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ORIGINAL RESEARCH

PEDIATRIC CARDIOLOGY

Percutaneous Pulmonary Flow Restriction in Infants With Congenital Heart Disease

Matthew Warren, MD, Ana Vasquez Choy, MD, Mohammed Khan, MD, Matthew Brown, MD, Damien LaPar, MD, Jorge Salazar, MD, Kiran Mallula, MD

ABSTRACT

BACKGROUND Restriction of PBF in infants born with CHD is often required to avoid pulmonary over-circulation prior to definitive intervention. The current standard is to surgically place pulmonary artery bands, but these have limitations and are associated with complications.

OBJECTIVES The purpose of this study was to a single-center experience with a relatively novel technique to percutaneously restrict pulmonary blood flow (PBF) in select infants with congenital heart disease (CHD).

METHODS Patients were selected to undergo this procedure either due to low birth weight or prematurity. All of them had CHD that would result in over-circulation without control of PBF. By a percutaneous method, modified vascular plug devices were placed in the bilateral branch pulmonary arteries.

RESULTS Seven neonates with CHD resulting in left-sided obstruction underwent this procedure. All patients demonstrated evidence of restricted PBF with a decrease in mean oxygen saturation from 95% to 84%. One patient required pulmonary artery band placement due to over-circulation 5 days after the procedure. All patients proceeded to full surgical intervention without device embolization or need for pulmonary arterioplasty. Hemodynamics demonstrated adequate limitation of PBF in 5 patients who underwent presurgical cardiac catheterization with a mean pulmonary vascular resistance of 1.52 WU $\times$ m^2 and a mean transpulmonary gradient of 5.9 mm Hg.

CONCLUSIONS Percutaneous PBF restriction appears to be safe and a less invasive option to delay surgical intervention in a select population to allow for somatic growth and gestational maturation. It results in a decrease in the total number of sternotomies. (JACC Adv 2024;3:101031) © 2024 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Patients born with hypoplastic left heart syndrome often present with a multitude of difficulties in management due to underlying congenital heart disease (CHD), other comorbidities, and in some cases prematurity or small birth weight. Prematurity presents a unique challenge in the management of these infants, as undergoing cardiopulmonary bypass is relatively contraindicated in this

From the Children's Heart Institute, Children's Memorial Hermann Hospital, UTHealth, Houston, Texas, USA.
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ABBREVIATIONS AND ACRONYMS

CHD = congenital heart disease

LPA = left pulmonary artery

PBF = pulmonary blood flow

PFR = pulmonary blood flow restrictors

RPA = right pulmonary artery

population. However, simply waiting for the patient to mature is often not an option, as the patent ductus arteriosus maintained with prostaglandin will lead to excessive left to right shunt as the pulmonary vascular resistance naturally drops. Kept unchecked, this may lead to compromised systemic perfusion. Additionally, this has been shown to lead to pulmonary hypertension in animal models[1] as well as in our clinical experience. Medical management is limited to reducing the pulmonary blood flow (PBF) by lowering the prostaglandin infusion rate as low as possible to shrink the patent ductus arteriosus, as well as maintaining slight respiratory acidosis to increase pulmonary vascular resistance. However, these strategies are only short-term temporizing measures prior to surgical intervention. In select infants who cannot undergo stage 1 palliation, surgical branch pulmonary artery bands can be placed to restrict pulmonary blood flow prior to the stage I palliation.[2] However, this procedure requires a median sternotomy and may require multiple readjustments of the bands. The use of percutaneously placed pulmonary blood flow restrictors (PFRs) using modified vascular plugs has been previously described in the literature, though its use has been very limited.[3-6] Since our center has a propensity for caring for unusually small and/or premature infants, we sought to employ this novel technique in select patients.

METHODS

This is a retrospective single-center case series with a goal to demonstrate the safety and feasibility of a novel technique to restrict pulmonary blood flow. Informed consent was obtained prior to the procedure. Emphasis was placed on the discussion of the risks and benefits of the procedure, as well as the novelty of the procedure compared to pulmonary artery banding. Prior to data collection, Institutional Review Board approval was acquired.

