center experience. *Front. Cardiovasc. Med.* 11:1445987. doi: 10.3389/fcvm.2024.1445987 *(JIF 2.8)*
4) **Mini N**, Schneider MBE, Mikus M (2024) Transcatheter Intervention of Modified Blalock-Taussig Shunts in Patients with Hypoplastic Left Heart Syndrome Undergoing Stage 1 Palliation. Front. Cardiovasc. Med. 11: 1502801 doi: 10.3389/fcvm.2024.1502801 *(JIF 2.8)*

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*To my beloved family…*

# 1. Abbreviations

CHD: congenital heart disease

CCHD: cyanotic conginital heart disease

TOF: tetralogy of Fallot

MBTS: modified Blalock-Taussig shunt

PA: pulmonary atresia

DDPC: duct-dependent pulmonary circulation.

PDA: patent ductus arteriosus

ECMO: extracorporeal membrane oxygenation

DS: duct stenting

HLHS: hypoplastic left heart syndrome

NP: Norwood palliation

DCI: ductal curvature index

RVDCC: right ventricular dependent coronary circulation

RVOT: right ventricular outflow tract

PA-IVS: pulmonary atresia with intact ventricular septum

# 2. Introduction

Congenital heart disease (CHD) is one of the most common congenital disorders, affecting approximately 0.8% to 1.2% of live births worldwide (Bouma et al., 2017; van der Linde, 2011). Despite significant advancements in cardiovascular medicine and surgery over the past few decades, which have dramatically reduced mortality and allowed most patients to survive into adulthood, CHD remains the leading cause of death from birth defects and contributes to a significant global disease burden (Liu et al., 2019; van der Bom et al., 2011; Global et al., 2017).

CHD can be classified into cyanotic and non-cyanotic types. Cyanotic CHD (CCHD) involves defects that reduce blood flow to the pulmonary arteries, leading to decreased oxygen delivery to the body. CCHD encompasses structural abnormalities in the heart or great vessels that result in systemic venous blood mixing with arterial circulation. CCHD can be divided into:

- **Group 1**: Malformations of right-sided valves, including tricuspid atresia, severe tricuspid stenosis, pulmonary atresia, and severe pulmonary stenosis.
- **Group 2**: Malformations originating from the great vessels, such as dextro-transposition of the great arteries (dTGA).
- There are also other complex malformations, including anomalous pulmonary or systemic venous connections; hypoplastic left heart syndrome, single ventricle anomalies, and positional abnormalities of the heart, such as dextrocardia or levocardia, including asplenic syndromes.

It's important to note that cyanosis can occur in some patients with large, untreated ventricular septal defects, atrial septal defects, or patent ductus arteriosus due to the reversal of left-to-right shunting caused by increased pulmonary vascular pressure or resistance. Eisenmenger’s syndrome describes this phenomenon, where an untreated congenital cardiac defect with intracardiac communication leads to pulmonary hypertension, reversal of blood flow, and cyanosis (Wood, 1958; Diller et al., 2007). This condition represents a progressive, irreversible pulmonary vascular disease with shunt reversal.

In early childhood, cyanosis due to Eisenmenger syndrome is rare, as the progression of pulmonary vascular obstructive disease is slow and usually does not become apparent until after the first decade of life.

For children born with CCHD, surgical or interventional palliation is often necessary in the neonatal period to manage symptoms and cyanosis. Surgical approaches include creating a pulmonary-to-systemic shunt to ensure adequate pulmonary perfusion, though this procedure is associated with high morbidity and mortality. Early or partial repairs of certain CCHD types, such as Tetralogy of Fallot, total anomalous pulmonary venous drainage, pulmonary atresia with ventricular septal defect, and dTGA, have shown satisfactory outcomes (Martin et al., 2018).

Despite advancements in surgical techniques, not all CCHD cases are operable due to factors such as prematurity, low birth weight, or the infant's medical condition (Alsoufi et al., 2014). Transcatheter palliation has emerged as a pivotal strategy in the management of cyanotic congenital heart defects (CCHD) in newborns and infants under one year of age (Meliota et al., 2023; Khalil et al., 2019). These heart defects, which compromise the oxygenation of blood and lead to cyanosis, require timely interventions to ensure survival and improve long-term outcomes. In this vulnerable population, early palliative measures are often necessary to stabilize patients before they are eligible for more definitive surgical repair. Historically, surgical palliation such as the modified Blalock-Taussig shunt (MBTS) has been the standard of care, but over the past few decades, transcatheter interventions have gained significant traction as a less invasive alternative.

Transcatheter techniques, including ductal stenting and balloon valvuloplasty, offer several advantages in the neonatal period and in infants who are too fragile for early surgery. These catheter-based approaches can be repeated, if necessary, avoid the need for cardiopulmonary bypass, and typically result in shorter recovery times. By improving pulmonary blood flow or relieving obstructive lesions, transcatheter palliation can alleviate cyanosis and allow for better systemic oxygenation, acting as a bridge to later surgical interventions such as complete repair or staged procedures (e.g., Glenn or Fontan).

One of the primary goals of transcatheter palliation is to maintain or restore adequate pulmonary perfusion, especially in cases where pulmonary blood flow is duct-dependent, as seen in conditions like pulmonary atresia (PA) or tetralogy of Fallot

(TOF). Ductal stenting, for instance, has become a favored option in many centers for maintaining patency of the ductus arteriosus, particularly in neonates with duct-dependent pulmonary circulation (DDPC). Balloon valvuloplasty, on the other hand, is frequently used to address severe pulmonary or aortic stenosis, providing relief of obstruction without the need for open-heart surgery

Despite its advantages, transcatheter palliation in neonates and infants presents its own set of challenges (Barry OM et al., 2022; Giordano et al., 2020; Alakhfash et al., 2020; Vitiello R et al., 1998.). Factors such as patient size, the complexity of the underlying anatomy, and the presence of associated syndromes or genetic conditions can impact the success and safety of these procedures. For example, stenting tortuous or highly curved ducts remains technically demanding, and procedural complications, such as stent migration or restenosis, may require additional interventions. As a result, patient selection and careful planning are critical to achieving optimal outcomes.

This manuscript aims to explore the current role of transcatheter palliation in cyanotic congenital heart defects in newborns and infants under one year of age. It will review the most commonly performed procedures, evaluate their safety and efficacy, and discuss emerging techniques and technologies that may further improve care for this high-risk population. Through a comprehensive analysis of clinical outcomes and procedural innovations, we seek to highlight the evolving landscape of transcatheter therapies and their impact on the management of CCHD in early life.

### 2.1. Transcatheter palliation in duct-dependent pulmonary circulation

Transcatheter palliation has emerged as a critical intervention for managing cyanotic infants with DDPC. In this condition, the pulmonary blood flow relies on a patent ductus arteriosus (PDA) to maintain oxygenation. Infants with DDPC typically present with severe cyanosis due to restricted blood flow to the lungs, which can arise from various CHDs such as PA, TOF, and other forms of right ventricular outflow tract obstruction (RVOTO). In these infants, maintaining ductal patency is essential to ensure adequate pulmonary perfusion and oxygenation until more definitive surgical procedures can be performed.

Historically, surgical palliation, particularly the MBTS, has been the standard approach to increase pulmonary blood flow in these patients. However, transcatheter interventions have gained traction over the past two decades as a less invasive and more flexible alternative. Ductal stenting, in particular, has become a popular strategy for maintaining or re-establishing PDA patency in neonates with DDPC, avoiding the need for early thoracotomy and cardiopulmonary bypass. Additionally, balloon valvuloplasty is often utilized to relieve obstructive lesions in cases of severe pulmonary valve stenosis or atresia, further enhancing pulmonary flow.

Over the past few decades, multiple studies have demonstrated the safety and efficacy of PDA stenting as an alternative to surgically creating a MBTS. Stenting offers several benefits, including avoiding thoracotomy, reducing postoperative complications, and preventing asymmetrical development of the pulmonary arteries. Additionally, it lowers the mortality rate and decreases the need for extracorporeal membrane oxygenation (ECMO) (Schranz et al., 2010; Glatz et a., 2018; Alwi et a., 2004).

Despite the introduction of advanced coronary stents, such as drug-eluting stents designed to minimize in-stent stenosis and prolong stent patency, stenting ducts with increased tortuosity—mainly when associated with pulmonary stenosis—remains challenging and carries significant risks (Alwi et al., 2013; Qureshi et al., 2019).

While duct stenting (DS) has become an important alternative to surgical shunts in patients with DDPC, not all ducts are suitable for stenting, and not all interventions with DS lead to favorable outcomes. Stenting tortuous ducts is associated with a higher risk of complications, including early in-stent thrombosis and stent failure. In these situations, surgical interventions may offer better outcomes compared to DS.

Qureshi et al. developed a ductal classification system based on duct tortuosity, showing that patients with highly tortuous ducts had an increased need for PDA stent re-intervention and pulmonary arterioplasty. However, no studies have identified a clear-cut threshold for ductal morphology that could define high-risk patients who may not respond well to stenting. A clinical index would be crucial for predicting outcomes and guiding treatment decisions.

## 2.2. Transcatheter palliation in MBTS-dependent pulmonary circulation

The MBTS, a synthetic tube graft made of polytetrafluoroethylene (PTFE; Gore-Tex), is frequently employed as a palliative surgical procedure in congenital heart disease. It establishes adequate pulmonary perfusion by creating a connection between the subclavian artery or brachiocephalic trunk and the pulmonary arteries. MBTS plays a crucial role in the management of patients with HLHS who have undergone Norwood palliation (NP), as well as in those with PA, severe pulmonary stenosis, and tricuspid atresia, particularly when interventional options are challenging. Despite its widespread use, MBTS is associated with significant morbidity and mortality (Fenton et al., 2003; Headrick et al., 2022).

Transcatheter palliation has become an essential tool in managing complications that arise in infants with complex congenital heart defects, particularly those undergoing staged surgical palliation, such as the NP for HLHS and similar conditions like PA (Ligon et al., 2017; Moszura et al., 2009).

The MBTS is frequently employed as a crucial component of the NP to ensure adequate pulmonary blood flow. However, stenosis or narrowing of the MBTS is a common complication in these patients, leading to compromised pulmonary perfusion, increased cyanosis, and hemodynamic instability (Wells et al., 2004; Vaughn et al., 2015). In such high-risk patients, prompt intervention is necessary to relieve the obstruction and restore sufficient oxygenation.

Traditionally, surgical revision of a stenosed MBTS has been the approach of choice. However, it carries significant risks for these fragile neonates, who are often still recovering from the initial NP. Transcatheter palliation, specifically balloon angioplasty or stenting of the stenosed MBTS, has emerged as a minimally invasive alternative that can provide immediate relief without the need for reoperation. By avoiding the additional trauma of a second surgery and cardiopulmonary bypass, transcatheter techniques offer a safer, quicker, and repeatable solution to address MBTS stenosis, allowing the patient to continue progressing through the staged palliation process.

Maintaining optimal pulmonary blood flow is critical in patients with HLHS or PA to ensure adequate systemic oxygen delivery and prevent heart failure or other life-threatening complications. Stenosis of the MBTS can significantly reduce the shunt's efficacy, increasing right ventricular pressure, worsening cyanosis, and impairing overall systemic circulation. The transcatheter approach can restore the shunt patency, improve oxygenation, and stabilize the patient.

Studies have reported that 34% of MBTS patients exhibit luminal narrowing, and 0.2% experience significant (>50%) stenosis during elective shunt takedown (Wells et al., 2004). These complications can range from mild to life-threatening and often necessitate emergent interventions to restore shunt patency and ensure adequate pulmonary perfusion. Although many studies have explored the physiology of MBTS and demonstrated the safety and efficacy of interventions on the shunt, complications such as cardiac tamponade, catheter-induced atrioventricular block, thromboembolic events, arrhythmias, and vascular access damage have been reported (Vaughn et al., 2004; Bonnet et al., 2015) .

In our text, we aim to review our experience in shunt intervention, the intervention technique, and the outcome of shunt stenting in our cohort and to focus on the essential points we have learned regarding intervention on MBTS especially in those underwent NP.

### 2.3. Objective

The following chapters present the findings of four retrospective clinical studies that evaluate the effectiveness of transcatheter strategies for managing cyanosis in newborns and infants under six months of age. The focus is on patients with DDPC and those with MBTS-dependent pulmonary circulation, including patients with PA who require a shunt to ensure adequate pulmonary perfusion and those with HLHS who underwent MBTS as part of NP.

The first study focuses on the outcomes of ductal stenting in newborns with PA and DDPC, evaluating the safety and efficacy of the intervention as an alternative to surgical options. Additionally, it seeks to establish, for the first time, whether a quantitative curvature threshold can aid in risk stratification for ductal stenting in

DDPC patients (Mini et al., 2021). Data on ductal curvature index (DCI) in this context has not been evaluated until now

Since no data existed comparing the outcomes of DS and MBTS in patients with PA and increased ductal tortuosity, as well as in those with pulmonary atresia with intact ventricular septum (PA-IVS) and right ventricle-dependent coronary circulation (RVDCC), the second study is the first to evaluate the outcomes of these two procedures in high-risk patients with a DCI greater than 0.45 (Mini et al., 2022).

The third study explores the techniques and outcomes of interventional dilation and stenting of the stenosed and abstructed MBTS in patients with pulmonary atresia and those with HLHS for alleviating cyanosis at our center, offering a detailed overview of our practices over the past four years.

The fourth study examines the risk factors linked to this intervention in critically ill patients with HLHS who underwent NP and subsequently required shunt intervention during the same period. This study specifically addresses the associated morbidity that could adversely affect the outcomes of the intervention in this vulnerable cohort

# 3. Results

### 3.1. Use of the ductal curvature index to assess the risk of ductal stenting in patients with duct dependent pulmonary circulation

Mini N, Schneider MBE, Zartner PA. Use of the ductal curvature index to assess the risk of ductal stenting in patients with duct-dependent pulmonary circulation. Transl Pediatr 2021;10(5):1307-1316. doi: 10.21037/tp-21-17 *(JIF 4.047)*

Background and objective**:** This study aims to assess whether a quantitative curvature threshold, the ductal curvature index (DCI), can aid in risk stratification for ductal stenting in patients with duct-dependent pulmonary circulation (DDPC).

Methods**:** This retrospective cohort analysis focused on 71 patients with PA and DDPC who underwent PDA stenting between January 2011 and October 2019. The study aimed to evaluate the impact of duct morphology on stent outcomes, excluding patients with MAPCAs or pulmonary stenosis. The DCI was calculated for each patient, and ducts were categorized into four classes based on DCI quartile thresholds: class I (≤0.12), class II (0.13–0.33), class III (0.34–0.44), and class IV (≥0.45). The primary outcome was defined as being free from the following: (I) procedure-related death, (II) the need for unplanned surgery, (III) the need for unplanned pulmonary valve perforation (PVP) with stent placement in the right ventricular outflow tract (RVOT), and (IV) procedure-related permanent complications. Additionally, pulmonary artery growth was assessed using indices such as TLLI, Nakata, and McGoon before the next planned surgery or intervention.

Results**:** In class IV (DCI ≥0.45), 80% of patients failed to achieve the primary outcome, with an odds ratio (OR) of 9 (95% confidence interval [CI]: 3.7–21.4), compared to 26.6% in classes with DCI <0.45. Additionally, 66.7% of class IV patients required unplanned surgery or PVP with RVOT stent, OR 12.4 (95% CI: 4–39). Major complications were predominantly observed in class IV (80%, P<0.01), and the need for pulmonary arterioplasty was significantly higher in class IV at 53.3%, OR 3.3 (95% CI: 1.5–7.1).

Conclusions**:** Ducts with a high ductal curvature index are associated with significant complications and an increased risk of stent failure compared to those with a lower

curvature index. This study suggests that establishing a clinical cut-off based on ductal curvature severity could help identify high-risk patients, for whom duct stenting may be insufficient to bridge them to the next planned surgery or intervention. The findings indicate that patients with a DCI ≥0.45 represent a high-risk group with poor stenting outcomes, while those with a DCI below 0.45—comprising 75% of the cohort—showed highly satisfactory outcomes.

The DCI may be an essential tool in clinical decision-making for patients with highly tortuous ducts. Specifically, those with severe ductal tortuosity (DCI >0.45) accounted for over 75% of cases requiring unplanned surgery or pulmonary valve perforation (PVP) with RVOT stenting due to inadequate pulmonary perfusion. Nearly half of those requiring pulmonary arterioplasty for duct-associated pulmonary stenosis were in this group. Ducts with a high DCI often required in-stent reintervention due to restenosis caused by thrombogenesis and remodelling. Survival analysis showed a rapid deterioration in patients with a DCI >0.45, while those with lower DCI values had better survival rates. Thrombophilia screening is highly recommended for high-risk patients to minimize thrombotic complication. A prospective study is needed to confirm these results and assess whether this curvature-based classification can be applied to other patient cohorts.

Original Article

# Use of the ductal curvature index to assess the risk of ductal stenting in patients with duct-dependent pulmonary circulation

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**Background:** To evaluate whether a quantitative curvature threshold can contribute to risk stratification of ductal stenting in patients with a duct-dependent pulmonary circulation (DDPC).

**Methods:** A single-center retrospective analysis was performed. The ductal curvature index (DCI) was calculated in 71 patients with DDPC. The ducts were divided into four classes based on quartile thresholds of DCI: class I (≤0.12), class II (0.13–0.33), class III (0.34–0.44), and class IV (≥0.45). The primary outcome of this study was defined as free from all of the following: (I) intervention related death, (II) need of unplanned surgery (III) need of unplanned pulmonary valve (PV) perforation with stent in right ventricular outflow tract (RVOT), and (IV) intervention related permanent complications.

**Results:** Eighty percent of patients in class IV (DCI ≥0.45) failed to achieve the primary outcome; odds ratio (OR) 9 and 95% confidence interval (CI): 3.7–21.4 compared to 26.6% in all classes with DCI <0.45. 66.7% of these patients needed unplanned surgery or PVP with RVOT stent; OR 12.4 (95% CI: 4–39). 80% of major complications were observed in class IV (P<0.01). Need of pulmonary arterioplasty was in class IV 53.3%; OR 3.3 (95% CI: 1.5–7.1).

**Conclusions:** DCI can be useful to guide the clinical decision-making in patients with torqued ducts. Patients with a DCI ≥0.45 belong to a high-risk group, in which ductal stenting is associated with an elevated risk for early surgery or unplanned re-intervention.

**Keywords:** Pulmonary atresia; ductus arteriosus; ductal stenting; pulmonary perfusion and ductal curvature index

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## Introduction

All patients with a duct-dependent pulmonary circulation (DDPC) need an adequate pulmonary perfusion for survival. Although surgical techniques have advanced significantly in recent years (1), some biventricular heart diseases with DDPC remain unamenable to be corrected in the neonatal period due to variable reasons (2-5). Such cardiac defects and all other DDPC with a single ventricle require a palliative procedure to ensure a sufficient pulmonary perfusion until the next planned operation. Either a surgical creation of an aorta- pulmonary shunt or an interventional PDA stenting will be required for bridging to the next surgery. Multiple studies in the last decades have demonstrated safety and efficacy of duct stenting as an alternative to a surgical creation of modified Blalock-Taussig Shunt (mBT Shunt) (6-8). Stenting can spare

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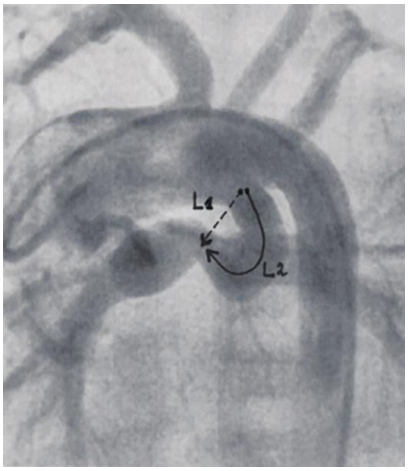


**Figure 1** Demonstration of the two measured distances used to calculate the ductal curvature index. L1 represents the straight short distance between duct origin from aorta and duct insertion onto pulmonary arteries (PA). L2 represents the entire length of the duct between the aortic origin and the insertion of the duct onto PA.

patients the need for thoracotomy and reduce postoperative complications as well as asymmetrical development of pulmonary arteries. Additionally, it reduces the mortality rate and the need for extracorporeal membrane oxygenation (ECMO) (9-13). Despite the new developments in the field of coronary stents and the introduction of drug eluting stents that minimise in-stent stenosis and prolong the stent patency (12,14), stenting of ducts with increased tortuosity ,especially when associated with pulmonary stenosis, is still challenging and fraught with risks (15-17).

