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EDITORIAL COMMENT

Pulmonary Flow Restrictors in Patients With Single-Ventricle Physiology

Are They Restrictive Enough?

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For patients born with hypoplastic left heart and its variants deemed high risk for an initial heart transplant or Norwood (ie, Blalock-Taussig-Thomas shunt or Sano) operation, surgical pulmonary artery banding (PAB) remains the standard palliative approach to protect the pulmonary vascular bed from excessive flow and pressure, particularly those who require time to mature before undergoing cavopulmonary anastomosis. Under median sternotomy, surgeons will commonly place 1 to 2 mm polytetrafluoroethylene (PTFE) bands in the proximal pulmonary arteries alone, along with the continuation of prostaglandin e1 infusion or with complimentary ductal stenting (ie, hybrid palliation), to temporarily stabilize the patient's condition, aiming to balance cardiac output and limit pulmonary overcirculation. Despite technical modifications over the years, namely, appropriate sequence and timing of PAB, inherent concerns and potential complications associated with this strategy remain, including various degrees of pulmonary artery stenosis or distortion requiring complex and challenging reconstruction that could hinder stage II palliation.[1]

In recent years, an out-of-the-box catheter-based intervention has been grabbing attention inside and outside cardiac laboratories worldwide. The goal is simple, or at least that's the rationale behind it. What if, instead of traditional surgical banding of the pulmonary arteries, a less invasive approach could be offered to "restrict" pulmonary blood flow, thus allowing tolerable hemodynamics for later surgical palliation? After previous failed attempts with unreliable and cumbersome technology, a novel transcatheter approach involving the so-called pulmonary blood flow restrictors (PFRs) using a modified, by partially removing the PTFE membrane, Medtronic Vascular Plug to be implanted as a partially occlusive device to control pulmonary flow predictably and be eventually retrieved was successfully described by Khan et al[2] in a growing swine model. Shortly after that, the reputable center from Giessen in Germany, renowned for its tireless and valuable contributions to the management of infants with single ventricle physiology, adopted this approach in neonates, mostly with hypoplastic left heart, to offer a purely endovascular hybrid procedure by safely stenting the arterial duct and implanting the modified PFRs in the pulmonary arteries demonstrating promising results.[3,4] Extended application of PFRs in 2-ventricle patients with large left to right shunts before complete repair has been recently reported.[5] Their role in biventricular congenital heart disease, which is likely subject to a different analysis, remains outside the scope of this editorial.

In this issue of *JACC: Advances*, Warren et al[6] expand and offer valuable insights into this novel strategy. The study included 7 neonates, precisely 5 with hypoplastic left heart and 2 with Shone's complex variants with significant left-sided obstruction, who underwent percutaneous pulmonary blood flow restriction using the modified Medtronic Vascular Plug PFRs, particularly in cases where prematurity or small birth weight (average birth weight of 2.4 kg) were considered a contraindication for immediate stage I palliation or repair. Devices were selected to be 20 to 40% larger than each proximal branch pulmonary artery, and all except 1 device had $1 \times 1 \times 1$ triangular blade fenestrations, resulting in an

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effective opening area of 0.44 mm^2. The authors describe the procedure as evidence of restricted pulmonary blood flow, with a decrease in mean oxygen saturation from 95% to 84% and reassuring hemodynamics assessed by cardiac catheterization before surgery, with 6 out of 7 patients eventually undergoing surgical stage II palliation (n = 5) and 1 patient with Shone's complex and a large ventricular septal defect undergoing complete repair. Notably, there were no procedure- or device-related complications, including device embolization. Furthermore, all devices except one (remaining in situ for 67 days) were easily retrieved by the surgeons without needing pulmonary artery plasty. The latter is in keeping with an uneventful device explantation reported by the Giessen series performed instead by snaring in most of their patients, although, in their experience, attempted snare removal of the PFR from the left pulmonary artery in one of their patients induced an intimal flap necessitating left pulmonary artery stenting immediately after surgery.[3]

Upon closer inspection, however, we must be aware of critical potential drawbacks before adopting a widespread total transcatheter strategy. As stated by Nageotte et al,[7] a word of caution is more than fitting. In their experience, similar in number and patient characteristics, distal migration of the PFR was common (in 5 out of 6 patients) into the right pulmonary artery crossing the upper lobe takeoff despite what was considered appropriate device oversizing, and 1 patient (who had the PFRs for 96 days) was noticed to have left pulmonary artery stenosis upon surgical removal requiring stenting, reflecting potential scarring and pulmonary artery distortion are latent. Even more concerning is clinically significant pulmonary overcirculation remains a constant in all published series, requiring either repeat catheterization with device removal and replacement with larger devices or device removal and complimentary surgical PAB, as described by the authors in 1 patient only 5 days after PFRs were implanted.[3,4,6,7] Where hemodynamics play a huge role in decision-making in infants with single-ventricle physiology and where a healthy pulmonary vascular bed is highly desirable, a valid question arises: are PFRs restrictive enough? One would consider an affirmative answer based on the German experience and the results shown by the authors, with mean pulmonary artery pressure (13.2 ± 2.5 mm Hg), mean pulmonary vascular resistance (PVRi) (1.52 ± 0.25 WU/m^2), and mean transpulmonary gradient (5.9 ± 1.2 mm Hg) all within ideal values obtained during cardiac catheterization before surgical repair. In contrast, one would refrain or at least reconsider the answer based on data reported by Nageotte et al, where despite what was considered successful PFR implantation, 4 out of 6 patients undergoing repeat catheterization revealed elevated Qp: Qs >2:1 (2 even >4:1) and elevated mean pulmonary pressure (>20 mm Hg) in 3 of these 4 patients where PVRi could not be accurately calculated.[7] The latter reflects that performance predictability remains an issue, at least for now. Limiting pulmonary flow around the device, establishing an appropriate device size selection, and, more importantly, deciding on an appropriately sized PTFE fenestration to promote accurate flow restriction are all open queries that must be addressed as the growing experience with PFRs continues to expand. However, it is true that many of these technical considerations still apply to surgical PAB, which is far from an ideal or mastered procedure.

Thus, it remains crucial for health professionals devoted to pediatric heart patients to carefully weigh the risks and benefits of surgical PAB compared to pulmonary blood flow restrictors according to each pediatric heart center's local preference and competence and to consider it only part of a broader treatment algorithm for managing this often fragile and complex subset of patients born with a hypoplastic left heart or other complex heart anatomies. While acknowledging the study's limitations, including small sample size and variations in technique due to the procedure's novelty, the results by Warren et al[6] proved to be a safe and less invasive option, effectively delaying surgical intervention and warranting further exploration. Future studies with larger cohorts are essential to refine device and fenestration sizing, technique refinement, and standardization, contributing to advancing our clinical practice.

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