PROCEDURE TECHNIQUE. Based on previous literature, Medtronic vascular plug devices (Medtronic) were selected.[3] The devices were sized based on angiographic measurement of the proximal branch pulmonary arteries (Figure 1). To account for stretch of the pulmonary arteries as well as future growth, we selected devices with an external diameter approximately 20% to 40% more than the diameter of each proximal branch pulmonary artery. Each device was then modified with a Sharpoint stab knife 15° straight blade (Sharpoint) to create an equilateral triangular opening in the Gore-Tex membrane of approximately $1 \times 1 \times 1$ mm that results in an effective opening area of 0.44 mm^2 in an unconstrained device (Figure 2). The small size of the opening was determined to be necessary while accounting for possible para-device blood flow in those patients with decreased apposition of the Gore-Tex membrane with the vessel wall. In 1 case, no opening was made in the RPA device covering to understand the relative contribution of intra-device flow with para-device flow. In that patient, there was residual para-device flow likely from reduced radial occlusive forces of the device frame. After the procedure, all patients were started on systemic anticoagulation with heparin infusion and transitioned to aspirin with or without low-molecular-weight heparin, until undergoing stage I palliation or definitive repair. All patients were maintained on prostaglandin infusion while awaiting the next intervention. The timing of the next intervention was based on reaching appropriate gestational age to undergo cardiopulmonary bypass or as clinically optimized to undergo further intervention.

STATISTICS. Basic descriptive statistics including mean and median with standard deviation were used for data analysis.

RESULTS

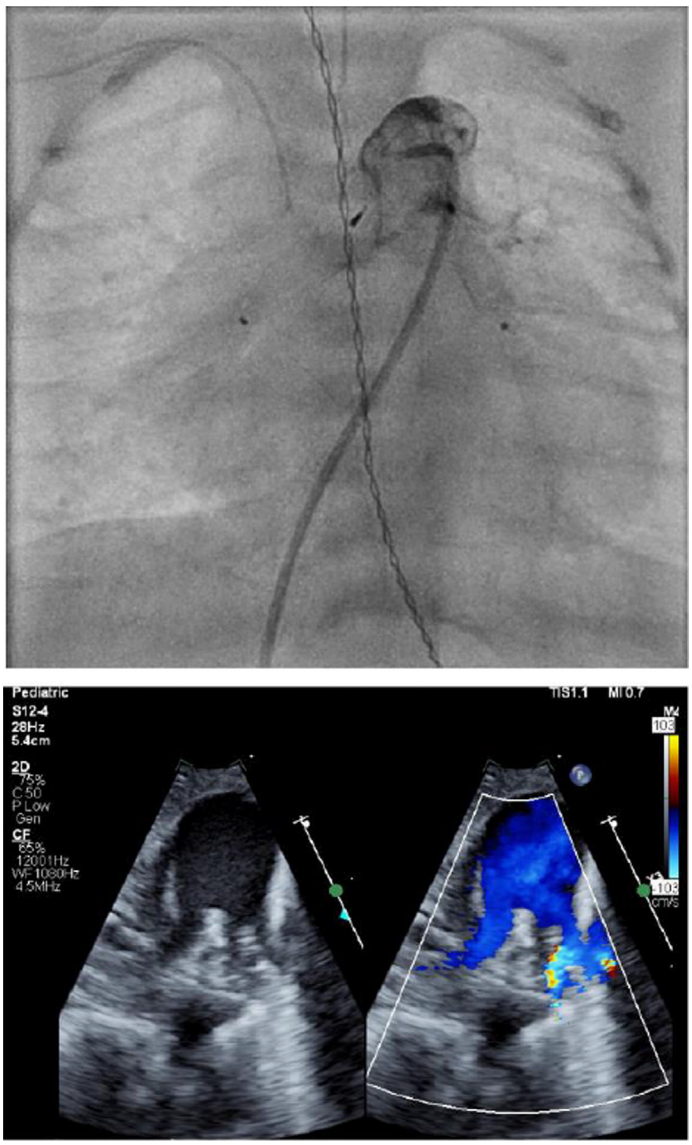
BASELINE CHARACTERISTICS. In total, 7 patients were selected for this intervention. Five were born at <37 weeks gestation and one was born at term but was small for gestational age. All patients were deemed to have contraindication for undergoing immediate stage I palliation or repair. All patients demonstrated clinical signs of pulmonary overcirculation despite medical therapy and were deemed to require pulmonary blood flow restriction after multidisciplinary discussion. Seven patients underwent percutaneous pulmonary blood flow restriction. Five patients were diagnosed with hypoplastic left heart syndrome. One patient was diagnosed with a Shone's complex variant with severe aortic stenosis that required single ventricle palliation, and 1 patient was diagnosed with a Shone's complex variant with a large ventricular septal defect that later underwent full repair. Five patients were born prematurely, with an average gestational age of 35.8 weeks. Most patients were small, with an average birth weight of 2.43 kg. Except 2 patients, all underwent this procedure within the first week of life (Table 1). By angiography, the mean proximal right pulmonary artery (RPA) diameter was 5.4 ± 1.0 mm, and the left pulmonary artery (LPA) mean diameter was 5.3 ± 0.9 mm. Preintervention, the mean oxygen