Qureshi el al used a ductal classification scheme based on the tortuosity of the duct and found that patients with the highest tortuosity had increased the need of PDA stent re-intervention and pulmonary arterioplasty (18). No studies to date, however, have identified a ductal morphology index with a clear-cut threshold that defines patients with high risk who may not respond favourably to stenting. Such a clinical index would be essential to provide a predive ability and guide the management decisions.

In search of a clearly defined threshold value that could mark the risk of an inappropriate PDA stent, we tried, as part of this retrospective cohort analysis, to first create a quantitative ductal morphology index and, second, to examine whether the risk for complications and/or unplanned re-interventions can be estimated through this particular threshold.

We present the study in accordance with the STROBE reporting checklist (available at: http://dx.doi.org/10.21037/tp-21-17).

## Methods

This is a single-center retrospective cohort analysis. All our consecutive patients with pulmonary atresia (PA) and DDPC undergoing PDA-stenting between Jan. 2011 and Oct. 2019 were recruited to evaluate the impact of their duct morphology on the stent outcome (diagnoses summarized in *Table 1*). Patients with PA and major aorta pulmonary collateral Arteries (MAPCAs) were excluded from the analysis as well as patients with pulmonary stenosis (PS) who have significant antegrade pulmonary perfusion.

The primary endpoint of this study was a composite outcome defined as free from all of following: (I) intervention related death, (II) need of unplanned surgery (III) need of unplanned PV-perforation (PVP) with RVOT-stent, and (IV) intervention related permanent complications. The occurrence of one or more of the endpoints was defined as an impaired outcome. DCI was calculated in all ducts using the following formula, which was adopted from a previous study (18): DCI = (L2-L1)/L2, where L1 represents the straight short distance between duct origin from aorta and duct insertion onto pulmonary arteries. L2 represents the entire length of the duct between the aortic origin and the insertion of the duct onto pulmonary arteries (*Figure 1*). The two measurements were documented in millimetres. To optimize L2 measurement, especially in ducts with looping, multiple projections were analyzed including anterior-posterior (AP), left anterior oblique (LAO), and right anterior oblique (RAO) views with cranial and caudal angulation. The L2 was then measured using the best projection which best demonstrated the entire duct and its multiple complex turns.

The lower, median, and upper quartile values of the DCI in this patient cohort were used to classify the ducts into the following four classes: class I (≤ 0.12), class II (0.13–0.33), class III (0.34–0.44), and class IV (≥0.45) (*Figure 2*).

Associated pulmonary arterial stenosis (PAS) was documented. Total lower lobe index (TLLI), Nakata index and McGoon index were used as pulmonary parameters to estimate the growth of pulmonary arteries at closest time before the next planned surgery or intervention.

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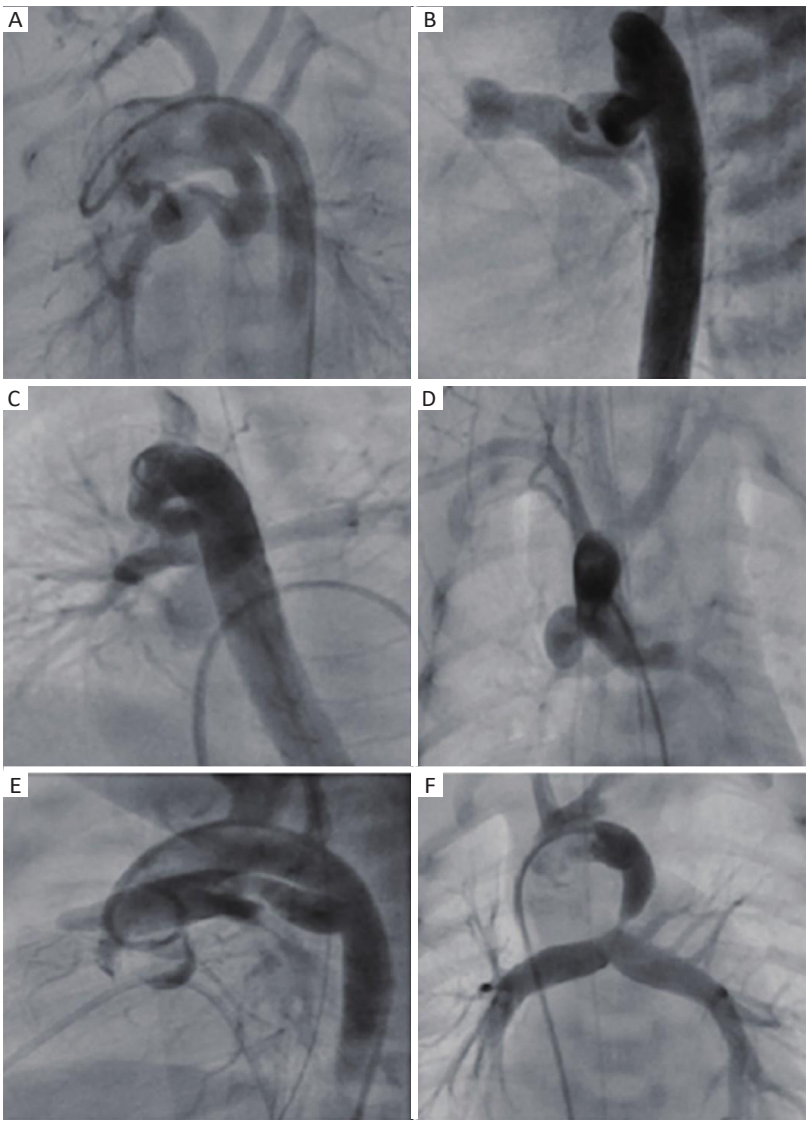


**Figure 2** Demonstration of various ductal classes from the study patients. (A) Class III with ductal origin from underside of aortic arch; (B) class IV with origin from descending aorta; (C and D) class IV with ductal origin from underside of aortic arch; (E) class I with origin from descending aorta; (F) class II with origin from left brachiocephalic trunk.

### *Statistical analysis*

All statistical analyses were performed using SPSS version 22. Continuous variables were reported as means ± standard deviations (SD), and categorical variables as count (percentage). Non-paired Student's *t*-test was used to compare the means of continuous variables between

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the four different ductal morphology classes, while paired *t*-test was applied for comparing the means of pulmonary parameters before and after PDA stenting for the whole cohort. Chi square test was used for comparing categorical variables.

Odds ratios (ORs) ± 95% confidence intervals (95% CI) for the following parameters were calculated to assess any differences between the four ductal morphology classes: failure of stent-dependent survival (impaired outcome), need for PA arterioplasty, and need for unplanned surgery or RVOT-stent. A P value of 0.05 was set as the threshold for clinical significance. Kaplan-Meier survival curve of the four different classification classes was performed. The survival was defined according to the primary outcome i.e., arrival at the next planned surgery without death, permanent complications, or unplanned surgery/unplanned re-intervention in RVOT.

### *Ethical statement*

The study complies with the Declaration of Helsinki (as revised in 2013). Owing to the purely retrospective study design, using available institutional clinical records, with an absence of impact on management of the patients included and completely anonymous data presentation, informed consent of the subjects (or their parents) and ethical approval have not been obtained.

## Results

A total of 96 stents were implanted in 71 ducts for patients with DDPC. All stents were bare metal stents (BMS). The stenting was performed retrograde in 59 (83.09%) and antegrade in 12 (16.91%) patients. At the intervention, mean weight was 3.3 kg (SD 0.68), median 3.2, range 3.2 (2–5 kg). Mean body surface area (BSA) was 0.20 $m^2$ (SD 0.028), median 0.2, range 0.14 $m^2$ (0.14–0.18). Mean age was 18 days (SD 23.18) median 7 (range, 1–120 days).

No significant differences were found between the ductal morphology class and any of the following: hospital deaths, vascular access, and number of stents (P>0.05). Statistically significant differences were identified between the four classes in each of the following: primary outcome, need of unplanned surgery or unplanned PV-perforation/RVOT-stent due to stent related inadequate pulmonary perfusion, pulmonary arterioplasty, origin of duct and in-stent re-intervention with P value <0.05 (*Table 1*).

### *Mortality and complications*

No intervention-related mortality was reported in the catheterisation laboratory. Three hospital deaths (4.22%) were reported 1, 7 and 47 days after the intervention (2 patients with class II, one with class IV). The first one was born in preterm twin pregnancy (30 gestational age) and died due to a septic shock. The second patient required an unplanned stent implantation in RVOT one week after duct stenting due to low oxygen saturation. Following the procedure, the patient was decompensated and died on ECMO. The third was born in preterm twin pregnancy (33 gestational age) and died in the intensive care unit (ICU) due to infant respiratory distress syndrome (IRDS) and multi-organ failure before reaching the next planned surgery. Five major complications (7.04%) were reported; four in class IV and one in class I (*Table 2*). One patient had intervention-related permanent complications. This patient belonged to class IV and developed severe chronic neurologic complications associated with severe motoric retardation (*Table 2*). An impaired thrombophilia screening was reported in 40% of patients with in-stent thrombotic events. Three patients needed an emergency surgical shunt in the catheterisation laboratory during an in-stent re-intervention. Complete occlusion of the stent occurred while attempting to recanalize the stent in all of these patients; one of them needed ECMO.

### *Primary and secondary outcome results*

The primary outcome in this study, defined earlier in the methods, was achieved in the majority of patients with DCI <0.45 (in class I, II, and III with 100%, 84.2%, and 94.4% success rate respectively) compared to only 20% of those with DCI ≥0.45 in class IV in which patients had very high risk of failure, odds ratio (OR) of 9 and 95% confidence interval (CI): 3.7–21.4. Need for unplanned surgery/PVP with RVOT-stent due to stent related insufficient pulmonary perfusion was reported in 13 patients, 10 (77%) of which from class IV with OR 12.4 (95% CI: 4–39), 2 (15.3%) from class II, and one (7.7%) from class III (*Tables 1,3*). A total of 9 patients (43.6%) needed unplanned in-stent re-intervention (5 of them in class IV and 2 in III and II respectively). Need of pulmonary arterioplasty due to duct associated pulmonary stenosis was observed in 18 patients (25.3% of total); eight in class IV with OR 3.3 (95% CI: 1.5–7.1), six in class III, three in class II, and one in class I. Fifty-six patients completed the next planned procedure: 51.8% univentricular and 48.2% biventricular. Pulmonary parameters showed significant

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**Table 1** Summarize of diagnosis, PDA characteristic and outcome in cohort study

| | Percentage | Class I | Class II | Class III | Class IV | P |
|---|---|---|---|---|---|---|
| Diagnosis | | | | | | |
| PA-IVS | 10 (14.1%) | 0 | 4 (40%) | 3 (30%) | 3 (30%) | |
| Critical PS-IVS | 12 (16.9%) | 10 (83.3%) | 2 (16.4%) | 0 | 0 | |
| PA-VSD | 49 (69%) | 9 (18.5) | 13 (26.5%) | 15 (30.6%) | 12 (24.4%) | |
| Origin of duct | | | | | | 0.0001* |
| Descending of aorta | 40 (56.4%) | 17 (89.4%) | 12 (63.1%) | 8 (44.5%) | 2 (13.3%) | |
| Underside of aortic arch | 22 (30.9%) | 1 (5.3%) | 4 (21.1%) | 6 (33.3%) | 12 (80%) | |
| Brachiocephalic trunk | 9 (12.7%) | 1 (5.3%) | 3 (15.8%) | 4 (22.2) | 1 (6.7%) | |
| Need for PA arterioplasty | 17 (23.9%) | 1 (5.2%) | 2 (10.5%) | 6 (33.3%) | 8 (53.3%) | 0.023* |
| Number of stents | | | | | | 0.195 |
| 1 Stent | 52 (73.3%) | 16 (84.2%) | 14 (73.7%) | 13 (72.2%) | 9 (60%) | |
| 2 Stents | 14 (19.7%) | 1 (5.3%) | 4 (21%) | 3 (16.7%) | 6 (40%) | |
| 3 Stents | 4 (5.6%) | 2 (10.5%) | 0 | 2 (11.1%) | 0 | |
| 4 Stents | 1 (1.4%) | 0 | 1 (5.3%) | 0 | 0 | |
| Vascular access | | | | | | 0.093 |
| Femoral artery | 46 (64.8%) | 12 (63.1%) | 15 (79%) | 9 (50%) | 10 (66.7%) | |
| Femoral vein | 12 (16.9%) | 6 (31.6%) | 2 (10.5%) | 4 (22.2%) | 0 | |
| Axillary artery | 8 (11.3%) | 1 (5.3%) | 2 (10.5%) | 2 (11.1%) | 3 (20%) | |
| Carotid artery | 5 (7%) | 0 | 0 | 3 (16.7%) | 2 (13.3%) | |
| Major complications | 5 (7.04%) | 1 (5.3%) | 0 | 0 | 4 (26.7%) | 0.008* |
| Permanent complications | 2 (2.8%) | 0 | 0 | 0 | 1 (6.7%) | |
| Unplanned surgery/PVP | | | | | | 0.0001* |
| MBT shunt | 9 (12.7%) | 0 | 1 (5.3%) | 0 | 8 (53.3%) | |
| Early repair | 2 (2.8%) | 0 | 0 | 1[§] (5.6%) | 1[^] (6.7%) | |
| PVP+RVOT-stent | 2 (2.8%) | 0 | 1[†] (5.3%) | 0 | 1 (6.7%) | |
| Mortality | | | | | | 0.29 |
| Hospital | 3 (4.2%) | 0 | 2[†] (10.5%) | 0 | 1 (6.7%) | |
| Late (after surgery) | 4 (5.6%) | 0 | 0 | 1[§] (5.6%) | 3[^] (20%) | |
| Outcome | | | | | | 0.0001* |
| Primary outcome | 54 (77.5.1%) | 19 (100%) | 16 (84.2%) | 17 (94.4%) | 3 (20%) | |
| Impaired outcome | 16 (22.5%) | 0 | 3 (15.8%) | 1 (5.6%) | 12 (80%) | |

PA, pulmonary atresia; IVS, intact ventricular septum; VSD, ventricular septum defect; LPA, left pulmonary artery; RPA, right pulmonary artery. MBT Shunt: modified Blalock Taussig Shunt. PVP: pulmonary valve perforation. RVOT: right ventricular outflow tract, *P value <0.05 significant. [§]the same patient. [†]the same patient. [^]the same patient.

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**Table 2** Intervention related Major complications

| | Patient 1 | Patient 2 | Patient 3 | Patient 4 | Patient 5 |
|---|---|---|---|---|---|
| Diagnosis | PA-VSD | PA-VSD | PA-VSD | PA-VSD | PA-IVS |
| Origin of duct | Underside of a.a. | DAO | Underside of a.a. | TBC | Underside of a.a |
| Vascular access | Fem. A | Fem. A | axil. A | Fem. A | axil. A |
| DCI | 0.62 (IV) | 0 (I) | 0.54 (IV) | 0.52 (IV) | 0.62 (IV) |
| Complications | S. Thrombosis | S. Thrombosis | Vessel damage | S. Thrombosis | S. Thrombosis |
| Thrombophilia screen | FFVLM | FFVLM | Not tested | Not tested | Not tested |
| Outcome | MBT shunt | Glenn | Retardation | MBT shunt | MBT shunt |

PA, pulmonary atresia; VSD, ventricular septum defect; IVS, intact ventricular septum; Underside of a.a., underside of aortic arch; DAO, descending aorta; TBC, truncus brachiocephalicus; DCI, ductal curvature index; axil. A, axillary artery; Fem. A, femoral artery; mBT, modified Blalock-Taussig shunt; S. Thrombosis, Stent thrombosis; FFVLM, familial factor V Leiden mutation.

**Table 3** Need of unplanned surgery/unplanned RVOT stent

| Patient | Stent in mm | Number of stents | Intervention | DCI | Class | Stent patency (days) |
|---|---|---|---|---|---|---|
| 1 | 4 | 1 | Early repair | 0.42 | III | 13 |
| 2 | 3.5 | 2 | PVP/RVOT-stent | 0.53 | IV | 7 |
| 3 | 4 | 1 | Shunt | 0.63 | IV | 71 |
| 4 | 3.5 | 1 | Shunt | 0.62 | IV | 0 |
| 5 | 3 | 1 | Shunt | 0.6 | IV | 30 |
| 6 | 3 | 1 | Shunt | 0.62 | IV | 77 |
| 7 | 4 | 2 | PVP/RVOT-stent | 0.18 | II | 12 |
| 8 | 4 | 1 | Early repair | 0.5 | IV | 16 |
| 9 | 4 | 2 | Shunt | 0.25 | II | 7 |
| 10 | 3.5 | 1 | Shunt | 0.57 | IV | 77 |
| 11 | 3.5 | 1 | Shunt | 0.5 | IV | 19 |
| 12 | 4 | 2 | Shunt | 0.52 | IV | 7 |
| 13 | 3.5 | 2 | Shunt | 0.5 | IV | 150 |

Stent in mm, stent in millimeter; PV-perforation, pulmonary valve perforation; DCI, ductal curvature index.

increases in all of the 56 patients in whom the next planned procedure was achieved. Nakata index improved from a mean of 171 before to 286 $mm^2/m^2$ after stenting, McGoon index from 1.5 to 2.7, and TLLI from 90 to 169 $mm^2/m^2$) ($P<0.001$).

## Discussion

Multiple formulas have been suggested to quantitatively measure the tortuosity of blood vessels in recent years (19) and this study adopted a formula of DCI that was previously used in a PDA-study (18). Calculating the DCI, we applied a ductal classification system on a cohort of patients with DDPC. The quartile approach was used to divide patients into four classes depending on their DCI-value, with the upper quartile threshold (DCI ≥0.45) defining class IV; the group with the highest curvature index.

### *High curvature index (class IV) and outcome*

While the majority of patients with DCI <0.45 achieved

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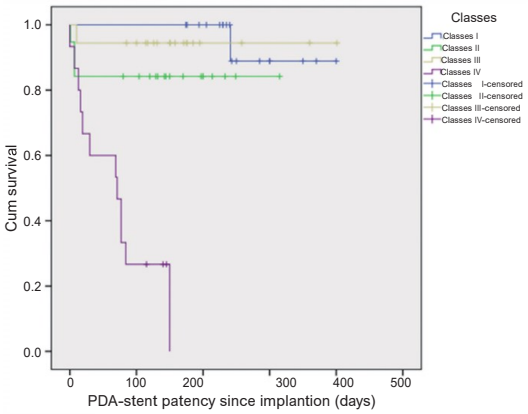


**Figure 3** Kaplan-Meier curve: Probability of stent-dependent survival. Compared with class IV which showed very low survival, patients with class I-III had a much better survival rates with the majority reaching their next planned surgery. PDA: patent ductus arteriosus.

the primary outcome, only 20% of patients with DCI ≥0.45 (class IV) achieved this endpoint in this study arriving uneventfully at their planned surgery. Class IV also, asymmetrically, represented more than 75% of all the cases that required unplanned surgery or unplanned PVP with RVOT-stent due to stent related inadequate pulmonary perfusion (*Table 3*). Additionally, almost half of all the patients requiring pulmonary arterioplasty due to duct associated pulmonary stenosis were found in class IV. Furthermore, all patients in this class needed either unplanned surgery/PVP and RVOT-stent or unplanned in-stent re-intervention. Early in coronary stent stenosis (ICS) and thrombosis, a phenomenon usually occurring in the elastic lamina, was highly observed in class IV of this cohort. Recoil and relocation of axially transmitted plaque have been suggested as potential causes of ICS (20,21). These two factors can be induced and speeded up by increased tortuosity, deployment of long stent, and stent deformation as well as stent overexpansion and under-expansion (22) The need for in-stent reintervention in the present study, which was more frequent in ducts with low curvature index, may be explained by in-stent restenosis, which can take place weeks or even months after the intervention due to thrombogenesis, neointima formation, and remodelling (20,21). We found that stent deformation and malposition were more often observed in patients whose ducts had increased DCI (class IV) making the in-stent reintervention a high-risk procedure in these patients.

The survival analysis demonstrated a clear and early dissociation between class IV and the rest of the classes with patients in the former group experiencing a sharp and mostly very acute outcome failure (*Figure 3*). Patients with DCI <0.45, however, had a much better survival rate with the majority reaching their next planned surgery.

Although some studies have demonstrated the safety and efficacy of duct stenting as an alternative to a surgical creation of mBT Shunt (8,23,24) very few have assessed the impact of ductal morphology on the duct stenting outcome (25,26). Qureshi *et al*. in 2019 described a new ductal morphological scheme based on ductal tortuosity classifying the ducts into three types: type I = straight, type II = one curve, and type III = multiple complex turns (18). Their results showed a significantly higher rate of pulmonary arterioplasty and unplanned reintervention in patients with type III. The latter observation is in agreement with the results of the present study that demonstrated a significantly greater need for pulmonary arterioplasy in patients with increased curvature Index (class IV). Comparison between the two cohorts was summarised in *Table 4*.

Although the mentioned study calculated the DCI and found it to be correlated with the tortuosity type, no cut-off values were provided for estimating the severity of the DCI in the previous report. In our cohort, we proposed a quantitative cut-off threshold (DCI ≥0.45) to estimate high-risk PDA-stenting.

Three-dimensional computed tomography (3D CT) and 3D echocardiography may offer more accurate calculation of the curvature index and should be considered in future studies.

A good understanding of the duct morphology and a correct selection of the best suitable vascular access based on the duct origin as well as the use of an appropriate soft-tipped guide-wire, which does not alter the ducts native course too much, but gives enough support to safely advance the stent [e.g., Mailman, comp], are essential to optimise the stenting outcome and minimize major complications. Also wire retraction is a critical moment, because of the soft ductal tissue. The use of a long sheath can help to stabilize the stent, while retrieving the wire.

It is also worth noting that a significant proportion of patients with thrombotic events in this cohort were found to have abnormal thrombophilic tests. Thrombophilia screening is, therefore, highly recommended prior to stenting to minimize thrombotic events especially in high

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**Table 4** Distribution of ductal morphology: ductal curvature index classification versus ductal tortuosity index scheme

| TI | DCI | | | | Total |
|---|---|---|---|---|---|
| | Class I | Class II | Class III | Class IV | |
| Type I | 19 (100%) | 0 | 0 | 0 | 19 |
| Type II | 0 | 19 (100%) | 17 (94.4%) | 3 (20%) | 39 |
| Type III | 0 | 0 | 1 (5.5%) | 12 (80%) | 13 |

TI, tortuosity index; DCI, ductal curvature index.

risk patients.

Limitations: as a retrospective observational study potentially important secondary outcome measures could not be fully assessed. The single-center data collection limits the total number of patients to be recruited and reflects the ambitions and experiences of only a small number of interventionalists. Additionally, all stents used in this cohort were bare metal stents (BMS) and the results may not be applicable to drug eluted stents.

## Conclusions

Ducts with a high ductal curvature index are associated with significant complications and are at higher risk to fail stenting compared to ducts with a lower curvature index. This study suggests that a clinical cut-off point based on the severity of ductal curvature may well identify high risk patients for stenting in whom the duct stenting may be insufficient to bridge them to the next planed surgery or intervention. The results indicate that class IV (DCI ≥0.45), represents a truly high-risk group of patients with unfavorable stenting outcome. In contrast, patients with curvature index lower than 0.45, which represents 75% of total cohort, have very satisfactory outcomes. A prospective study is needed to validate these results and see if the new curvature-based classification system can perform similarly in different cohorts.

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## Footnote

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*Ethical Statement:* The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study complies with the Declaration of Helsinki (as revised in 2013). Owing to the purely retrospective study design, using available institutional clinical records, with an absence of impact on management of the patients included and completely anonymous data presentation, informed consent of the subjects (or their parents) and ethical approval have not been obtained.

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### 3.2. Duct Stenting vs. modified Blalock-Taussig shunt: new insights Learned from high-risk patients with duct-dependent pulmonary Circulation

Mini N, Schneider MBE, Asfour B, Mikus M and Zartner PA (2022) Duct Stenting vs. Modified Blalock-Taussig Shunt: New Insights Learned From High-Risk Patients With Duct-Dependent Pulmonary Circulation. Front. Cardiovasc. Med. 9:933959. doi: 10.3389/fcvm.2022.933959 *(JIF 3.8)*

Background: Limited data compare the outcomes of modified Blalock-Taussig shunts (MBTs) versus ductal stenting (DS) in patients with pulmonary atresia (PA) and increased ductal tortuosity, as well as in those with pulmonary atresia and intact ventricular septum (PA-IVS) with right ventricle-dependent coronary circulation (RVDCC). This study aims to address this gap through a single-center retrospective evaluation.

Methods: Between 2010 and 2019, 127 patients with duct-dependent pulmonary circulation (DDPC) underwent either MBTs (without additional repairs) (n = 56) or DS (n = 71). The primary endpoint was defined as successfully progressing to the next planned surgery (Glenn or biventricular repair) while avoiding:

1. Unplanned surgery or unplanned pulmonary valve perforation (PVP) with stent placement.
2. Procedure-related permanent complications.
3. Death.

Two subgroups were analyzed: (1) patients with a ductal curvature index (DCI) >0.45 (n = 32) and (2) patients with PA-IVS and RVDCC (n = 13). DCI was used to assess ductal tortuosity, with patients having a DCI >0.45 classified as high-risk for DS. Previous research indicated that patients with a DCI <0.45 had better outcomes than those with a DCI >0.45.

Results: The primary outcome was achieved in 77.5% of the DS group and 75% of the MBTS group. However, hospital deaths, the need for ECMO, and major complications were more frequent in the MBTs group, with odds ratios (OR) of 5, 0.8, and 4, respectively, and 95% confidence intervals (CI) of 1.1–22.6, 0.7–0.9, and 1.6–10.3, respectively (P-value <0.05). Among the subgroups, 64% of patients with a DCI >0.45 who received MBTs achieved the primary outcome, compared to only 20% in the DS group (OR 3.5, 95% CI 1.2–10, P = 0.005). In patients with PA-IVS and

RVDCC, 74.1% of those who received DS achieved the primary outcome, while all patients receiving MBTs had impaired outcomes (OR 3.5, 95% CI 1–11.2, P = 0.004).

Conclusion: With low mortality and morbidity, DS offers a viable palliative alternative to MBT shunts for ensuring pulmonary blood flow in patients with PA and DDPC. Hospital mortality was higher in the MBT group (14.2%) compared to DS (2.8%), largely due to hemodynamic instability and complications like coronary artery steal. Although both groups required unplanned surgeries, major complications and ECMO needs were more frequent in the MBT group. DS supports the symmetrical growth of pulmonary arteries, but this benefit is less evident in cases with tortuous ducts and a DCI above 0.45. Contrary to previous studies, this research suggests that MBTs may be more suitable for patients with a DCI > 0.45, despite the higher hospital mortality in the MBT group. Notably, 57% of hospital deaths in the MBT group occurred in patients who underwent emergency DS and MBTs due to desaturation or acute ductal occlusion, indicating that ductal stent failure complicates subsequent MBTs. DS appears to be an effective and preferred palliative strategy for patients with PA-IVS and RVDCC, as it helps minimize intra- and postoperative ischemia, reduces the risk of ventricular arrhythmias, lowers hospital mortality, and decreases the need for ECMO.

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# Duct Stenting vs. Modified Blalock-Taussig Shunt: New Insights Learned From High-Risk Patients With Duct-Dependent Pulmonary Circulation

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Background: As no data were available on the comparison of outcomes between modified Blalock-Taussig shunts (MBTs) vs. duct-stenting (DS) in patients with pulmonary atresia (PA) and an increased ductal tortuosity and in patients with pulmonary atresia and intact septum (PA-IVS) with right ventricle-dependent coronary circulation (RVDCC), we aimed to perform a single-center retrospective evaluation.

Methods: Between 2010 and 2019, 127 patients with duct-dependent pulmonary circulation (DDPC) underwent either MBTs (without additional repairs) ($n$ = 56) or DS ($n$ = 71). The primary endpoint was defined as arriving at the next planned surgery (Glenn or biventricular repair) avoiding one of the following: (1) unplanned surgery or unplanned perforation of the pulmonary valve (PVP) with a stent, (2) procedure-related permanent complications, and (3) death. Two subgroups were considered: (1) patients who had a ductal curvature index (DCI) >0.45 ($n$ = 32) and (2) patients with PA-IVS and RVDCC ($n$ = 13). Ductal curvature index (DCI) was measured in all the patients to assess the tortuosity of the ducts. Patients with DCI >0.45 were considered as being in a high-risk group for the duct-stenting; a previous study showed that the patients with a DCI< 0.45 had a better outcome when compared with those with a DCI> 0.45.

Results: The primary outcome was achieved equally in the two groups (77.5% in DS, 75% in MBTs). Hospital deaths, need for ECMO, and the occurrence of major complications was more frequent in the group with MBTs with an Odds Ratio (OR) of 5, 0.8, and 4, respectively, and a 95% Confidence Interval (*CI*) 1.1–22.6, 0.7–0.9, and 1.6–10.3, respectively, and a $P$-value <0.05. For the two subgroups, the primary outcome was achieved in 64% of patients with a DCI >0.45 who received MBTs compared to 20% in those with DS (OR 3.5, 95% *CI* 1.2–10, $P$ 0.005). While 74.1% of the patients with PA-IVS and RVDCC after DS had achieved the primary outcome, all patients with MBTs had an impaired outcome (OR 3.5, 95%*CI* 1–11.2, $P$ 0.004).

Conclusion: MBTs showed a better outcome in patients with tortuous ducts compared to DS. DS seems to be superior in patients with DDPC with DCI <0.45 and patients with PA-IVS with RVDCC.

Keywords: duct stenting, mBT shunt, sinusoid blood flow, duct-dependent pulmonary circulation, ductal curvature index, tortuosity index, pulmonary atresia (PA)

## INTRODUCTION

In patients with pulmonary atresia (PA) and a duct-dependent pulmonary circulation maintaining pulmonary blood flow may be achieved either by the surgical creation of a modified Blalock Taussig shunt or the percutaneous ductal stenting. Although surgical techniques have advanced in recent years (1), achieving a biventricular repair with DDPC is still challenging in the neonatal period (2–5). The efficacy of DS as an alternative to MBTs has been documented in multiple studies (6, 7). The mortality rate, need for ECMO, and procedure-related complications were reported to be higher in the MBTs group compared to the DS group due to post-operative hemodynamic instability (8–10). Thus, in patients with PA and DDPC, the DS has become the preferred method of choice in some centers. However, no study has compared the outcome between the two procedures in patients with highly tortuous ducts in which the DS is challenging and the outcome can become inadequate. In an earlier study from 2021, (11) we were able to show that the patients with a ductus curvature index (DCI) above 0.45 belong to a high-risk group for proper stent placement, which resulted in inadequate palliation to the next planned operation. Data on the outcome of this high-risk group with MBTs is not published yet. So, we focused on this group as well as on the comparable complex group of the patients with PA and an intact ventricular septum with a coronary sinusoid to identify the preferable palliative procedure in these two groups.

## PATIENTS AND METHODS

We performed a single-center retrospective cohort analysis. All patients with PA and DDPC undergoing either DS (n = 71) or MBTs (without additional repair n = 56) between 2010 and 2019 were recruited and the outcome between DS and MBTs were compared. To evaluate the severity of ducts-tortuosity the ductal curvature index (DCI) was measured in all patients who received either diagnostic or interventional heart catheterization (n = 88). DCI was measured using the following formula adopted from a previous study (8): DCI = L2-L1/L2 (L1 represents the straight short distance between duct origin from the aorta and duct insertion onto pulmonary arteries, L2 represents the entire length of the duct between the aortic origin and the insertion of the duct onto PA.

Based on our previous study published in 2021 (9) high-risk patients for stenting were defined as patients having DCI equal or higher than 0.45.

**Abbreviations:** PDA, patent ductus arteriosus; DCI, ductal curvature index; PA, pulmonary atresia; CI, confidence interval; mBT shunt, modified blalock-taussig Shunt; RVDCC, right ventricle-dependent coronary circulation.

Additionally, two subgroups were established to study more specifically and for the first time the outcome between DS and MBTs in special cases. The first subgroup includes the patients who belong to the high-risk group for stenting (9) with DCI >0.45 (n = 32) and the second includes the patients who have PA-IVS and coronary sinusoids (n = 13). All patients with an additional pulmonary blood supply like patients with PA and major aorta pulmonary collateral Arteries (MAPCAs) were excluded from this study, as well as patients with pulmonary stenosis who have significant antegrade pulmonary perfusion. All patients who received MBTs with additional repair were also excluded from the analysis to focus on the real impact of MBTs and DS on the outcome.

The primary outcome of this study is defined as the successful bridging of patients, who received either DS or MBTs, to the next planned procedure (Glenn or biventricular repair) with freedom from the following: (1) unplanned surgery or perforation of the pulmonary valve (PVP) with a stent, (2) permanent procedure-related complications, and (3) death.

The secondary outcome is defined as the need for ECMO, the occurrence of procedure-related complications, the need for pulmonary artery plasty (PA-plasty) at the time of the next surgery, and the need for additional stent-implantations into the stented duct or into the MBTs.

Additional comparison between the two procedures was performed for the two subgroups (patients with DCI >0.45 and patients with PA-IVS and coronary sinusoid). Hospital deaths, major procedure-related complications, the need for ECMO, and the need for PA-plasty at the time of surgery was documented. Total lower lobe index (TLLI), Nakata and McGoon index were used as pulmonary parameters to estimate the growth of pulmonary arteries at the closest time before the next planned procedure.

### Statistical Analysis

All statistical analyses were performed using SPSS version 22 (IBM). Continuous variables were reported as means ± standard deviations (SD) and categorical variables as count (percentage). The non-paired Student's t-test was used to compare the means of continuous variables between the two different categories, while paired t-test was applied for comparing the means of the pulmonary parameter before and after the two procedures for the whole cohort. The Chi-square test was used for comparing categorical variables. Odds ratios (ORs) ± 95% confidence intervals (95% CI) for the following parameter were calculated to assess any differences between DS and MBTs: hospital deaths, procedure-related complications, need for ECMO, the need for unplanned surgery/PVP with a stent, the need for PA-Plasty, the need for additional stent implantation in DS or MBTs, and the outcome. A P-value of 0.05 was set as the threshold for clinical

TABLE 1 | A summarized overview of diagnoses, complications, and outcomes in this cohort study.

| Description | DS | MBTs | OR | 95% *CI* | *P*-value |
|---|---|---|---|---|---|
| Patients | 71 | 56 | | | |
| PA IVS | 10 (14.1%) | 7 (12.5%) | | | |
| PA VSD | 49 (69%) | 49 (87.5%) | | | |
| Critical PS IVS | 12 (16.9%) | | | | |
| Primary outcome | | | | | |
| Unplanned surgery | 11 (15.5%) | 3 (5.3%) | 1.1 | 0.5–2.8 | 0.89 |
| Unplanned PVP with stent | 2 (2.8%) | 0 | | | |
| Unplanned glenn | 1 (1.4%) | 1 (1.8%) | | | |
| Unplanned shunt-clips | | 6 (10.7%) | | | |
| Permanent complication | 1 (1.4%) | 1 (1.8%) | | | |
| Hospital deaths | 3∧ (4.2%) | 8 (14.2%) | 5 | 1.1–22.6 | *0.017** |
| Secondary outcome | | | | | |
| PA-Plasty at glenn time | 18 (25.3%) | 8 (14.2%) | 0.5 | 0.2–1.2 | 0.094 |
| At shunt time | | 11 (19.6%) | | | |
| Major complications | 5 (7%) | 16 (28.5%) | 4.05 | 1.6–10.3 | *0.001** |
| Need of ECMO | 0 | 9 (16%) | 0.83 | 0.7–0.9 | *0.000** |
| Unplanned stent implantation | 6 (8.4%) | 10 (17.8%) | 2.1 | 0.8–5.4 | *0.049** |
| Unplanned stent dilation or implantation | 15 (21.1%) | 10 (17.8%) | 0.8 | 0.3–2 | 0.4 |
| Primary outcome | *54 (77.5%)* | *42 (75%)* | *0.9* | *00.7–1.1* | *0.5* |
| Impaired outcome | *16 (22.5%)* | *14*** *(25%)* | | | |

*OR, odds ratio; 95% CI, confidence interval; PA IVS, pulmonary atresia; IVC, intact ventricular septum; VSD, ventricular septum defect; ECMO, extracorporeal membrane oxygenation; PA-Plasty, pulmonary artery plasty; PVP, perforation of pulmonary valve; ∧two hospital deaths (2.8%) were DS-related deaths, and one was a non-cardiac related death; **, Impaired outcome 15, one patient has died due to tumor-related problems. *P-value < 0.05 significant.*

significance. Kaplan-Meier survival curve of the two different procedures was performed.

## Ethical Statement

The study complies with the declaration of Helsinki (as revised in 2013). Owing to a purely retrospective study design, using available institutional clinical records, with an absence of impact on the management of the patients included and completely anonymous data presentation, informed consent of the subjects (or their parents) and ethical approval have not been obtained.

# RESULTS

A total of 127 patients with truly DDPC underwent either DS (71 patients) or MBTs (56 patients). The stenting was performed retrograde in 59 patients and antegrade in 12. At the time of DS mean weight was 3.3 kg (SD 0.68) with a range of 3.2 (2–5 kg). The Mean Age was 18 days (SD 23.18), (range 1–120 days). The ductal curvature index (DCI) was higher than 0.45 in 15 patients with DS. At surgical creation of MBTs mean weight was 3.6 kg, SD 1,1 (range 2.1–7.4 kg), and the mean age was 30.3 days with a SD of 34.8 days (range 1–155 days).

The size of MBTs was 4 mm in nine patients and 3.5 mm in the rest of the patients.

## Mortality and Complications

No intervention or operation-related mortality was reported during the two procedures. About three hospital deaths were reported in three patients (4.22%) 1, 7, and 47 days after DS compared to eight hospital deaths 1, 2, 10, 11, 14, 25, 30, and 39 days after MBTs. Two (2.8%) of hospital deaths after DS were DS-related death, and the third person died due to problems related to pre-maturity. All hospital deaths after MBTs (14.2%) were complication-related deaths after MBTs.

There were five major complications associated with DS compared to 15 associated with MBTs (**Table 1**). The DS-related complications were stent thrombosis in four and vessel damage with severe neurologic complications in one patient. The MBTs-related complications were shunt thrombosis in six patients, necrotic enterocolitis (NEC) in one patient, renal failure with NEC and intracranial hemorrhage in one patient, pericardial tamponade with a need for ECMO in one patient, ventricular tachycardia with secondary decompensation and need for ECMO in two patients, and desaturation and low cardiac output with a need for ECMO in four patients.