saturation was 95% ± 0.02% and the partial pressure of oxygen was 58.6 ± 11.1 mm Hg.

HEMODYNAMIC CHANGES. After intervention, the mean oxygen saturation decreased to 84% ± 0.07% with a corresponding decrease in partial pressure of oxygen to 50.4 ± 11.6 mm Hg. By echocardiography, the peak Doppler gradient across the RPA after device placement was 28.4 ± 10.4 mm Hg, and across the LPA was 29.7 ± 7.5 mm Hg. All patients required furosemide after the procedure. Prior to undergoing surgical intervention and device removal, the peak Doppler gradient across the RPA was 44.2 ± 15.2 mm Hg and across the LPA 49.8 ± 19.2 mm Hg. All patients that required single ventricle palliation underwent Norwood procedure with Sano conduit placement as the stage I palliation. One patient with Shone's variant with ventricular septal defect underwent full repair with ventricular septal defect patch closure and aortic arch augmentation. The mean time to surgical intervention was 23.4 ± 27.4 days, with 1 patient waiting for 67 days prior to intervention. One patient required surgical pulmonary artery band placement 5 days after PFR placement due to pulmonary over-circulation despite the procedure (**Central Illustration**).

INTERVENTIONAL OUTCOMES. All the procedures were successfully performed with no acute complications. There were no device embolization and none of them required removal prior to stage 1 palliation or repair. One patient developed *Candida* fungemia unrelated to the procedure, and 1 patient developed transient complete atrioventricular block while undergoing balloon atrial septostomy after PFR placement. During surgical palliation or repair, no patients required pulmonary arterioplasty or repair. All devices were easily removed except in 1 patient where they were in situ for 67 days, requiring prolonged retrieval at the time of surgery. At the time of writing, 5 patients underwent successful stage II palliation with bidirectional Glenn procedure and 1 patient underwent biventricular repair. On hemodynamic assessment prior to undergoing bidirectional Glenn, the mean pulmonary artery pressure was 13.2 ± 2.5 mm Hg, pulmonary vascular resistance was 1.52 ± 0.25 WU × m^2, and mean transpulmonary gradient was 5.9 ± 1.2 mm Hg. The branch pulmonary arteries were evaluated by angiography, showing a mean proximal RPA diameter of 4.9 ± 1.3 mm and a mean proximal LPA diameter of 3.8 ± 1.3 mm. One patient had significant angiographic narrowing of the LPA at the Sano conduit insertion site that was addressed surgically at the time of the bidirectional Glenn procedure.