## Primary and Secondary Outcome Results

The primary outcome was achieved in 54 patients undergoing DS compared to 42 patients undergoing MBTs. The need for the ECMO in patients with MBTs was observed in nine while there was no need for ECMO in the DS group. Unplanned surgery or PVP and RVOT-stent had to be performed in 13 patients with DS and in 9 patients with MBTs. PA-plasty at the next planned surgery (Glenn or repair) was necessary in 18 patients who received DS compared to 8 for those with MBTs**.** The rate of unplanned stent implantation was 10 in the MBTs group

TABLE 2 | DS vs MBTs in patients with ductal curvature index >0.45.

| Description | MBTs** | MBTs | DS | OR | 95%*CI* | *P*-Value |
|---|---|---|---|---|---|---|
| Number | 25* | 17 | 15 | | | |
| Primary outcome | | | | | | |
| Hospital deaths | 7 (28%) | 4 (23.5%) | 1 (6.6%) | 3.5 | 0.4–28 | 0.2 |
| Surgery/PVP/RVOT-stent | 1 | 0 | 10 | 3 | 1.5–6 | *0.000* |
| Permanent complication | 1 | 1 | 1 | 0.8 | 0.05–15 | 0.7 |
| Secondary outcome | | | | | | |
| Need of ECMO | 4 (16%) | 3 (17.6%) | 0 | 0.8 | 0.66–1 | 0.13 |
| Primary outcome | 16 (64%) | 12 (64.7%) | 3 (20%) | 3.5 | 1.2–10 | *0.005* |
| Impaired outcome | 9* (36%) | 5* (35.3%) | 12*(80%) | | | |

*OR, odds ratio; CI, confidence interval; DS, ductal stenting; MBTs, modified Blalock-Taussig shunt; **, includes patients receiving DS pre-operative, while these patients were excluded from the MBTs group. Statistical analysis was done between MBTs and DS. PVP, pulmonary valve perforation; RVOT, right ventricular outflow tract. *, in each of the two groups is one patient, who died due to non-DS/-MBTs related problems.*

TABLE 3 | DS vs. MBTs in patients with PA-IVS with coronary sinusoids.

| Description | DS | MBTs | OR | 95%*CI* | *P*-Value |
|---|---|---|---|---|---|
| PA IVS coronary fistel | 7 | 6 | | | |
| Primary outcome | | | | | |
| Need for unplanned shunt | 2 (28.5%) | | | | |
| Permanent complication | 0 | 1** | | | |
| Hospital death | 0 | 3 (50%) | 0.5 | 0.2–1.1 | *0.046* |
| Late death (before Glenn) | 0 | 2* | | | |
| Secondary outcome | | | | | |
| Major complications | 2 (28.6%) | 4 (57.1%) | 5 | 0.5–53 | 0.2 |
| Need of ECMO | 0 | 3 (50%) | 0.5 | 0.2–1.1 | *0.046* |
| Primary outcome | 5 (71.4%) | 0 | | | |
| Impaired outcome | 2 (28.6%) | 6 (100%) | 3.5 | 1–11.2 | *0.004* |

*OR, odds ratio; CI, confidence interval; DS, duct stenting; MBTs, modified Blalock-Taussig shunt; PA-IVS, pulmonary atresia with intact ventricular septum. *, one patient died due to cardiogenic shock 3 months after the operation, and the second died due to tumor-related problems. **, this patient could not be operated on due to shunt-related severe neurologic complications.*

compared with 6 in the DS group. The measured pulmonary parameters showed a significant increase in all patients of the two groups in whom the next planned procedure was achieved. Nakata index improved from a mean of 171 before to 286mm²/m² after stenting and to 270 mm²/m² after MBTs, McGoon index from 1.5 to 2.7 after the DS compared to 2 after MBTs and TLLI from 90 to 169 mm²/m² after the DS compared to 191 mm²/m² after MBTs.

## High Ductal Curvature Index (DCI >0.45) and Outcome

A total of 32 patients with true DDPC and a DCI of more than 0.45 underwent cardiac catheterization. DS was performed in 15 patients (**Table 2**). About eight of these patients needed emergency MBTs due to desaturation or due to severe reintervention-related complications (Stent thrombosis n = 5, stent dislocation1, severe obstruction 2). The patients (n = 17), who received catheterization without intervention, were referred to surgery for surgical creation of MBTs due to increased tortuosity (DCI >0.45). MBTs were established in 25 patients (8 of them underwent DS). The primary outcome was achieved in 16 patients receiving MBTs compared to 1 in the DS group. Implementation of an ECMO was necessary for four patients in the MBTs group (due to hemodynamic instability in two and shunt thrombosis in two) and none in the DS group.

## PA-IVS With RVDCC and Outcome

A total of five patients undergoing DS have completed the primary outcome while all (n = 6) patients in MBTs had impaired outcomes (**Table 3**). Of these two patients with DS needed MBTs to improve the pulmonary perfusion and one needed an unplanned Glenn anastomosis. The hospital deaths tallied three with MBTs and one in the DS group. The ECMO support was necessary for three patients with MBTs, while no ECMO was reported in the patients with DS. The major complications were related to DS in two and MBTs (low cardiac output with a need for ECMO in three and thrombosis in the right pulmonary artery with pericardial tamponade in 1) in four patients.

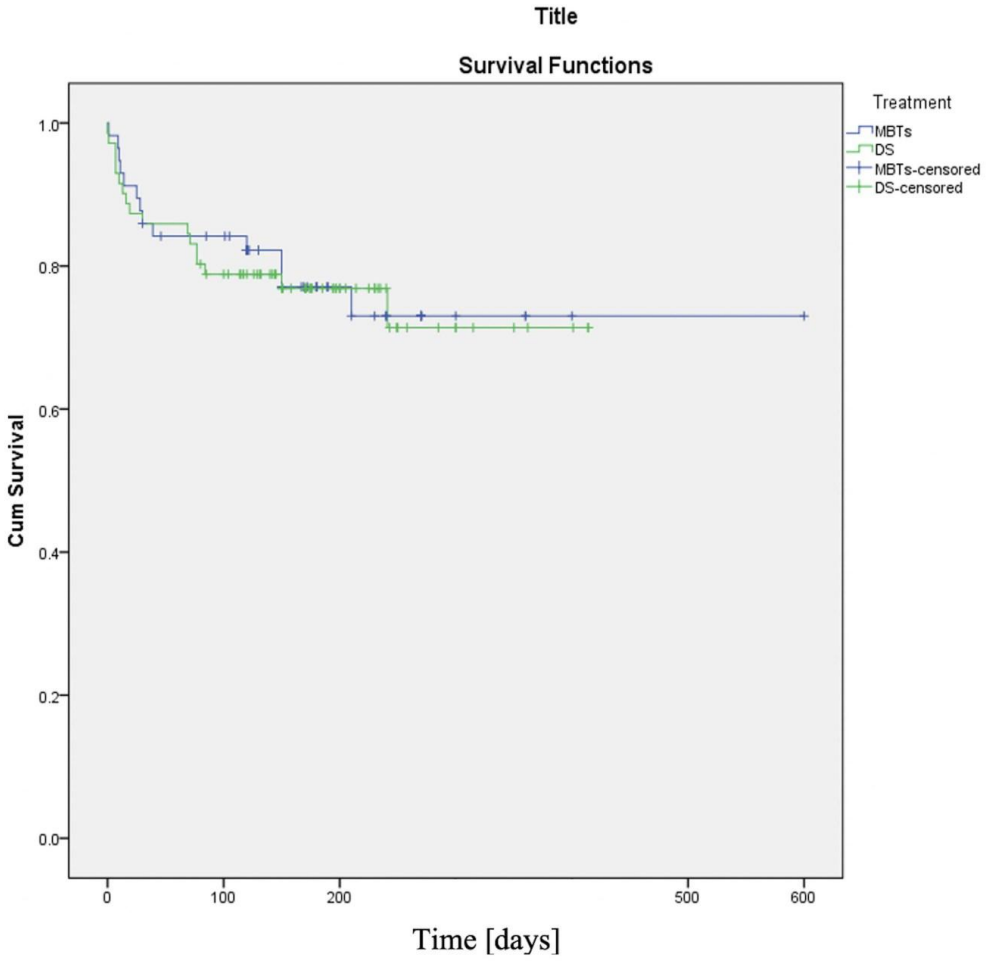


FIGURE 1 | Kaplan-Meier curve (DS vs. MBTs). The two procedures showed the same decay over the whole population while reaching the primary endpoint. X-axis time since procedures is indicated in days.

## DISCUSSION

All published comparisons between MBTs and DS were performed regardless of the complexity of ductal morphology (10–13). In a previous study published in 2021 (9), the results of our center showed that the patients with an increased ductal tortuosity and ductal curvature index (equal to or more than 0.45) have to be classified as the high-risk patients for duct stenting. The primary outcome in these patients was achieved in only 20% of them. However, the outcome in the patients from the same group who underwent MBTs is still unknown and the preferable palliative approach for this group is still controversial. In the current era, we have chosen first to establish a general comparison between the two procedures (DS and MBTs) regardless of the ductal morphology in the DS cohort and, secondly, to compare the outcome, more specifically in the two high-risk groups with PA and DDPC. The first group includes the patients with a high DCI >0.45, and the second includes patients with PA-IVC and coronary sinusoids in which the best palliative strategy seems to be controversial. For reasons of consistency, we have only included patients with a single lung supply (shunt or stent) in the analysis without concomitant additional repairs.

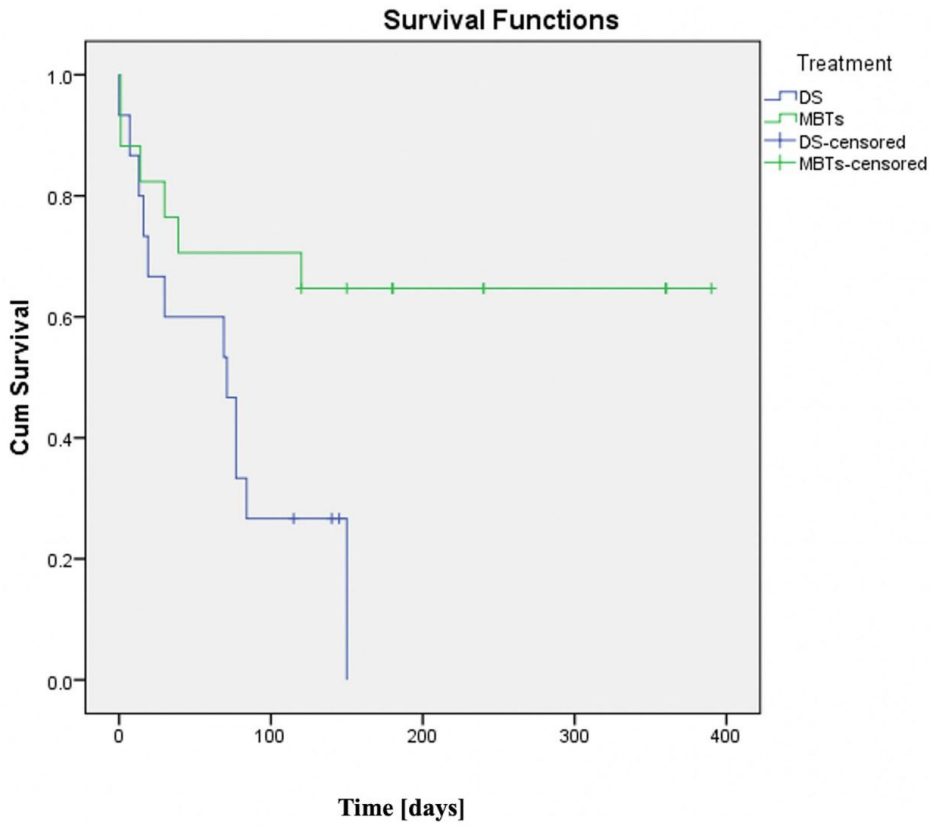


FIGURE 2 | Kaplan–Meier curve (DS vs. MBTs in ducts with ductal curvature index (DCI) >0.45). Compared with DS-group with DCI >0.45 which showed very low survival, patients with a DCI >0.45 underwent MBTs and had much better survival rates with the majority reaching their next planned surgery. Time since procedures is indicated in days.

## General Comparison Between MBTs and DS

The primary outcome of this study was achieved equally in the two procedure groups (77% in DS and 75% in MBTs), and no significant difference was observed. The survival analysis demonstrated no dissociation between the two procedures (**Figure 1**). The hospital deaths were dominated by patients who underwent MBTs (14.2%) compared to only 2.8% in the DS group (P-value 0.017). The same observations were documented in previous studies, which compared the two palliative strategies (11, 14). The high mortality rate in the MBTs group largely results from hemodynamic instability associated with diastolic run-off through the shunt and coronary artery steal (11), this phenomenon was observed in 75% of hospital deaths, while 25% were related to shunt occlusion. It is also worth noting that all patients who died following operations were on ECMO. The need for unplanned reoperation showed no significant differences between the two groups. The unplanned surgery in the DS group was required to treat desaturation related to stent failure or secondary to failure of ductal recanalization after acute ductal occlusion during the intervention. The unplanned surgeries in the MBTs group had to be performed either to treat a hemodynamic significantly pulmonary overload using shunt clips or to improve the saturation and the development of the pulmonary arteries by the creation of a large shunt (5 mm).

The major complications and need for ECMO were observed pre-dominantly in MBTs due to post-operative hemodynamic instability, shunt thrombosis, ventricular tachycardia, pericardial effusion, multiorgan failure related to a low cardiac output, and neurologic complications (intracranial bleeding and seizures). In contrast, the major complications observed in the DS groups were acute in-stent-thrombosis, stent dislocation, and vessel damage with the secondary severe neurologic complication. Alsagheir et al. (14) showed that DS demonstrates lower mortality

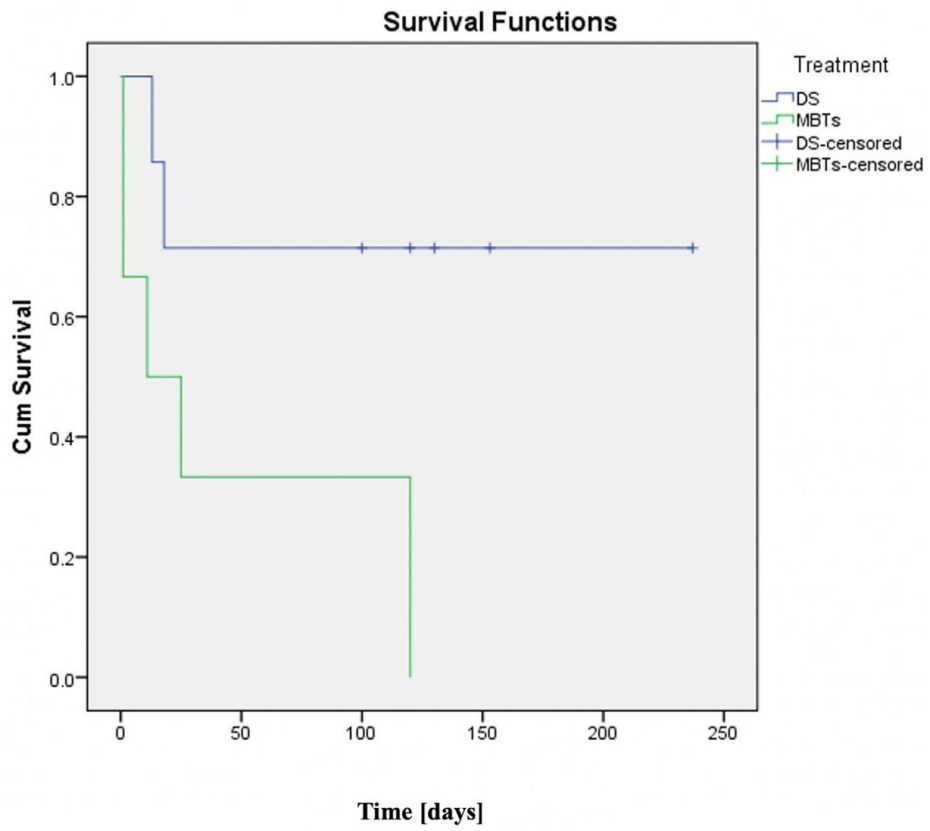


FIGURE 3 | Kaplan-Meier curve (DS vs. MBTs in patients with PA-IVS and right ventricle-dependent coronary perfusion). DS group showed better survival rates compared with the MBTs group which had very low survival. No patient in this group has reached the next surgery. Time since procedures is indicated in days.

and a lower risk of procedural complications. This observation is in agreement with the results of the present study.

The higher number of hospital deaths, complications, and need for ECMO in MBTs have made DS in many centers around the world the preferable palliative strategy in patients with DDPC. Contrary to the results of the previous studies, the current results showed that the need for PA-plasty was higher in the DS group. This can be explained by the highly tortuous ducts associated with a resulting functional pulmonary stenosis in our DS cohort (9).

## MBTs vs. DS in High-Risk Patients for Stenting (DCI >0.45)

Although 64% of the patients in the MBTs group have achieved the primary outcome compared to only 20% in the DS group; the mortality and the need for ECMO in MBTs remained dominant compared to DS in this high-risk group. The survival analysis in **Figure 2** demonstrates a significant difference between the two groups. DS seems inappropriate to bridge these patients to the next planned surgery without the need for additional operation.

It is important to note that a significant portion of hospital deaths in the MBTs group (57%) happened in patients who underwent DS and MBTs performed as an emergency either due to desaturation or after reanimation related to an acute ductal occlusion happened during the intervention. The last observation suggested that ductal stent failure in tortuous ducts might have a negative impact on the outcome of unplanned MBTs and make the surgery more challenging in these patients due to pre-operative desaturation and its related negative changes in pulmonary arteries and the lungs.

## MBTs vs. DS in Patients With PA-IVS and RVDCC

Although there was repeated interest to find out the solutions for patients with PA-IVS with RVDCC over the last decade (15, 16), there was no comparison published evaluating the two palliative

procedures. We found that 57.2% of the patients in the DS group achieved the primary outcome compared to only 16.7% in the MBTs group. The use of cardiopulmonary bypass during cardiac operation seems not to have an impact on the outcome (four patients were operated on with bypass initiated via aortic and right atrial cannulation and two without it). The survival analysis (**Figure 3**) demonstrates a clear dissociation between the two palliative strategies. Hospital deaths and the need for ECMO were reported in half of the patients who underwent MBTs. The post-operative documented significant ST changes and ventricular arrythmia, decreased ejection fraction of the single ventricle due to ischemia and diastolic run-off through the shunt and coronary steal can explain the higher mortality and morbidity in these patients compared to those undergoing DS. There were no significant differences in complications between the two groups (**Table 3**).

## CONCLUSION

With low mortality and morbidity, the DS is an alternative palliative strategy to be considered in relation to MBTs to secure the pulmonary blood flow in patients with PA and DDPC. It can improve the symmetrical growth of the pulmonary arteries. This advantage seems less dominant in stenting the tortuous ducts with a DCI of more than 0.45 (9).

Contrary to the previous result, this study suggests that the MBTs could be preferred to DS in patients with DCI higher than 0.45. However, the hospital deaths remain dominant in the MBTs while the DS seems to be suitable for the palliative strategy in the patients with PA-IVS and RVDCC by decreasing the risk of intra- and post-operative ischemia and ventricular arrhythmia observed.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements. Written informed consent was not obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

NM: conception and design of the work and data collection. NM and PZ: data analysis and interpretation and drafting the article. MS, BA, and PZ: critical revision of the article. NM, MS, BA, MM, and PZ: final approval of the version to be published all authors. All authors contributed to the article and approved the submitted version.

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### 3.3. Transcatheter dilation and stenting of the modified Blalock-Taussig shunt in cyanotic heart diseases: points to consider. A single-center experience

Mini N, Zartner PA and Schneider MBE (2024) Transcatheter dilation and stenting of the modified Blalock-Taussig shunt in cyanotic heart diseases: points to consider. A single-center experience. *Front. Cardiovasc. Med.* **11**:1445987. doi: 10.3389/fcvm.2024.1445987 *(JIF 2.8)*

Background: This study evaluates the techniques and outcomes of interventional dilation and stenting of the modified Blalock-Taussig shunt (MBTS) at our center over the past four years, offering a detailed review of our clinical practice.

Methods: Between January 2020 and May 2024, we retrospectively analyzed 42 interventions in 32 patients with MBTS stenosis, conducted in our catheterization laboratory. Among the patients, 18 had hypoplastic left heart syndrome (HLHS), 10 had pulmonary atresia, and 4 had tricuspid atresia. Shunt sizes varied: 3.5 mm in 18 patients, 4 mm in 11, 5 mm in 1, and 6 mm in 1. All patients underwent angiographic examination of the shunt and pulmonary branches. Activated clotting time (ACT) was measured during catheterization, aiming for a value between 160 and 180 seconds, with 100 units/kg of heparin administered. We documented saturation levels before and after the intervention, early and late complications, ECMO requirements, reintervention needs, in-stent-thrombotic events and early and late mortality. As there were no signs of neurological events, these were assessed clinically without any elective CT or MRI. Echocardiograms were performed at 6, 24, and 48 hours post-intervention to monitor for pericardial effusion. The interventions included 11 balloon dilatations and 31 stent placements.