FIGURE 1 Intraoperative Image Guidance for PFR Placement

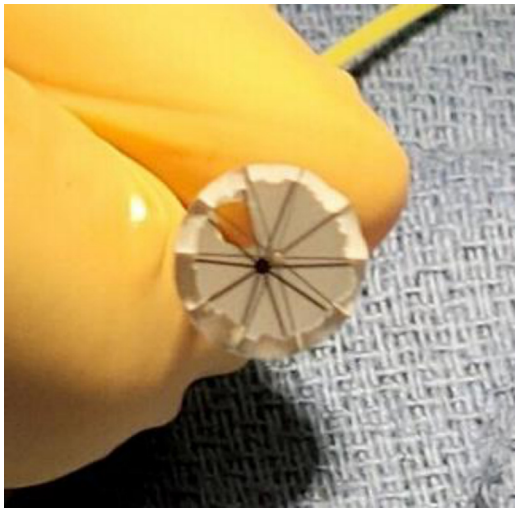


(A) Fluoroscopic image with angiography after deployment of bilateral pulmonary flow restrictors showing restricted but equal flow to the branch pulmonary arteries (B) Echocardiographic image from the suprasternal notch view after pulmonary blood flow restrictor placement.

DISCUSSION

In patients with associated variables like prematurity or low birth weight, requiring pulmonary blood flow regulation, primary surgical repair, or palliation can be deferred by surgical pulmonary artery banding. However, a percutaneous approach to restricting pulmonary blood flow is less invasive as it does not require a sternotomy. Our experience demonstrates a

FIGURE 2 Preimplantation Device Modification



Modified Medtronic Vascular Plugs prior to implantation with fenestration created.

safe and feasible alternative approach to pulmonary blood flow restriction using a percutaneous approach in infants with CHD requiring control of pulmonary blood flow prior to definitive repair or palliation. There were no procedure-related complications. One patient required surgical placement of pulmonary artery bands due to inadequate pulmonary restriction. The reasons for this are unclear but hypothesized to be due to the patient's larger pulmonary artery size and thus the need for the use of Medtronic vascular plug 9Q devices in comparison to the 7Q devices used in all other cases. The slightly different shape of the larger device may allow for increased para-device flow of blood and thus lesser restriction of pulmonary blood flow. One patient's PFR devices remained in place for much longer than initially intended due to *Candidemia* unrelated to device placement. Reassuringly, this patient's circulation remained well balanced for the duration of the life of the devices. Complications such as device embolization and scarring resulting in pulmonary artery stenosis have been reported.[4] However, there were no device embolizations in this series. Even in the aforementioned case where the devices remained in situ for 67 days, there was no requirement of pulmonary arterioplasty after device retrieval.

The flow restrictors do not appear to result in immediate cessation of pulmonary over-circulation. Medical management with diuretic therapy was required in the immediate postprocedure period, to achieve a balanced circulation. Though there was a concern that this transient phase of mild over-circulation may result in suboptimal pulmonary vasculature bed, reassuringly, the 5 patients that underwent pre-bidirectional Glenn invasive hemodynamic assessment demonstrated normal pulmonary artery pressures, transpulmonary gradient, and calculated pulmonary vascular resistance, indicating the presence of a healthy pulmonary vascular bed not significantly affected by this transient over-circulation.