Results: The median age, weight, body surface area, and procedural radiation time at intervention were 100 days (range: 15–870 days), 5 kg (range: 2.6–12 kg), 0.3 m² (range: 0.19–0.54 m²), and 12 minutes (range: 7–28 minutes), respectively. Four procedures were performed emergently on three patients, three of whom were on ECMO support. Of the remaining interventions, 22 were semi-emergent due to severe hypoxia, while the rest were elective for mild desaturation. All procedures were completed successfully without intervention-related complications or mortality. Improvement in saturation was observed in 82% of balloon dilations and 97% of

stent placements. One patient experienced late stent thrombosis, and two patients had sudden death and cardiac decompensation requiring resuscitation.

Conclusion: MBTS interventions are highly effective in managing severe hypoxia in both emergent and semi-emergent situations. These procedures can be performed safely and without complications when well-prepared, with a thorough understanding of materials and access routes. While balloon dilatation can improve luminal diameter, stenting is often required for definitive treatment, and it may serve as an alternative to surgical revision, especially when conditions delay subsequent operations. To avoid new stenosis, complete stenting is recommended over partial stenting in cases of localized shunt stenosis. In cases of atypical shunt anastomosis, considering alternative access routes, such as axillary and carotid approaches, can help shorten intervention time. The need for multiple stents or reinterventions increases the risk of shunt thrombosis, highlighting the importance of dual antiplatelet therapy to minimize thrombotic events. Stenting of 3.5 mm and 4 mm shunts to 4.5 mm and 5 mm, respectively, offers an effective alternative to surgical revision, delaying surgery in unfit patients.

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# Transcatheter dilation and stenting of the modified blalock-taussig shunt in cyanotic heart diseases: points to consider. A single-center experience

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Background: Our study focuses on the technique and results of interventional dilation and stenting of the modified Blalock–Taussig shunt (MBTS) performed in our center, providing a comprehensive review of our practice over the past 4 years.

Methods: 42 catheter interventions on MBTS performed on 32 patients between January 2020 and May 2024 included 11 balloon dilatations and 31 stenting procedures. They were analyzed retrospectively. We documented early and late complications, the need for in-shunt reintervention or surgical revision, in-stent thrombotic events, and sudden death.

Results: The median age, weight, body surface area, and procedural radiation time at the time of the intervention were 100 days (15–870 days), 5 kg (2.6–12 kg), 0.3 $m^2$ (0.19–0.54 $m^2$), and 12 min (7–28 min). Four interventions were performed as an emergency in three patients, of which three were performed with ECMO support. The interventions were semi-emergent for severe hypoxia in 22 patients and elective for mild desaturation in the rest. All interventions were successfully performed without any intervention-related complications or death. Eighty-two percent of the shunt dilations led to saturation improvement. Of the 31 shunt stentings performed in 26 patients, saturation improvement was documented in 97% of the cases. The late complication with stent thrombosis was documented in one patient. In two patients, sudden death and cardiac decompensation with the need for resuscitation were documented.

Conclusion: MBTS interventions are effective in emergent and semi-emergent situations with severe hypoxia. While serial balloon dilatations improved the luminal diameter in clipped MBTS, most patients needed stenting as a definitive procedure. In some cases, enlargement of the shunt via stenting may be an alternative to the surgical shunt revision to accommodate the shunt size and weight and delay the subsequent operation when there are contraindications. Dual antiplatelet therapy is strongly recommended to reduce thrombotic events, especially in shunts with more than one stent and those that need reinterventions.

KEYWORDS

mBT shunt, shunt stenting, shunt stenosis, HLHS, hypoplastic left heart syndrome, shunt obstruction, pulmonary atresia

Abbreviations

MBTS, modified Blalock–Taussig shunt; PTEF, polytetrafluoroethylene; HLHS, hypoplastic left heart syndrome; PA, pulmonary atresia; PS, pulmonary stenosis; CPB cardiopulmonary bypass; LPA, Left pulmonary artery; RPA, Right pulmonary artery; ECMO, Extracorporeal membrane oxygenation.

## Introduction

The modified Blalock–Taussig shunt (MBTS) is a synthetic tube graft of polytetrafluoroethylene (PTEF; Gore-Tex). The shunt is created between the subclavian artery and the branch pulmonary artery to provide adequate pulmonary perfusion in patients with cyanotic heart failure, like hypoplastic left heart syndrome (HLHS), who have undergone Norwood palliation and in those with pulmonary atresia (PA), in whom interventional palliation could be difficult. However, MBTS palliation is associated with high morbidity and mortality (1).

Over time, many shunts will develop some degree of stenosis due to shunt intima proliferation, thrombosis, and, in some cases, shunt torsion. Wells et al. reported that 34% of shunts showed a luminal narrowing during elective shunt takedown, and 0.2% of patients had >50% stenosis of the shunt (2). Shunt obstruction, shunt stenosis, and thrombosis can occur early or late after the operation, ranging in severity from mild to severe to life-threatening. In such cases, an emergent intervention is required to recanalize the shunt and regain the shunt's patency and pulmonary perfusion to save the patient's life. Many studies about the MBTS have been conducted for a better understanding of its physiology and to prove the safety and efficacy of the intervention on it (3–6). At the same time, intervention-related complications like cardiac tamponade, catheter-induced transient complete atrioventricular block, and massive thrombo-embolic stroke were reported (4), as well as arrhythmias and damage of the vascular access (5).

In this study, we aim to review our experience in shunt intervention, the intervention technique, and the outcome of shunt stenting in our cohort and to focus on the essential points we have learned regarding intervention on MBTS.

## Patients and methods

Between January 2020 and May 2024, we retrospectively recruited 42 interventions in 32 patients with MBTS stenosis in our catheterization laboratory. Of these, 18 had HLHS, 10 had pulmonary atresia, and 4 had tricuspid atresia.

The shunt size was 3.5 mm in 18 patients, 4 mm in 11, 5 mm in 1, and 6 mm in 1. The interventions were performed as emergency procedures in four patients, semi-emergent for severe hypoxia in 22 patients and elective for mild desaturation in the rest. An angiographic examination of the shunt and the pulmonary branches was performed on all patients.

Activated clotting time (ACT) was examined at the time of catheterization (the aimed value of ACT ranges between 160 and 180 s), and 100 units/kg heparin was substituted.

Saturation before and after the intervention, early and late intervention-related complications, the need for ECMO, the need for reintervention in the shunt stent, and early and late death were documented. Since there was no evidence of neurologic events, they were clinically evaluated without planning any elective CT or MRI. An echocardiogram was used 6, 24, and 48 h after the intervention to exclude pericardiac effusion.

## Statistical analysis

All statistical analyses were performed using SPSS version 22. Continuous variables were reported as median ± standard deviation (SD), and categorical variables as count (percentage).

## Ethical statement

The study complies with the Declaration of Helsinki (as revised in 2013). As this retrospective study used previously available institutional clinical records, presented completely anonymized data, and did not impact patient management, no ethical committee approval was required. Parental consent for the shunt intervention was obtained for all interventions, including the emergent and semi-emergent procedures needed in 62% of the cohort.

## Intervention description

All interventions were performed under sedation by an experienced anesthesiologist. The exception was one patient who was resuscitated and intubated at the ICU for a suboccluded shunt. Parental consent was obtained before the interventions. Heparin 100 units/kg was administered as a bolus. ACT was measured, and an additional heparin bolus was given based on the ACT that was maintained between 180 and 200 s.

A 4-French (F) sheath (Terumo, Radifocus®, Introducer II) was introduced into the femoral artery. Aortic arch angiogram using a 4F angiographic catheter was used to demonstrate the shunt and the pulmonary arteries. The subclavian artery was then accessed with a 4 F end-hole catheter (usually Terumo®, Radifocus®, Glidecath™, or Cobra C1). The tip of the catheter was then positioned at the aortic side of the shunt.

### Shunt stenting

In the case of stenting, we introduced a 4 F long sheath (Flexor® Check-Flo® Introducer, 45 cm) into the TBC/subclavian artery. After that, ACT was measured again, and the heparin dose was adapted based on ACT. The shunt was then accessed using a 0.014-inch wire (such as WIZDOM™ Steerable Guidewire-Cordis or Mailman™ Guidewire, which can provide satisfactory balloon stability). The wire was positioned at the lower lobe of the branch pulmonary artery. In most cases, we delivered the stent into the shunt without pre-dilatation. After angiography ensured shunt patency, adequate pulmonary perfusion and excluded dissection, thrombosis, and stent malposition, the balloon and the guidewire were removed. The pericardial and pleural effusions were excluded based on echocardiograms.

We used the long sheath in stenting to ensure the stability of the wire and the stent, position the stent in the shunt while

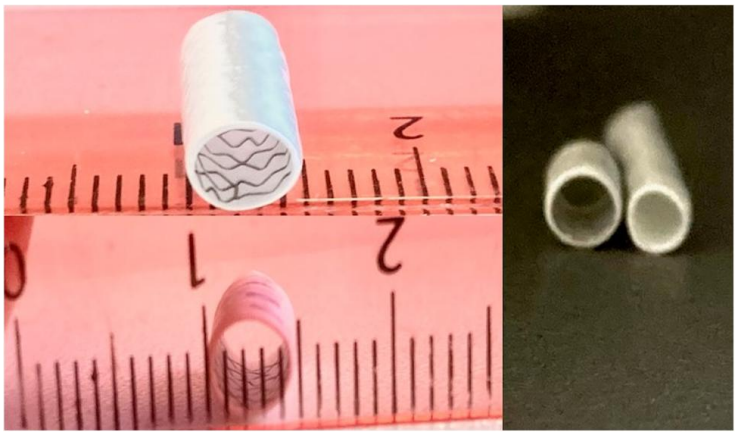

FIGURE 1
Demonstration of the shunt before and after stenting. (A) 3.5 mm shunt before and after stenting with a coronary stent of 4 mm, the shunt stent was dilated to a diameter of 4.5 mm.

performing angiography using the side port of the long sheath, and prevent any stent dislocation by facilitating the removal of the stent balloon by pushing the long sheath while retrieving the balloon through the sheath.

In small children weighing under 4 kg, the stent size should equal the shunt size to prevent secondary pulmonary overcirculation. In patients weighing >4 kg who have contraindications for surgery in the usual time (age of 5–6 months) and will need the shunt longer than others, the stent size could be 1 mm more than the shunt size (Figure 1).

## Dilation of the shunt

In the case of dilating the clipped shunt without stenting, we did not require a long sheath for the intervention. However, when the shunt was challenging to access because of torsion or atypical shunt connection to the TBC, a long sheath was required to provide more stability to the used materials. We accessed the shunt using a 0.035-inch GLIDEWIRE® Hydrophilic Coated Guidewire, which should be exchanged for a 0.014-inch coronary wire to accommodate the coronary balloon. In the latter case, we preferred to use the Mailman™ Guidewire from Boston Scientific, which provides satisfactory stability for the balloon (Figure 2).

The balloon size should be equal to the shunt diameter. A coronary balloon (like the NC EMERGE™ PTCA Dilatation Catheter) was then advanced over the 0.014-inch wire to the shunt, and the shunt clip was dilated. After that, the intervention result was ensured with angiography and echocardiography. The time of balloon-related shunt occlusion during the balloon inflation should be limited to a few seconds. At the same time, an experienced anesthesiologist must carefully monitor the vital and hemodynamic parameters.

Heparin 400 units/kg/d was administered for 48 h after the intervention. Aspirin 2–3 mg/kg/d was our choice as antiplatelet therapy until the subsequent surgery.

# Results

The median weight, age, BSA, and radiation time were 5 kg (2.6–12 kg), 100 days (15–870 days), 0.3 $m^2$ (0.19–0.54 $m^2$), and 12 min (7–28 min). The median stent patency was 79 (1–500 days) (Figure 3).

There was no intervention-related complication or death. No pericardiac or pleural effusion was documented 24, 48, and 72 h after the intervention.

## Emergency interventions

Four emergency interventions were needed due to acute shunt obstruction in three patients, twice in a same patient.

The first patient with HLHS needed a shunt stent due to shunt stenosis and underdevelopment of the right or the left branch pulmonary artery. He was referred to palliative therapy. Sixty days after the shunt stenting, he had to be resuscitated during his hospital stay due to hemodynamic deterioration after a crying attack. Burst massage during resuscitation led to stent deformation. The stent was completely compromised with no perfusion. The shunt revascularization was performed while the patient was on ECMO (Figure 4). The ECMO was decannulated 24 h after stenting.

The second patient (HLHS) had an impaired thrombophilia diagnostic, which led postoperatively to multiple thrombotic events, including multiple cerebral thromboses and infarcts and

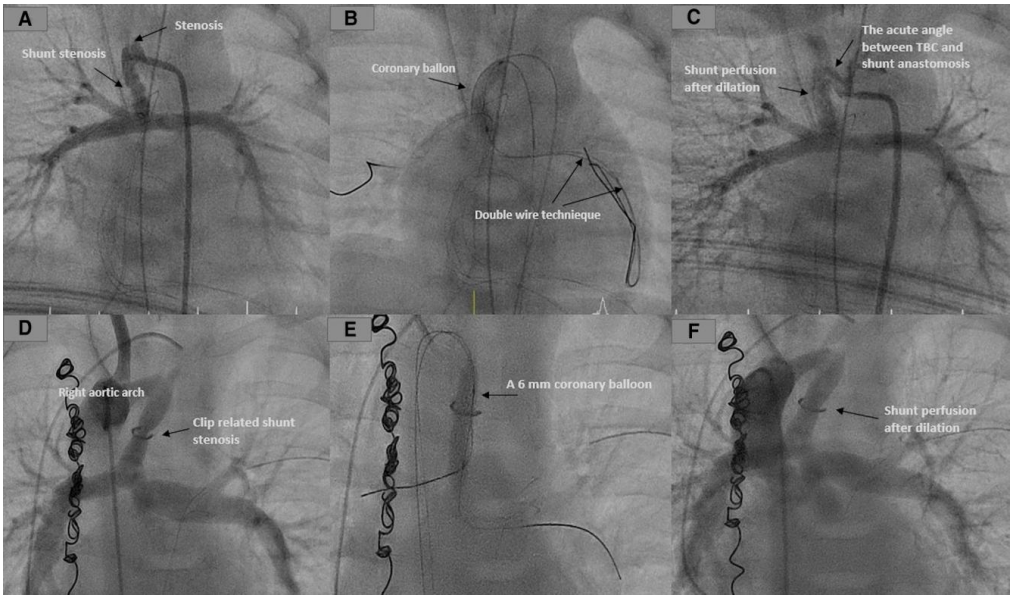


FIGURE 2
Dilation of shunt stenosis. (A–C) Dilation of the shunt stenosis in a patient with HLHS 2 days after the Norwood palliation due to desaturation. The acute angle between TBC and shunt anastomosis made crossing the shunt difficult. A double-wire technique was used to stabilize the introduction of the catheter and the balloon. The shunt was dilated with a coronary balloon, and there was significant saturation improvement. (D–F) Demonstrate the Dilation of the 6 mm clipped shunt in a patient with PA and congenitally corrected transposition of the great arteries (ccTGA). The Dilation was performed directly after the operation due to desaturation. The shunt was crossed using two wires and dilated to 6 mm with significant saturation improvement.

thrombotic occlusion of the brachiocephalic vein. Stenting of the obstructed brachiocephalic vein with the need for redilation by acute thrombosis was required. The patient was resuscitated by acute obstruction of the shunt postoperatively, and the shunt stenting was performed by ECMO standby in the hemodynamically unstable child, who needed a high dose of catecholamine (Figure 5). Despite the continuous intravenous heparin, a new in-stent intervention was required due to thrombosis of the shunt stent and the pulmonary arteries, which occurred 30 days after stenting.

The third patient (HLHS, Norwood Palliation) had an acute shunt obstruction postoperatively and needed ECMO for survival. The interventional shunt revascularization was performed while the patient was on ECMO (Figure 6). The shunt was revised after 24 h due to an ECMO-related thrombotic event. The patient died postoperatively on ECMO.

## Shunt dilation

Eleven balloon dilatations included seven procedures in clipped MBTS in six patients, one procedure in a shunt without a clip and three to balloon dilate a previously stented shunt. The shunt size was 3.5 mm in 2 patients, 4 mm in 2, 5, and 6 mm in 1. The weight at the intervention was 2.6, 2.7, 2.8, 3.9,4.4, 8.6, and 11 kg, respectively. The balloon size used for dilation was equal to the shunt size. In one patient weighing 2.6 kg, the clip of the 3.5 mm shunt was dilated first with 3 mm to avoid pulmonary overcirculation. He needed a second intervention to dilate the clip with a 3.5 mm balloon to accommodate the shunt size based on weight.

We reported the same condition in the second patient with a clip in a 4 mm shunt, who needed two separated shunt dilations with balloon sizes of 3.5 mm and 4 mm, respectively.

Shunt stent dilation was reported in three patients. In the first one, the stent had to be dilated to accommodate the shunt size and weight. In the second one, the obstructed shunt stent was recanalized. In the third patient, the wholly deformed stent was recanalized after resuscitation in the second patient, who was on ECMO.

All shunt and shunt stent dilations were performed without intervention-related complications.

The dilation of shunt clips and stents effectively improved the saturation in 9 of 10 interventions. In one patient with pulmonary atresia and hypoplastic right pulmonary artery, the dilation of the shunt (4 mm) was inadequate to improve the saturation. Two weeks later, the patient needed surgical shunt revision to a 5 mm shunt; then, the shunt in this patient had to be exchanged for a Sano shunt.

There were no shunt-related late complications.

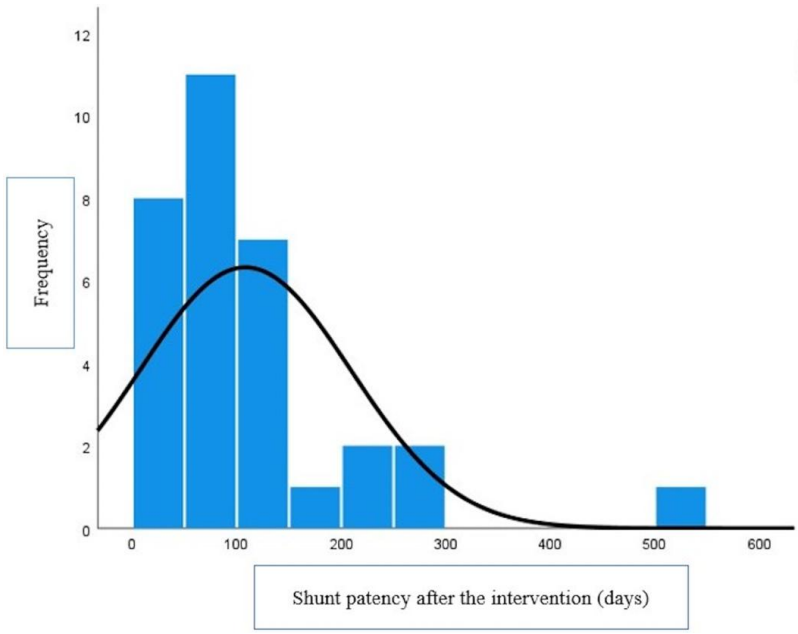


FIGURE 3
Histogram for shunt patency after intervention in 32 patients.

## Shunt stenting

In 26 patients, 31 separate interventions with shunt stents were needed. Fifteen patients had HLHS, of whom 14 were in Stage I palliation and one had Glenn anastomosis and MBTS; four patients had tricuspid atresia, and the rest had pulmonary atresia with shunt palliation.

The indication of the shunt stent was shunt stenosis with desaturation in 23 interventions and acute shunt obstruction in 2, with the need for resuscitation and ECMO for survival. In 1 patient with MBTS in the left pulmonary artery and Glenn anastomosis in the right pulmonary artery, the indication of stenting was first to treat the shunt stenosis and second to separate the two circulations using a covered stent. One patient needed two interventions for stenting due to shunt stenosis in the first one and new stenosis distally of the first stent in the second one. Three patients needed a larger stent to delay the surgery due to hypoplastic branch pulmonary arteries at the time of operation.