CONCLUSIONS

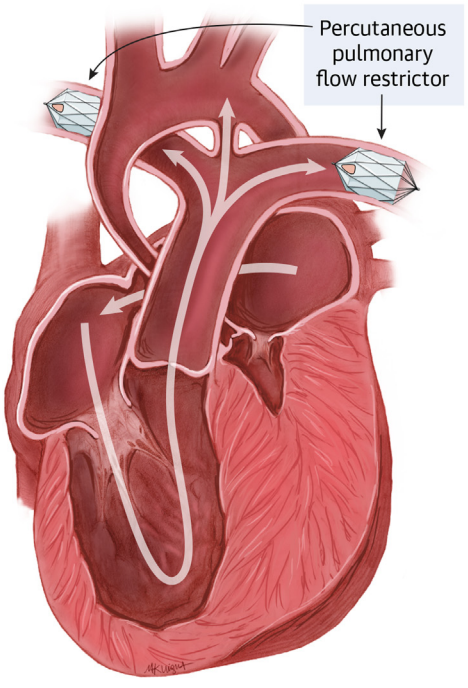
We report a technique using a percutaneous method to restrict pulmonary blood flow in infants with CHD, demonstrating safety and efficacy of this procedure. Limitations of the study include the small sample size, as well as the novelty of the procedure at our institution, resulting in slight variations in technique related to placement of the devices, as well as the postoperative management of these patients. Future studies should include a larger cohort of patients undergoing this procedure so that parameters such as

TABLE 1 Patient Demographics

Diagnosis	Gestational Age (wk)	Birth Weight (kg)	Age at PFR (d)	Weight at PFR (kg)	Age at Removal (d)	Days With PFR
HLHS (MA/AS)	34.1	1.95	6	1.9	73	67
HLHS (MA/AS)	34.6	1.98	14	2	28	14
HLHS (MA/AA)	35	1.97	6	2	25	19
HLHS (MA/AA)	39.2	3.89	7	3.64	31	25
HLHS (MS/AS)/Shone's complex variant	38	2.13	5	2	10	5
HLHS (MA/AA)	36	3	4	2.8	17	13
Shone's complex variant	33.5	2.1	13	2.07	33	21
Mean ± SD	35.8 ± 2.1	2.43 ± 0.7	7.9 ± 4.0	2.3 ± 0.7	31 ± 20.2	23.4 ± 27.4

AA = aortic atresia; AS = aortic stenosis; HLHS = hypoplastic left heart syndrome; MA = mitral atresia; MS = mitral stenosis; PFR = pulmonary flow restrictors.

CENTRAL ILLUSTRATION **Percutaneous Pulmonary Flow Restriction in Infants With Congenital Heart Disease Process Model for Percutaneous Pulmonary Flow Restrictor Placement**



Patient Selection
Neonate with CHD with left obstructive lesions at risk for pulmonary overcirculation AND with contraindications for definitive intervention

Device Selection
- Angiographic measurement of RPA and LPA diameters
- MVC device selection sized 20%-40% larger than vessel measurement

Device Preparation
- Sharpoint stab knife 15 straight blade to create fenestration in Gore-Tex membrane of device
- Device implantation in the branch pulmonary arteries under fluoroscopic and echocardiographic guidance

Post-Procedural Monitoring
With adequate pulmonary flow restriction there is a decrease in SO_2 and PaO_2

Device Removal
At the time of definitive surgical intervention, ideally <8 weeks after implantation

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CHD = congenital heart disease; LPA = left pulmonary artery; RPA = right pulmonary artery.

device sizing, technique of modification of the device, and postoperative management such as anticoagulation can be better defined. Multicenter collaborative studies may help in that regard.

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The authors have reported that they have no relationships relevant to the contents of this paper to disclose.

ADDRESS FOR CORRESPONDENCE: Dr Kiran Mallula, Division of Pediatric Cardiology, UTHealth Houston, 6410 Fannin, Suite #425, Houston, Texas 77030, USA. E-mail: Kiran.k.mallula@uth.tmc.edu.

PERSPECTIVES

COMPETENCY PATIENT CARE AND PROCEDURAL SKILLS: Percutaneous pulmonary flow restriction is safe and effective and avoids pulmonary over-circulation prior to definitive repair or palliation in infants with CHD.

TRANSLATIONAL OUTLOOK: Further studies should explore the optimal patient cohorts with CHD who will benefit from this procedure and describe the collective mid- and long-term outcomes.

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KEY WORDS congenital heart disease, HLHS, prematurity, pulmonary overcirculation