In 26 interventions, the stents were coronary (1 BeGraft covered coronary stent, 4 Pro Kinetic Energy Biotronik, 3 Scaffold Magmaris stents and 18 Integrity stents).

Three interventions with three Magmaris® coronary resorbable magnesium scaffold stents were performed in 2 patients. One of them had pulmonary atresia and severe hypoplasia of the native branch pulmonary arteries with MAPCAs and required two interventions for stenting of the RPA with Magmaris stents. The interval between the two stents was three months. The need for reintervention was due to restenosis in the RPA and pulmonary side of the shunt. The pulmonary side of the shunt had to be included in stenting to ensure coverage of the proximal side of the RPA and to stent the distal stenosis of the shunt. The second patient had distal stenosis of the shunt with severe proximal LPA stenosis, and the shunt was included in stenting to cover the proximal stenosis of LPA.

The sirolimus level was checked 8 h, 24 h, and 48 h after stenting and was under 5 ng/ml without any documented side effects.

All shunt stentings were successfully performed without intervention-related complications or deaths. Follow-up was done in all patients except for the patient on ECMO with an impaired thrombophilia diagnostic, who got a new shunt after 24 h due to pulmonary thrombosis; the patient died one week after that due to disseminated thrombosis in the shunt and the pulmonary arteries.

No pleural or pericardial effusions were documented (24, 48, and 73 h after stenting), and saturation improved in all patients.

No hematoma or acute femoral artery damage after the intervention was documented.

## Thrombotic events and sudden death after shunt stenting

We reported one case with the in-stent thrombotic event and one case with resuscitation after a crying attack without evidence of in-stent thrombosis. Both patients were already mentioned above. The third case was a sudden death in a patient with

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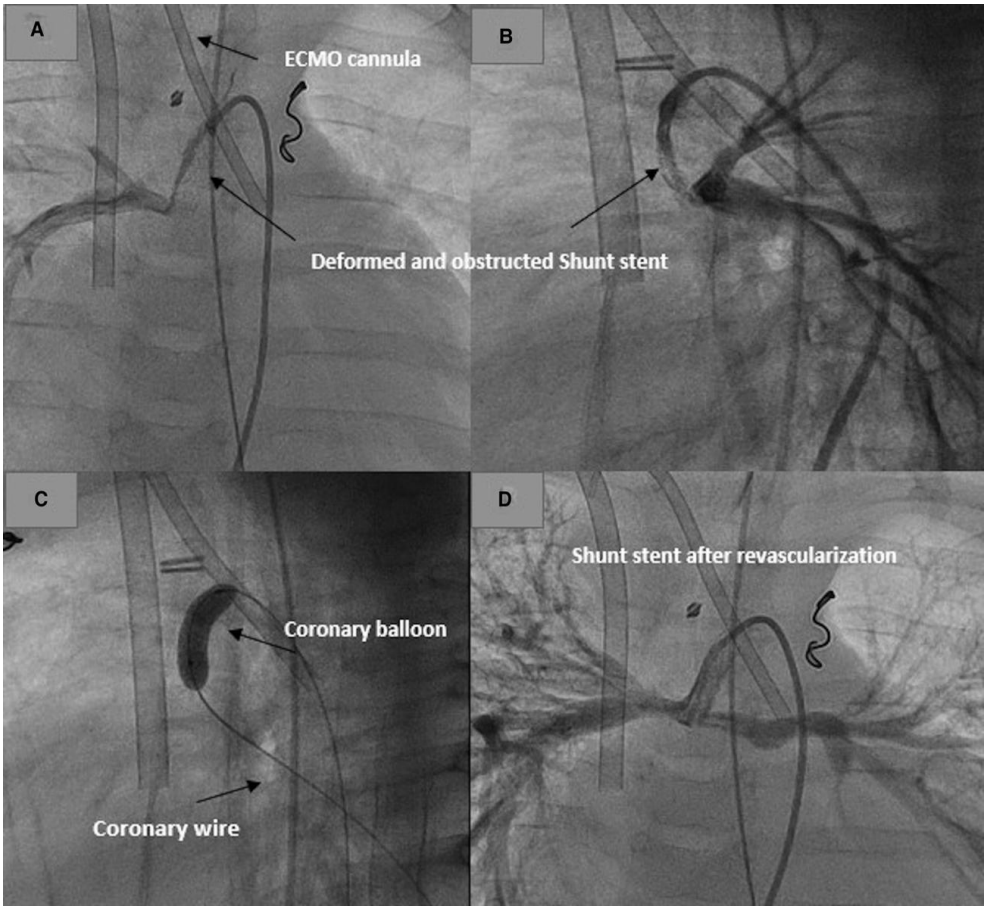


FIGURE 4
Revascularization of a deformed shunt stent after resuscitation in a patient on ECMO. (A,B) Deformed stent in AP and lateral projections. (C) Recanalization and dilatation of the stent. (D) Shunt and pulmonary perfusion after shunt revascularization.

HLHS and partial anomalous drainage of the right pulmonary veins at a higher level in the vena cava superior. He had Stage I palliation with a 4 mm shunt. The shunt was stented with a 4.5 mm stent due to a stenosis. Three months later, a new stent of 5 mm diameter was required to delay the Glenn operation due to atypical insertion of the pulmonary veins in the SVC. Sudden death happened at home 60 days after the discharge. The patient was on aspirin. An acute shunt stent obstruction with a thrombosis was suspected to be the cause of the death.

## Antiplatelet therapy

At discharge, one patient was on rivaroxaban due to thrombocytopenia; four were on Aspirin and clopidogrel (inclusive of patients with Magnesium stents), and the rest were on Aspirin (inclusive of the patient with two stents in shunt, in whom a sudden death was reported).

## Follow up

Twenty-six patients were operated on (Glenn in 19, biventricular repair in 5, and 1.5 repair in 1 patient). One patient was operated on with tricuspid reconstruction 40 days after stenting and died postoperatively. Four patients were unfit for Glenn due to severe hypoplastic pulmonary arteries and were referred to palliation; two of them died. A sudden death was documented in the first one 40 days after stenting, and the second one died due to septic shock 34 days after the intervention. The

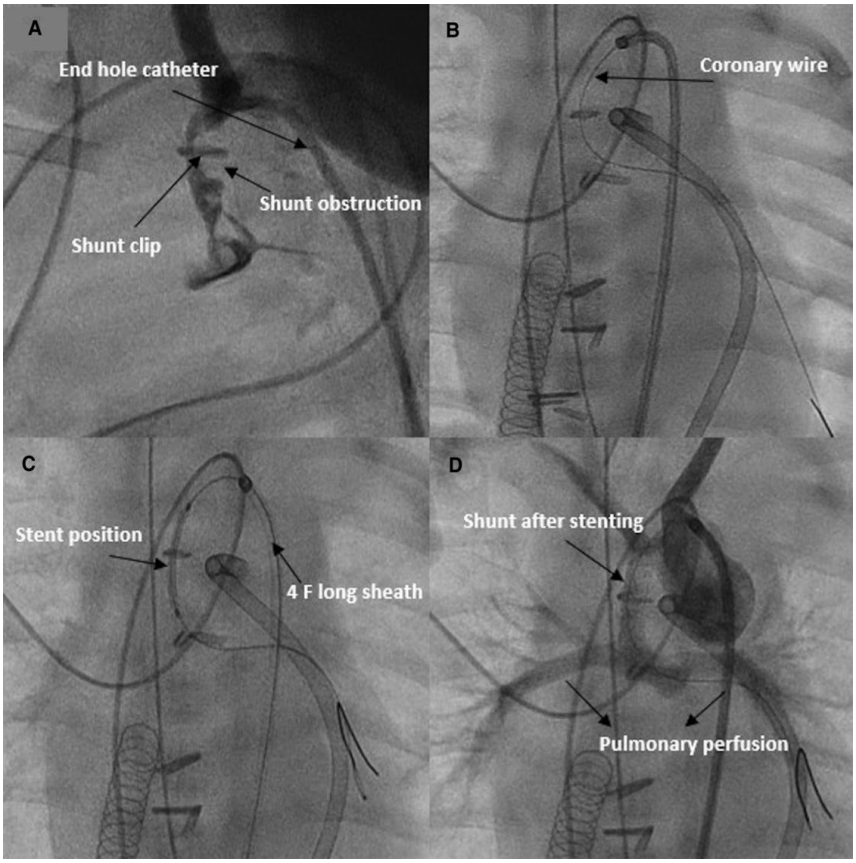


FIGURE 5
Revascularization and stenting of obstructed shunt postoperative. (A,B) Demonstrating the thrombosed shunt postoperatively in AP and lateral projection. (C) Recanalize the shunt with coronary wire and introduce the stent into the shunt. (D) Shunt and pulmonary perfusion after stenting.

need for a surgical revision of the shunt was documented in 2 patients. One of them was on ECMO after shunt obstruction, which was revascularized and stented. Twenty-four hours after stenting, the shunt was revised due to an ECMO-related thrombotic event. The patient died 1 week after the operation. In the other patient, the 3.5 mm shunt was changed to a 4 mm shunt 2 weeks after shunt dilation due to inadequate saturation

## Discussion

Several studies and case reports about MBTS interventions and treatment of shunt thrombosis in infants and adults have been conducted in the past 2 decades due to their importance in improving pulmonary artery growth and saving lives in some life-threatening cases of shunt obstruction (6–9).

This study aims to review our technique for intervening in stenosed and obstructed shunts and the results of the interventions done in our center in the past 4 years. Ligon et al. (6) showed that 25% of MBTSs during interventions were not amenable to access from the femoral artery, and accessing the carotid artery was required in these patients to achieve the interventions with a lower procedure time. In contrast to the previous results, all intervened shunts in our current report were successfully accessed from the femoral artery without the need to access the carotid or axillary artery; in one case, the anastomosis between the shunt and the TBC led to an acute angle, which made crossing the shunt from the femoral artery difficult, but the shunt was accessed using three wires, which stabilized the advancement of the materials to the shunt (Figure 6). However, the intervention-related radiation time in our cohort, which included the intervention and the diagnostic performed in stable patients, was equal to or lower than that reported via carotid artery shunt interventions. Bonnet et al. (4) reported about 33 interventions in obstructed shunts over 20 years with 15% intervention-related complications,

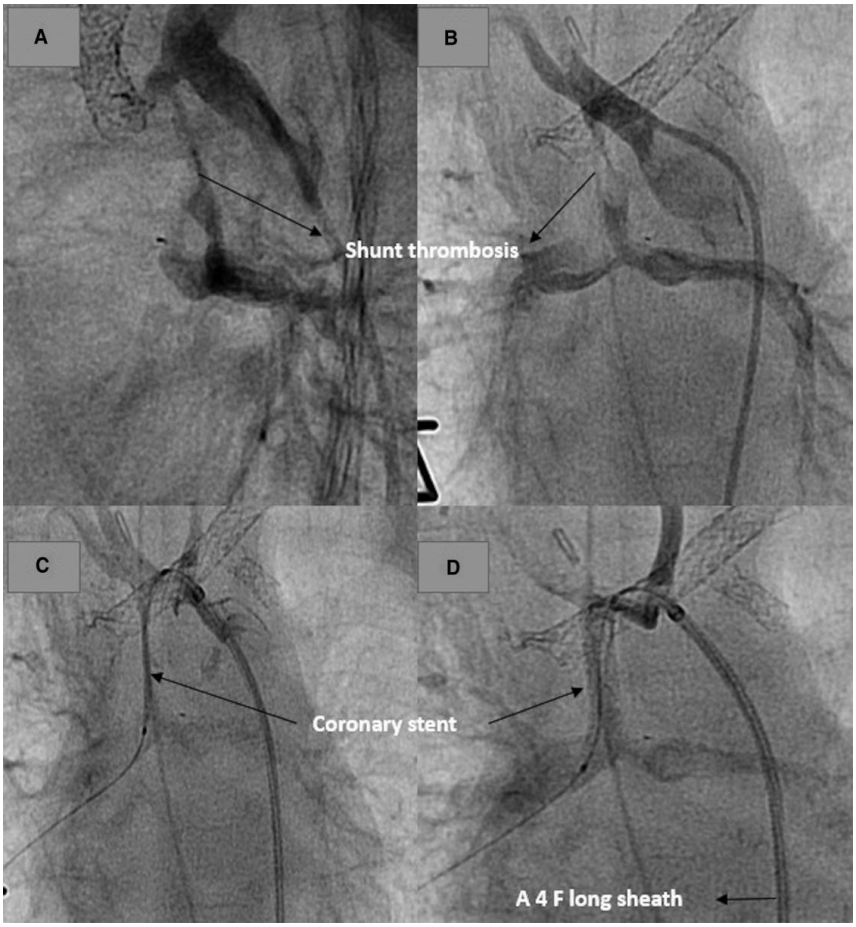


FIGURE 6
Revascularization of an obstructed shunt in a patient on ECMO. (A,B) demonstrate the thrombosed shunt with the clip. (C) Stent position after recanalization of the shunt. (C) Shunt and pulmonary perfusion after stenting.

including one catheter-induced transient complete atrioventricular block, one cardiac tamponade, and one massive thrombo-embolic stroke. In contrast, in our report with 24 emergent interventions due to severe stenosis, including 4 with totally obstructed shunts, we have documented no intervention-related complications, including no intervention-related accessed vessel damage or occlusion (5). Our results are in agreement with a previous study (5) regarding the complete surgical resection of the stents implanted in the shunts at the time of elective shunt takedown.

Wells et al. (2) showed that most MBTSs showed evidence of stenosis by the time of takedown, and 21% have greater than 50% obstruction with histological evidence for myofibroblastic proliferation often associated with organized thrombosis, which can lead to obstruction. Dilatation and stenting of thrombotic shunts might lead to the embolization of thrombotic material into the pulmonary arteries (10). For this reason, good heparinization is required during and after the intervention to prevent against an acute thrombotic event in the shunt and the pulmonary arteries. In our cohort, severe thrombotic events in the shunt and the pulmonary arteries were difficult to avoid in patients with an impaired thrombophilia diagnostic and a previous history of multiple thrombotic events despite intensive intravenous anticoagulation and intensive control of the coagulation laboratory in the ICU. A thrombotic event, arrhythmias and septic shock were suspected to be the cause of sudden resuscitation in 1 patient and sudden death in another without reported evidence. Both were on aspirin, which seems to be ineffective alone in patients with more than one stent per shunt, and dual antiplatelet therapy should be considered in such cases (5).

## Lessons learned from our experience and conclusion

Interventions on stenosed and obstructed MBTS to save lives are feasible and could be performed without intervention-related complications or deaths when the procedure is well prepared with adequate knowledge of all materials and accessed routes needed for the interventions, which could facilitate the procedure and lead to satisfactory results.

We recommend performing a thrombophilia diagnostic in all patients who require shunts and shunt interventions to minimize thrombotic events by choosing a better anticoagulation strategy as early as possible.

Partial stenting of the shunt could lead to a new stenosis in the non-stented shunt tissue. In the case of localized shunt stenosis, the shunt should be completely stented to avoid new stenosis and the need for a second stent.

In some cases of atypical shunt anastomosis, the axillary and carotid accesses should be considered to facilitate the intervention and shorten the radiation and intervention time.

The need for shunt stenting with more than one stent or the need for reintervention seems to increase the risk of shunt thrombosis. Aspirin alone seems ineffective, and dual antiplatelet therapy is strongly recommended.

Based on our experience, the diameter of the 3.5 mm and 4 mm shunts could be enlarged via stent to 4.5 and 5 mm, respectively. This makes shunt stenting, in some cases, an alternative to surgical revision of the shunt to delay the subsequent operation when the patient is unfit for surgery or when there is a contraindication.

Avoiding diuretics and dehydration in patients with shunt stenting who are discharged home with effective antiplatelet therapy and closed echocardiographic controlled to exclude shunt stenosis is crucial to minimize the risk of sudden death related to shunt thrombosis.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Author contributions

NM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. PZ: Writing – review & editing. MS: Validation, Writing – review & editing.

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### 3.4. Transcatheter Intervention of Modified Blalock–Taussig Shunts in Patients with Hypoplastic Left Heart Syndrome Undergoing Stage 1 Palliation

Mini N, Schneider MBE, Mikus M (2024), Transcatheter Intervention of Modified Blalock–Taussig Shunts in Patients with Hypoplastic Left Heart Syndrome Undergoing Stage 1 Palliation. Front. Cardiovasc. Med. 11: 1502801, doi10.3389/fcvm.2024.1502801.

Background: While several studies have explored the outcomes of transcatheter interventions for modified Blalock–Taussig shunts (MBTSs) in a broad range of congenital heart diseases, none have specifically examined the interventions in patients with hypoplastic left heart syndrome (HLHS) who underwent Norwood palliation (NP).

Methods: This retrospective study was conducted between 2020 and 2024, when 24 urgent interventions were performed on 17 patients at our center. We recorded several key outcomes, including early and late intervention-related complications, the need for reintervention, the interval between the NP and the first intervention, shunt patency following the intervention, associated morbidities, and thrombosis-related sudden events. Additionally, during follow-up, we documented the outcomes for patients who underwent the Glenn procedure and those who were palliated, including late death. Echocardiographic evaluations were performed 24- and 48-hours post-intervention to assess for pericardial or pleural effusions. In small children (<4 kg), the stent size matched the shunt size to avoid secondary pulmonary overcirculation. For patients weighing >4 kg with contraindications for surgery and extended shunt use, the stent size was 1 mm larger than the shunt size. The Glenn operation was conducted for patients weighing ≥5 kg meeting specific criteria, including adequate pulmonary artery development and normal pulmonary pressures.

Results: The median age and weight at the time of intervention were 88 days (range: 15–300 days) and 5 kg (range: 2.6–7.6 kg), respectively. The median interval between the NP and the transcatheter intervention was 61 days (7–160 days), with median shunt patency lasting 62 days (1–150 days). Notably, there were no intervention-related complications or deaths. In-stent thrombosis, a late complication,

occurred in four patients; two of these had impaired anticoagulation, including extracorporeal membrane oxygenation (ECMO)-related causes, while the other two, who were on aspirin, had multiple stents within the shunt, one of whom experienced sudden death. Six patients required seven reinterventions: four due to shunt obstruction or restenosis and two to delay surgery or provide palliation for patients unfit for surgery, aiding in pulmonary development.

Conclusion: Transcatheter intervention of MBTSs in patients with HLHS undergoing NP is both safe and potentially life-saving in emergent situations. This approach can enhance pulmonary development, delay the need for subsequent surgeries, and provide critical palliative care. However, managing late complications, such as stent thrombosis, remains a significant challenge. Our study identified several risk factors for shunt thrombosis, including ECMO therapy, underlying coagulation disorders, the need for multiple stents, and a prior history of shunt thrombosis. Dual antiplatelet therapy is recommended to reduce thrombotic risk in this population.

Our findings also revealed that patients who received MBTS solely for pulmonary perfusion—such as those with tetralogy of Fallot, pulmonary atresia, and tricuspid atresia—had better outcomes compared to those who underwent more complex procedures like NP combined with MBTS. Among patients who underwent MBTS alone, 92% required further surgical interventions: 46% received Glenn procedures, 38% underwent biventricular repair, and 8% needed a Fontan procedure or Sano shunt. The NP cohort showed higher rates of shunt-related complications, including pulmonary torsion, shunt stenosis, ECMO-related thrombosis, and sudden death, compared to patients with pulmonary atresia treated with simple MBTS, indicating that these factors negatively impacted outcomes for the Norwood group.

Finally, our results suggest that lower morbidity is associated with better outcomes in patients with HLHS and NP. Conditions such as tricuspid regurgitation, aortic arch abnormalities, pulmonary distortion, and coagulation disorders were found to negatively impact outcomes in our cohort. These findings highlight the critical importance of effectively managing these factors to improve prognosis in this high-risk patient population.

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# Transcatheter intervention of modified Blalock–Taussig shunts in patients with hypoplastic left heart syndrome undergoing stage 1 palliation

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Background: While several studies have explored the outcomes of transcatheter interventions for modified Blalock–Taussig shunts (MBTSs) in a broad range of congenital heart diseases, none have specifically examined the interventions in patients with hypoplastic left heart syndrome (HLHS) who underwent Norwood palliation (NP).

Methods: This retrospective study was conducted between 2020 and 2024, when 24 urgent interventions were performed on 17 patients at our center. We recorded several key outcomes, including early and late intervention-related complications, the need for reintervention, the interval between the NP and the first intervention, shunt patency following the intervention, associated morbidities, and thrombosis-related sudden events. Additionally, during follow-up, we documented the outcomes for patients who underwent the Glenn procedure and those who were palliated, including late death.

Results: The median age and weight at the time of intervention were 88 days (range: 15–300 days) and 5 kg (range: 2.6–7.6 kg), respectively. The median interval between the Norwood procedure and the transcatheter intervention was 61 days (7–160 days), with median shunt patency lasting 62 days (1–150 days). Notably, there were no intervention-related complications or deaths. In-stent thrombosis, a late complication, occurred in four patients; two of these had impaired anticoagulation, including extracorporeal membrane oxygenation (ECMO)-related causes, while the other two, who were on aspirin, had multiple stents within the shunt, one of whom experienced sudden death. Six patients required seven reinterventions: four due to shunt obstruction or restenosis and two to delay surgery or provide palliation for patients unfit for surgery, aiding in pulmonary development.

Conclusion: The transcatheter intervention of the MBTSs in patients with HLHS undergoing NP is considered both safe and potentially life-saving in emergent situations. This approach may facilitate improved pulmonary development, postpone the need for subsequent surgeries, and provide medium-term palliative care for critically ill patients. However, managing late complications such as stent thrombosis remains a significant challenge. Our findings indicate that risk factors for shunt thrombosis include using ECMO therapy, underlying coagulation disorders, impaired lymphatic drainage, requiring multiple stents within the shunt, and a prior history of thrombosis before intervention. Dual antiplatelet therapy is recommended to alleviate the risk of thrombotic events in this population.

KEYWORDS

Norwood I, hypoplastic left heart syndrome, shunt stenting, shunt stenosis, mBT shunt, ECMO, shunt thrombosis

## Introduction

Hypoplastic left heart syndrome (HLHS) is a rare congenital heart defect that severely disrupts normal blood flow through the heart and carries a high risk of mortality if untreated, with survival rates of only 30% in the first week and 9% by 30 days (1). Norwood palliation (NP) is typically the first stage of palliation for HLHS patients.

Both early and late shunt obstructions significantly contribute to the morbidity and mortality of patients who undergo NP with a modified Blalock–Taussig shunt (MBTS) (2–4). Shunt stenosis or obstruction can arise from various factors, including intraluminal thrombosis, neointimal hyperplasia, suture line stricture, and vascular distortion due to surgery or ductal tissue constriction (5–7). These issues can lead to a gradual decline in oxygen saturation and exercise tolerance or result in rapid clinical deterioration characterized by acute hemodynamic instability and severe hypoxemia, which can become life-threatening (8).

The severity of shunt stenosis can vary widely, from mild to critical, often necessitating urgent intervention. The primary goal of transcatheter interventions for stenosed or obstructed shunts is to restore and maintain shunt patency, ensuring adequate pulmonary blood flow and minimizing the risk of cyanosis and other complications. However, these interventions are not without risk; complications such as cardiac tamponade, catheter-induced arrhythmias, atrioventricular block, thromboembolic stroke, and vascular access injuries have been reported (9).

Given the high rates of morbidity and mortality associated with HLHS, this study focused on shunt interventions within this patient cohort. We will review our results and outcomes, emphasizing the impact of associated morbidities on procedural success.

## Patients and methods

We conducted a retrospective analysis of 17 patients with HLHS who underwent NP and received 24 transcatheter interventions on MBTSs between January 2020 and May 2024. We documented several important outcomes, such as complications related to early and late interventions, the need for reintervention, the time elapsed between NP and the first intervention, post-procedure shunt patency, associated morbidities, and thrombosis-related sudden events. Furthermore, during follow-up, we tracked outcomes for patients who underwent the Glenn procedure and those who received palliative care, including cases of late mortality.

Table 1 summarizes patients' demographics, including age and weight at the time of intervention and the indications for emergent procedures. Table 2 summarizes the morbidities associated with the intervention. Echocardiographic assessments were performed 24 and 48 h post-intervention to monitor for any pericardial or pleural effusions. A previous study published a detailed description of the intervention techniques and the patients' management after the procedure in our center (10). In small children weighing under 4 kg, the stent size was equal the shunt size to prevent secondary pulmonary overcirculation. In patients weighing >4 kg who have contraindications for surgery in the usual time (age of 5–6 months) and will need the shunt longer than others, the stent size was 1 mm more than the shunt size.

The Glenn operation is conducted at our center for patients weighing ≥ 5 kg who satisfy the following criteria: well-developed central and lower lobes of the pulmonary arteries, as indicated by a total lower lobe index (TLLI) > 95 $mm^2/m^2$; normal pulmonary pressure; normal wedge pressure; absence of significant pulmonary vein stenosis; normal diastolic pressure of the right ventricle with satisfactory function; and no evidence of coagulopathy.

### Statistical analysis

All statistical analyses were performed using SPSS version 22. Continuous variables are reported as median ± IQR, and categorical variables as count (percentage).

Abbreviations

HLHS, hypoplastic left heart syndrome; NP, Norwood palliation; MBTS, modified Blalock–Taussig shunt; ECMO, extracorporeal membrane oxygenation; PAVM, pulmonary arteriovenous malformation; PAS, pulmonary stenosis; TR, tricuspid regurgitation; TVR, tricuspid reconstruction; PA, pulmonary arteries.

TABLE 1 Patients' descriptions and the indications and outcomes of the shunt interventions.

| N | NW/I interval (days) | Shunt Size (mm) | Indication | Stenting/ dilation | Size of stent/ balloon (mm) | Reinterventions | Outcome | Late death? |
|---|---|---|---|---|---|---|---|---|
| 1 | 160 | 4 | SS | Stenting | 4 | | TKR + aortic arch reconstruction | Death 7 days postoperatively |
| 2 | 55 | 3.5 | Desaturation by SS and severe PA hypoplasia | Stenting | 3.5 | 1. A new stent (4 mm) 120 days after the first one<br>2. Recanalization of the deformed stent after CPR 55 days after the second one | Hypoxic encephalopathy/ Palliative | Death in a rehabilitation center |
| 3 | 123 | 3.5 | SS + severe PA hypoplasia | Stenting | 4 | | Glenn | |
| 4 | 74 | 4 | SS + PAPVR | Stenting | 4.5 | A new shunt stent (5 mm) will delay the operation 70 days after the first stent. | No clear plan by associated PAPVR/ operation was delayed/ palliation | Sudden death 110 days after the first stent and 40 days after the second one |
| 5 | 69 | 3.5 | SS + PAVM | Stenting | 3.5 | | Glenn | |
| 6 | 81 | 3.5 | SS | Stenting | 4 | | Glenn | |
| 7 | 8 | 3.5 | Shunt obstruction postoperatively by severe ECMO-related thrombosis | Recanalization and Stenting on ECMO | 3.5 | | Shunt revision by disseminated thrombosis on ECMO and secondary shunt-stent obstruction | Death 7 days after the shunt revision on ECMO |
| 8 | 61 | 3.5 | SS | Stenting | 3.5 | | Glenn | |
| 9 | 270 | 4 | SS + hyp. PAs and PAVM | Stenting | 4.5 | | Palliative | |
| 10 | 7 | 3.5 | SS + PAS | Stenting | 4 | | Glenn takedown/Re-Glenn + TKR | |
| 11 | 100 | 3.5 | SS + PA hypoplasia | Stenting | 4 | | 3. Operation: TKR + PAR<br>4. Operation: Glenn | |
| 12 | 61 | 3.5 | SS | Stenting | 3.5 | | Glenn | |
| 13 | 62 | 4 | S. obstruction postoperatively | Stenting | 3.5 | Recanalization of the obstructed shunt-stent | Palliative by thrombotic event-related neurologic problem | Death 60 days after the first intervention and 20 days after the second one |
| 14 | 20 | 3.5 | Desaturation by shunt clip with PA hypoplasia | Dilation | 3.5 | Shunt clip dilation | Palliative | |
| 15 | 81 | 3.5 | Desaturation with severe PA hypoplasia | Stenting | 3.5 | | Improvement of PA development after stenting, the patient is waiting for Glenn | |
| 16 | 15 | 3.5 | Severe SS postoperatively with sharp angulation of the shunt | Dilation | 3.5 | Stenting to delay the operation by CoA/impaired RV 100 days after the first intervention | Glenn + shunt/aortic arch. Reconstruction + long ECMO-Therapy | |
| 17 | 13 | 3.5 | SS postoperatively | Dilation | 3.5 | Shunt clip redilation (4 mm) by desaturation 32 days after the first one | Glenn | |

NW/I interval between Norwood palliation and the intervention time. CoA, aortic coarctation; CPR, cardiac pulmonary resuscitation; MBTS, modified Blalock–Taussig shunt; PA, pulmonary; PAR, pulmonary reconstruction; PAS, pulmonary stenosis; PAVM, pulmonary arteriovenous malformation; SS, shunt stenosis; TKR, tricuspid reconstruction; Hyp.; PA, pulmonary hypoplasia.

## Ethical statement

According to the local ethical committee's decision (with running number 2024-406-BO), informed consent and patient agreement were waived due to the study's retrospective design.

## Results

In our study, we performed 24 transcatheter interventions across 17 patients with HLHS, four of which involved shunt clip dilations in three patients. The median age and weight at the time of intervention were 88 days (range 15–300 days) and 5 kg

TABLE 2 Illustrates the morbidities associated with shunt interventions, along with the antiplatelet therapy administered following the procedure.

| N | Aortic arch stenosis torsion? | TR? | Need for reoperation? | PA hypoplasia? PAS? PAVM? PAPVD? | Coagulation pathway? | Antiplatelet | Sudden life-threatening event? |
|---|---|---|---|---|---|---|---|
| 1 | Torsion | Yes | Yes | No | No | Heparin | |
| 2 | CoA | No | No | Bilateral hypoplasia | Yes, on ECMO | Aspirin | Yes |
| 3 | No | No | No | Bilateral hypoplasia | No | Aspirin | |
| 4 | No | No | No | PAPVR | No | Aspirin | Yes |
| 5 | No | No | No | Shunt related surgical RPA stenosis (torsion)/right PAVM | No | Aspirin | |
| 6 | No | No | No | No | No | Aspirin | |
| 7 | No | No | Yes | No | Yes, on ECMO | Enoxapam | Yes |
| 8 | No | No | No | No | No | Aspirin | |
| 9 | No | No | Yes | Shunt related RPA stenosis (torsion)/right PAVM | No | Aspirin | |
| 10 | No | Yes | Yes | No | No | Aspirin | |
| 11 | No | No | No | Bilateral hypoplasia | No | Aspirin | |
| 12 | No | No | No | No | Yes | Aspirin | |
| 13 | No | No | No | No | Factor VII | Heparin | Yes |
| 14 | No | No | No | Bilateral stenosis | No | Aspirin | |
| 15 | No | No | No | Severe hypoplasia (bilateral) | No | Aspirin + Clopidogrel | |
| 16 | Arch torsion + CoA | No | Yes | No | No | Xarelto | |
| 17 | No | No | No | No | No | | |

CoA, aortic coarctation; PA, pulmonary; PAPVC, partial abnormal pulmonary venous return; PAS, pulmonary stenosis; PAVM, pulmonary arteriovenous malformation; TR, tricuspid regurgitation.

(range 2.6–7.6 kg), respectively. The median interval between the Norwood procedure and the transcatheter intervention was 61 days (range 7–160 days), while the median duration of shunt patency was 62 days (range 1–150 days). Notably, there were no intervention-related complications or deaths, and follow-up echocardiography did not reveal any pericardial or pleural effusions.

## Emergent interventions for obstructed shunts

Among the 17 patients, two (12%) required emergent recanalization of obstructed shunts with stenting due to extracorporeal membrane oxygenation (ECMO)-related thrombotic events (Patient 7) and Factor VII deficiency (Patient 13), who had experienced multiple thrombotic incidents, including cerebral and systemic vein thrombosis. The shunt patency lasted 1 day for Patient 7 and 20 days for Patient 13. During follow-up, both patients experienced stent occlusions due to new thrombotic events, necessitating additional interventions: shunt and ECMO revision for Patient 7 and new recanalization for Patient 13.

## Emergent postoperative interventions

Approximately 29% (five patients) required urgent interventions due to shunt-related stenosis following surgery. Three patients (18%) underwent adequate shunt clip dilation, significantly improving oxygen saturation. Two of these patients (Patients 14 and 17) required end-size redilation, while the third patient (Patient 16) needed stenting to delay further surgery due to right ventricular dysfunction. Additionally, two other patients required stenting, including the previously mentioned one on ECMO.

## Interventions in patients with associated morbidities

Nine patients were deemed unfit for surgery due to severe pulmonary artery (PA) hypoplasia and stenosis, including one with tricuspid regurgitation (TR) and one with atypical partial anomalous pulmonary venous return (PAPVR). The goal of shunt stenting in these patients was to restore shunt patency, improve saturation, promote pulmonary development, and delay the Glenn surgery until pulmonary conditions were stable. Among five patients with PA hypoplasia, shunt stenting led to improved pulmonary parameters in four, of whom two underwent Glenn operations and one awaited surgery. The fifth patient was referred to palliative care.

In patients with PAVM, shunt interventions improved oxygen saturation but did not address the PAVM itself. One patient was referred to palliative care due to severe bilateral PAVMs and PA underdevelopment, while another successfully underwent a Glenn operation.

Patients with severe aortic arch torsion/stenosis had poorer outcomes. One underwent tricuspid and aortic reconstruction but died postoperatively. The other received aortic arch reconstruction and the Glenn procedure but later required additional shunt placement and extended ECMO therapy, ultimately resulting in palliative care.

## Reinterventions

Six patients (35%) required seven reinterventions due to acute shunt stent occlusion (in two patients, 12%), residual stenosis of the clipped shunt (in two patients, 12%), and dilation procedures for subsequent operations (in three patients, including Patient 3, who required two reinterventions).

## Thrombotic events and mortality

Thrombotic events occurred in four patients (24%), with two experiencing complications related to coagulation disorders from excessive ECMO-related transfusions (Patient 7) and Factor VII deficiency (Patient 13). The shunt stent patency was 1 day for Patient 7 and 40 days for Patient 13. Both were intensively anticoagulated with heparin.

The other two patients, Patients 2 and 4, received two stents in separate interventions. Patient 2 experienced sudden cardiac decompensation requiring ECMO, while Patient 4 suffered sudden death. Patient 2 was hospitalized at the time of the event, while Patient 4 was at home. Both patients were on aspirin. The first shunt stent patency lasted 120 days for Patient 2 and 100 days for Patient 4, while the second stent patency was 55 and 40 days, respectively.

## Follow-up

Nine patients underwent Glenn operations, including Patient 16, who required extended postoperative ECMO therapy. Five patients were referred to palliative care due to severe PA hypoplasia (three patients), a significant thrombotic event from Factor V Leiden (one patient), and atypical PAPVR (one patient). Of these, three died during follow-up. Two patients who underwent tricuspid valve replacement and shunt revision died 40 and 7 days postoperatively. At the time of writing, one patient with PA hypoplasia was still awaiting further surgery based on pulmonary artery development.

# Discussion

Despite improvements in operative mortality rates, complications arising from shunt failure continue to pose significant risks to patient morbidity and mortality. The estimated incidence of shunt failure for Blalock–Taussig shunts is approximately 9.3%, with early failures representing about 20% of these cases.

Numerous studies have explored the outcomes of transcatheter interventions for MBTSs, encompassing a broad spectrum of congenital heart diseases, including patients with HLHS. However (6, 9, 11), none have specifically focused on this particular cohort.

In our current report, we reviewed the results of transcatheter interventions for stenosed and obstructed MBTSs in this critical population, examining the associated morbidity and mortality that could influence outcomes.

Ensuring the MBTS's patency is crucial for the survival of patients with HLHS undergoing NP. Shunt failure can occur at various stages, driven by different mechanisms of obstruction. Acute obstructions are often associated with thrombus formation, while late obstructions typically arise from neointimal proliferation or calcification. In our experience, the median time to shunt failure or shunt intervention was about 2 months, although interventions were necessary at all points after shunt placement, including in critically ill patients supported by ECMO. This aligns with findings from a 2015 study that involved all patients who received MBTSs (n = 25), including those with HLHS (n = 10) (6).

In our cohort, the indications for shunt intervention in patients with HLHS undergoing NP were twofold: to restore the shunt lumen in cases of stenosis or obstruction or to postpone subsequent surgery in critically ill patients or those with underdeveloped pulmonary arteries. Although previous studies have reported some complications, all interventions performed in this critical cohort at our center over the past 4 years were free from procedure-related complications or deaths. Our study's median shunt patency after the intervention was approximately 2 months (64 days), including patients who underwent Glenn procedures at the optimal time and those who died due to non-stent-related causes. Shunt dilation and stenting were adequate in 76% of the patients in our cohort, providing palliative care or facilitating their progression to subsequent surgeries, such as the Glenn procedure or other necessary interventions like tricuspid valve reconstruction and aortic reconstruction. The first successful balloon angioplasty for shunt stenosis was documented in 1989 (12). This significant milestone led to further retrospective studies (10, 13, 14), which reported as high as 91% success rates. These findings align with our results, where the dilation of the shunt clip effectively improved oxygen saturation and served to bridge patients until the optimal time for subsequent surgery. Additionally, the dilation of the shunt clip in one patient was performed gradually to adjust the shunt size according to their weight. Approximately 24% of the patients experienced sudden thrombotic events, including instances of sudden death. In our cohort, the risk factors associated with thrombosis-related stent failure included a history of shunt occlusion, ECMO therapy necessitating transfusions, impaired coagulation pathways, and the presence of multiple stents within the shunt. Despite intravenous heparinization, preventing the recurrence of in-stent thrombosis in high-risk patients—especially those with impaired coagulation, including ECMO-associated thrombosis—remained challenging. In our cohort, aspirin alone was ineffective in preventing shunt thrombosis in patients with multiple stents, highlighting the need for dual antiplatelet therapy as a more suitable option for this population.

In a prior study conducted at our center (10), we investigated the outcomes of transcatheter MBTS interventions in patients with pulmonary atresia and those with HLHS. Our findings indicated that patients receiving MBTS solely to achieve adequate

pulmonary perfusion—specifically those with tetralogy of Fallot, pulmonary atresia, and tricuspid atresia—exhibited better outcomes compared to those undergoing more complex procedures, such as the NP combined with MBTS. Among the patients who underwent MBTS alone in our study, 92% subsequently required additional surgical interventions: 46% received Glenn procedures, 38% underwent biventricular repair, and 8% required a Fontan procedure. Additionally, 8% of patients needed a Sano shunt. We observed significantly higher rates of shunt-related pulmonary torsion, surgery-related shunt stenosis, ECMO-related shunt thrombosis, and sudden death in the NP cohort compared to patients with pulmonary atresia who underwent a simple MBTS. These factors adversely affected the outcomes of MBTS interventions in the Norwood group compared to the other cohort.

The current results indicate that lower associated morbidities were correlated with better outcomes for patients who underwent shunt intervention. Morbidities such as tricuspid regurgitation, surgery-related aortic arch issues, pulmonary distortion, the need for additional operations, severe pulmonary atresia, and coagulation pathway disorders adversely affected the outcomes of patients in our cohort.

## Conclusion

The transcatheter intervention of MBTSs in neonatal patients with HLHS is recognized as both safe and potentially life-saving in emergencies. This method can enhance pulmonary development, delay the need for subsequent surgeries, and provide medium-term palliative care for critically ill patients. However, managing late complications, such as stent thrombosis, poses a significant challenge. Our findings suggest that the risk factors for shunt thrombosis include ECMO therapy, underlying coagulation disorders, requiring multiple stents within the shunt, and a history of shunt thrombosis before intervention. We recommend implementing dual antiplatelet therapy and performing comprehensive echocardiographic evaluations to detect shunt stenosis at an earlier stage, especially in high-risk patients. Additionally, it is essential to prevent dehydration and avoid the use of diuretics to reduce the risk of thrombotic events in this population.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Author contributions

NM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MS: Validation, Writing – original draft, Writing – review & editing. MM: Validation, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# 4. Discussion

This retrospective study examines the outcomes of neonates with CHD who underwent transcatheter cardiac interventions to palliate the cyanosis in patients with duct- dpenedent and MBTS-shunt dependent pulmonary circulation at a university hospital in Bonn. The study evaluated these procedures' success rates, complications, mortality rates, short- and mid-term follow-up outcomes and compared the outcomes between the cohort who underwent interventional palliation and those who underwent a surgical one. A total of 177 neonatal patients and infants under six months of age with CCHD were included. These patients underwent stent placement in the arterial duct, dilation of the MBTS or MBTS stenting to alleviate cyanosis.

## 4.1. Significance of DCI in patients with DDPC

While some studies have validated the safety and efficacy of duct stenting as an alternative to surgical mBT shunt creation (Alwi et al., 2004; Gewillig et al., 2004; Schranz et al., 2010; Glatz et al., 2018), few have explored the impact of ductal morphology on stenting outcomes (Alwi, 2008; Jadhav et al., 2020; Qureshi et al., 2019). In recent years, various formulas have been proposed for quantitatively measuring the tortuosity of blood vessels (Han, 2012). This study utilized a DCI formula previously employed in a PDA study (Qureshi et al., 2019).

To calculate the DCI, we implemented a ductal classification system for a cohort of patients with DDPC. We used a quartile approach to categorize patients into four groups based on their DCI values, with the upper quartile threshold (DCI ≥ 0.45) designating class IV, which represents the group with the highest curvature index.

Findings indicate that patients in this category have a significantly higher risk of complications and unplanned interventions compared to those with lower DCI values (< 0.45). Patients with DCI ≥ 0.45 showed poor outcomes, with only 20% achieving the primary outcome without complications. A striking 80% of these patients required unplanned surgeries or additional need for interventional pulmonary valve perforation and RVOT stent due to inadequate pulmonary perfusion. Additionally, early cases of in-coronary stent stenosis (ICS) and thrombosis—often occurring in the elastic lamina—were frequently observed in class IV. Recoil and relocation of axially

transmitted plaque are suggested contributors to ICS (Alraies et al., 2017; Bennett, 2003), which can be exacerbated by

increased tortuosity, the use of long stents, and stent deformation, as well as overexpansion and under-expansion (Buccheri et al., 2016). These complications are compounded by the high tortuosity of the ducts, which increases the difficulty and risks associated with reintervention.

Interestingly, the study notes that ducts with lower DCI were more susceptible to in-stent restenosis over time due to thrombosis and neointima formation (Alraies et al., 2017; Bennett, 2003). However, high DCI values were more strongly associated with acute failures due to stent mispositioning and deformation, emphasizing the need for careful patient selection and intervention strategies in high-risk groups.

Survival analysis showed a stark contrast between patients in class IV and those with lower DCI values. Class IV patients experienced rapid outcome failures, while those with DCI below 0.45 had significantly better survival rates. In 2019, Qureshi et al., introduced a ductal morphological classification based on tortuosity, categorizing ducts into three types: type I (straight), type II (one curve), and type III (multiple complex turns). Their findings indicated a notably higher rate of pulmonary arterioplasty and unplanned reinterventions in type III patients, aligning with our results that showed a greater need for pulmonary arterioplasty in patients with a higher curvature index (DCI ≥ 0.45).

Although the previous study correlated DCI with tortuosity type, it did not establish cutoff values for assessing DCI severity. In our cohort, we proposed for the first time a quantitative cutoff threshold (DCI ≥ 0.45) to identify high-risk PDA stenting cases.

Future studies should consider using three-dimensional computed tomography (3D CT) and 3D echocardiography for more precise curvature index calculations. A thorough understanding of duct morphology and careful selection of the appropriate vascular access based on duct origin—along with the use of a suitable soft-tipped guide wire that maintains the duct's native course while providing adequate support for stent advancement—are crucial for optimizing stenting outcomes and minimizing major complications. Additionally, wire retraction is a critical phase due to the soft nature of ductal tissue, and using a long sheath can help stabilize the stent during

wire retrieval. Moreover, a significant number of patients with thrombotic events in this cohort had abnormal thrombophilic tests, highlighting the importance of thrombophilia screening prior to stenting to reduce thrombotic risks, especially in high-risk patients.

### 4.2. Comparison between MBTS and DS in high-risk patients

Previous comparisons between MBTs and DS in patients with DDPC have typically not considered the complexity of ductal morphology (Glatz et al., 2018; Santoro et al., 2010; Bentham et al., 2018; Boueck et al., 2019). In a previous study published in 2021 (Mini et al., 2021), our center found that patients with increased ductal tortuosity and a DCI of 0.45 or higher should be classified as high-risk for duct stenting, with only 20% achieving the primary outcome. However, the outcomes for patients in this group who underwent MBTs remain unclear, and the optimal palliative approach for them is still debated. For consistency, we have only included patients with a single lung supply (shunt or stent) in the analysis without concomitant additional repairs.

In the current study, we aimed first to establish a general comparison between the two procedures (DS and MBTs), irrespective of ductal morphology in the DS cohort. Second, we compared outcomes specifically within two high-risk groups: one comprising patients with DDPC and a high DCI (>0.45), and the other including patients with PA-IVS and right ventricular dependent coronary perfusion (RVDCC), where the most effective palliative strategy remains controversial.

#### 4.2.1. General Comparison Between MBTs and DS

When comparing the two procedures overall, we found that the primary outcome was achieved in 77% of the DS group and 75% of the MBTs group, with no statistically significant difference. However, hospital deaths were more prevalent among patients who underwent MBTs (14.2%) compared to only 2.8% in the DS group (*P*-value 0.017). These findings align with previous studies comparing the two palliative strategies (Bentham et al., 2018; Alsagheir et al., 2020). The higher mortality rate in the MBT group is largely attributed to hemodynamic instability caused by diastolic run-off through the shunt and coronary artery steal, observed in 75% of hospital

deaths, while 25% were related to shunt occlusion. Notably, all patients who died post-operation were on ECMO.

There were no significant differences in the need for unplanned reoperations between the two groups. In the DS group, unplanned surgery was required to address desaturation linked to stent failure or failure of ductal recanalization after acute ductal occlusion during the intervention. In the MBT group, unplanned surgeries were performed to manage significant pulmonary overload using shunt clips or to enhance saturation and promote pulmonary artery development by creating a large shunt (5 mm).

Major complications and the need for ECMO were predominantly seen in the MBT group due to postoperative hemodynamic instability, shunt thrombosis, ventricular tachycardia, pericardial effusion, multiorgan failure related to low cardiac output, and neurological issues (such as intracranial bleeding and seizures). Conversely, the main complications in the DS group included acute in-stent thrombosis, stent dislocation, and vessel damage, leading to severe neurological complications.

A previous study (Alsagheir et al., 2021) found that DS is associated with lower mortality and fewer procedural complications, a finding consistent with the results of this study. The increased incidence of hospital deaths, complications, and ECMO needs in the MBT group has led many centers worldwide to prefer DS as the palliative strategy for patients with DDPC. Contrary to previous studies, our results indicated a higher need for pulmonary arterioplasty in the DS group, which may be explained by the highly tortuous ducts leading to functional pulmonary stenosis in our DS cohort (Mini et al., 2021).

#### 4.2.2. MBTs vs. DS in High-Risk Patients for Stenting (DCI >0.45)

Although 64% of patients in the MBTs group achieved the primary outcome, compared to only 20% in the DS group, mortality and the need for ECMO remained higher in the MBTs group for this high-risk population. The survival analysis in Figure 2 shows a significant difference between the two groups. DS appears inadequate for bridging these patients to their next planned surgery without requiring additional operations.

Notably, a substantial proportion of hospital deaths in the MBTs group (57%) occurred among patients who underwent emergency procedures due to desaturation or after resuscitation following acute ductal occlusion during the intervention. This suggests that ductal stent failure in tortuous ducts may adversely affect the outcomes of unplanned MBTs, making surgery more challenging for these patients due to preoperative desaturation and its associated negative impacts on the pulmonary arteries and lungs.

### 4.2.3. MBTs vs. DS in Patients With PA-IVS and RVDCC

Despite ongoing interest in finding solutions for patients with PA-IVS and RVDCC over the past decade (Foker et al., 2008; Cools et al., 2013), no published comparisons have evaluated the two palliative procedures. Our findings indicate that 57.2% of patients in the DS group achieved the primary outcome, compared to only 16.7% in the MBTs group. The use of cardiopulmonary bypass during cardiac surgery did not seem to affect outcomes, as four patients were operated on with bypass initiated via aortic and right atrial cannulation, while two did not use bypass.

Survival analysis clearly shows a dissociation between the two palliative strategies. Hospital deaths and the need for ECMO were reported in half of the patients who underwent MBTs. The higher mortality and morbidity in these patients compared to those in the DS group can be attributed to significant postoperative ST changes, ventricular arrhythmias, and a decreased ejection fraction of the single ventricle due to ischemia, diastolic run-off through the shunt, and coronary steal. There were no significant differences in complications between the two groups.

Finally, our results indicate that, with low mortality and morbidity rates, DS is a viable alternative palliative strategy to MBTs for maintaining pulmonary blood flow in patients with PA and DDPC. It can encourage more symmetrical growth of the pulmonary arteries, although this advantage is less evident in tortuous ducts with a DCI greater than 0.45. Contrary to previous findings, this study suggests that MBTs may be favored over DS for patients with a DCI above 0.45. However, hospital deaths are more prevalent in the MBT group. In contrast, DS appears to be a suitable palliative option for patients with PA-IVS and RVDCC, as it reduces the risk of intra- and postoperative ischemia and ventricular arrhythmias

### 4.3. Transcatheter palliation of stenosed and obstructed MBTS cyanotic congentical heart diseases

Over the past two decades, numerous studies and case reports have highlighted the significance of MBTS interventions and the treatment of shunt thrombosis in infants and adults, particularly for enhancing pulmonary artery growth and addressing life-threatening shunt obstructions (Moszura et al., 2009; Brown et al., 2010; Diaz et al., 2016).

This study aims to review our techniques for intervening in stenosed and obstructed shunts and the outcomes of interventions performed at our center over the past four years. A previous study (Ligon et al., 2017) found that 25% of MBTS interventions were inaccessible via the femoral artery, necessitating access through the carotid artery to reduce procedure time. In contrast, all shunts in our current report were successfully accessed through the femoral artery, with no need for carotid or axillary access. In one case, an acute angle at the anastomosis between the shunt and the brachiocephalic trunc (TBC) posed a challenge for femoral access; however, we overcame this by utilizing three wires to stabilize the advancement of materials into the shunt. Notably, the radiation exposure for our cohort, which included both intervention and diagnostic procedures in stable patients, was equal to or lower than that reported for carotid artery shunt interventions.

Bonnet et al. (Bonnet et al., 2015) documented 33 interventions for obstructed shunts over 20 years, with a complication rate of 15%, including one case of catheter-induced transient complete atrioventricular block, one cardiac tamponade, and one significant thromboembolic stroke. In contrast, our report on 24 emergent interventions for severe stenosis, including four cases of complete obstruction, found no intervention-related complications, including vessel damage or occlusion (Vaughn et al., 2015). These findings align with previous studies (Vaughn et al., 2015) regarding the complete surgical removal of stents during elective shunt takedown.

Wells et al. (Wells et al., 2004) noted that most MBTSs exhibited stenosis by the time of takedown, with 21% showing more than 50% obstruction and histological evidence of myofibroblastic proliferation associated with organized thrombosis. The dilation and stenting of thrombotic shunts carry the risk of embolizing thrombotic

material into the pulmonary arteries (Jenab et al., 2023). Therefore, adequate heparinization during and after the intervention is crucial to prevent acute thrombotic events in the shunt and pulmonary arteries. In our cohort, severe thrombotic events were challenging to manage in patients with impaired thrombophilia diagnostics and a history of multiple thrombotic episodes, despite rigorous intravenous anticoagulation and coagulation monitoring in the ICU. One patient experienced sudden resuscitation, and another suffered sudden death without clear evidence, both being on aspirin, which appeared insufficient for those with multiple stents per shunt. Dual antiplatelet therapy should be considered in such cases (Vaughn et al., 2015).

### 4.4. Transcatheter intervention for stenosed MBTS: A focus on HLHS patients undergoing Norwood palliation

Despite improvements in operative mortality rates, complications from shunt failure remain a significant threat to patient morbidity and mortality. The estimated incidence of shunt failure for Blalock–Taussig shunts is around 9.3%, with early failures accounting for approximately 20% of these cases (Morris et al., 1990; Mini et al., 2023).

Many studies have investigated the outcomes of transcatheter interventions for MBTSs across a range of congenital heart diseases, including patients with HLHS. However, none specifically focused on this cohort (Wells et al.,2004; Bonnet et al., 2015).

In our current report, we assess the results of transcatheter interventions for stenosed and obstructed MBTSs in this critical population, examining the associated morbidity and mortality that could affect outcomes. Maintaining the patency of the MBTS is vital for the survival of HLHS patients undergoing Norwood procedures. Shunt failure can occur at various stages due to different obstruction mechanisms; acute obstructions are often linked to thrombus formation, while late obstructions typically result from neointimal proliferation or calcification. In our experience, the median time to shunt failure or intervention was about two months. However, interventions were always necessary post-shunt placement, including in critically ill patients supported by ECMO. This finding is consistent with a 2015 study involving

all patients who received MBTSs (n = 25), including those with HLHS (n = 10) (Vaughn et al., 2015).

In our cohort, indications for shunt intervention in HLHS patients undergoing NP included restoring the shunt lumen in cases of stenosis or obstruction and delaying subsequent surgeries in critically ill patients or those with underdeveloped pulmonary arteries. While previous studies have reported some complications, all interventions performed at our center over the past 4 years were free of procedure-related complications or deaths. Our study found a median shunt patency of approximately two months (64 days), which included patients who underwent Glenn procedures at the appropriate time and those who died from non-stent-related causes. Shunt dilation and stenting were successful in 76% of our cohort, providing palliative care or facilitating progression to surgeries such as the Glenn procedure, tricuspid valve reconstruction, or aortic reconstruction. The first successful balloon angioplasty for shunt stenosis was recorded in 1989 (Parsons et al.,1989), leading to further retrospective studies (Wang et al., 2001; Moszura et al., 2010; Mini et al.,2024) that reported success rates as high as 91%. Our results corroborate these findings, showing that shunt dilation effectively improved oxygen saturation and bridged patients to the optimal time for subsequent surgeries. In one case, the shunt clip dilation was performed gradually to match the patient's weight.

Approximately 24% of patients experienced sudden thrombotic events, including instances of sudden death. In our cohort, factors associated with thrombosis-related stent failure included a history of shunt occlusion, ECMO therapy necessitating transfusions, impaired coagulation pathways, and the presence of multiple stents within the shunt. Despite intravenous heparinization, preventing the recurrence of in-stent thrombosis in high-risk patients—particularly those with coagulation issues and ECMO-related thrombosis—remained difficult. Aspirin alone proved ineffective in preventing shunt thrombosis in patients with multiple stents, emphasizing the need for dual antiplatelet therapy in this population.

In a prior study at our center (Mini et al., 2024), we examined the outcomes of transcatheter MBTS interventions in patients with pulmonary atresia and those with HLHS. Our findings indicated that patients receiving MBTS solely for adequate pulmonary perfusion—particularly those with tetralogy of Fallot, pulmonary atresia,

and tricuspid atresia—had better outcomes than those undergoing more complex procedures, such as the NP combined with MBTS. Among patients who underwent MBTS alone in our study, 92% subsequently required additional surgical interventions: 46% received Glenn procedures, 38% underwent biventricular repair, and 8% required a Fontan procedure. Furthermore, 8% of patients needed a Sano shunt. We observed significantly higher rates of shunt-related pulmonary torsion, surgery-related shunt stenosis, ECMO-related shunt thrombosis, and sudden death in the NP cohort compared to those with pulmonary atresia who underwent a simple MBTS. These factors adversely impacted the outcomes of MBTS interventions in the Norwood group relative to the other cohort.

The current results indicate lower associated morbidities correlate with better outcomes for patients undergoing shunt interventions. Morbidities such as tricuspid regurgitation, surgery-related aortic arch issues, pulmonary distortion, the need for additional operations, severe pulmonary atresia, and coagulation pathway disorders negatively influenced the outcomes of our cohort.

# 5. Conclusion

Transcatheter intervention to palliate cyanosis in critically ill newborns and infants who depend on the PDA and MBTS for pulmonary perfusion is recognized as both safe and potentially life-saving in emergencies. Our findings provide new insights into these transcatheter interventions within this cohort.

Ducts with a high ductal curvature index are associated with significant complications and an increased risk of stenting failure compared to those with a lower curvature index. This study proposes that establishing a clinical cut-off based on the severity of ductal curvature could help identify high-risk patients for stenting, particularly those for whom ductal stenting may not sufficiently support them until their subsequent planned surgery or intervention. The results indicate that patients with DCI ≥0.45 represent a high-risk group with poor stenting outcomes. Conversely, patients with a curvature index below 0.45—75% of the total cohort—show satisfactory outcomes. A prospective study is needed to validate these findings and determine whether the new curvature-based classification system is effective across different cohorts.

With low mortality and morbidity rates, DS offers an alternative palliative strategy for managing pulmonary blood flow in patients with PA and DDPC. It can encourage symmetrical growth of the pulmonary arteries; however, this advantage appears to be less pronounced in tortuous ducts with a DCI greater than 0.45.

In contrast to earlier findings, this study suggests that MBTs may be preferable to DS for patients with a DCI above 0.45. Nevertheless, hospital mortality rates are still higher with MBTs, while DS appears to be a more suitable palliative option for patients with PA-IVS and RVDCC, as it reduces the risk of intra- and postoperative ischemia and ventricular arrhythmias.

Interventions for stenosed and obstructed MBTS can be safely performed to save lives, provided that the procedure is well-prepared with thorough knowledge of all necessary materials and access routes. This preparation can facilitate intervention and lead to positive outcomes without complications or fatalities. We recommend conducting thrombophilia diagnostics in all patients requiring shunts and related interventions to reduce thrombotic events by implementing an optimal

anticoagulation strategy as early as possible. Partial stenting of a shunt may lead to new stenosis in the non-stented tissue. In cases of localized shunt stenosis, complete stenting is advisable to prevent the development of new stenosis and the need for a second stent. For atypical shunt anastomoses, axillary and carotid access points should be considered to ease the intervention and reduce radiation and procedural time. The necessity for shunt stenting with multiple stents or the need for reintervention appears to increase the risk of shunt thrombosis. Aspirin alone has proven ineffective, so dual antiplatelet therapy is strongly recommended. From our experience, the diameters of 3.5 mm and 4 mm shunts can be expanded via stenting to 4.5 mm and 5 mm, respectively. This makes shunt stenting a viable alternative to surgical revision, allowing for a delay in subsequent operations when the patient is not fit for surgery or when contraindications exist. It is crucial to avoid diuretics and dehydration in patients with shunt stenting who are discharged home. Effective antiplatelet therapy and careful echocardiographic monitoring to rule out shunt stenosis are essential to minimize the risk of sudden death due to shunt thrombosis. Transcatheter interventions for MBTS in neonatal patients with HLHS are considered both safe and potentially life-saving in emergencies. This approach can promote pulmonary development, delay the need for subsequent surgeries, and provide medium-term palliative care for critically ill patients. However, managing late complications, such as stent thrombosis, remains a significant challenge. Our findings indicate that risk factors for shunt thrombosis include ECMO therapy, underlying coagulation disorders, the presence of multiple stents within the shunt, and a history of shunt thrombosis prior to intervention. We advocate for dual antiplatelet therapy and thorough echocardiographic evaluations to detect shunt stenosis earlier, particularly in high-risk patients. Additionally, preventing dehydration and avoiding diuretics are essential to mitigate the risk of thrombotic events in this population.

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