

Management of a Stenotic Right Ventricle-Pulmonary Artery Shunt Early After the Norwood Procedure

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Background. Inadequate pulmonary blood flow through a right ventricle-to-pulmonary artery (RV-PA) shunt early after the Norwood operation can be remedied by adding a modified Blalock-Taussig (mBT) shunt. We used multiscale computational modeling to determine whether the stenotic RV-PA shunt should be left in situ or removed.

Methods. Models of the Norwood circulation were constructed with (1) a 5-mm RV-PA shunt, (2) a RV-PA shunt with 3- or 2-mm stenosis at the RV anastomosis, (3) a stenotic RV-PA shunt plus a 3.0- or 3.5-mm mBT shunt, or (4) a 3.5-mm mBT shunt. A hydraulic network that mathematically describes an entire circulatory system with pre-stage 2 hemodynamics was used to predict local dynamics within the Norwood circulation. Global variables including total cardiac output, mixed venous oxygen saturation, stroke work, and systemic oxygen delivery can be computed.

Results. Proximal stenosis of the RV-PA shunt results in decreased pulmonary blood flow, total cardiac output,

mixed venous saturation, and oxygen delivery. Addition of a 3.0- or 3.5-mm mBT shunt leads to pulmonary overcirculation, lowers systemic oxygen delivery, and decreases coronary perfusion pressure. Diastolic runoff through the stenotic RV-PA shunt dramatically increases retrograde flow into the single ventricle. Removal of the stenotic RV-PA shunt balances systemic and pulmonary blood flow, eliminates regurgitant flow into the single ventricle, and improves systemic oxygen delivery.

Conclusions: Adding a mBT shunt to remedy a stenotic RV-PA shunt early after a Norwood operation can lead to pulmonary overcirculation and may decrease systemic oxygen delivery. The stenotic RV-PA shunt should be taken down. Conversion to an optimal mBT shunt is preferable to augmenting a stenotic RV-PA shunt with a smaller mBT shunt.

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Instead of a modified Blalock-Taussig (mBT) shunt, a right ventricle-to-pulmonary artery (RV-PA) shunt is an alternative source of pulmonary blood flow in the Norwood operation for hypoplastic left heart syndrome. By eliminating the obligatory diastolic runoff in the mBT shunt, the main proposed benefits of the RV-PA shunt include better coronary and systemic perfusion, more balanced and predictable pulmonary-to-systemic flow ratio, and decreased ventricular volume loading [1]. However, there are concerns of the consequences of the ventriculotomy and diastolic flow regurgitation on the single systemic RV. An ongoing randomized controlled trial aims to answer whether the theoretic advantages of the RV-PA shunt translate to improved clinical outcomes [2]. Controversies remain about which shunt strategy produces better postoperative hemodynamics, pulmonary arterial growth, and patient survival [3].

In the interim, there is a growing awareness that premature stenosis of the RV-PA shunt can lead to early oxygen desaturation and contribute to interstage morbidity and death [4–6]. Recognized initially by Sano and colleagues [5], early shunt obstruction is primarily due to proximal stenosis at the right ventricular anastomosis. Many centers are performing stage 2 palliation earlier in Norwood patients with RV-PA shunts, some as early as age 3 months, because of worsening cyanosis [7–9]. However, RV-PA shunt stenosis during or shortly after the Norwood operation, at a time when a superior cavopulmonary connection is not feasible, requires catheter intervention or surgical revision.

Two recent reports have documented an increased incidence of shunt intervention in Norwood patients with RV-PA shunts compared with patients with a mBT shunt [10, 11]. Stent placement can distort the RV-PA shunt, and many surgeons are reluctant to advocate catheter manipulation and stent deployment across a highly obstructed obligatory source of pulmonary blood flow [4, 12, 13]. Surgical revision of proximal RV-PA shunt stenosis requires re-arresting the heart to prevent air embolism. The other two alternatives are conversion to a mBT shunt or augmenting the RV-PA shunt with an additional mBT

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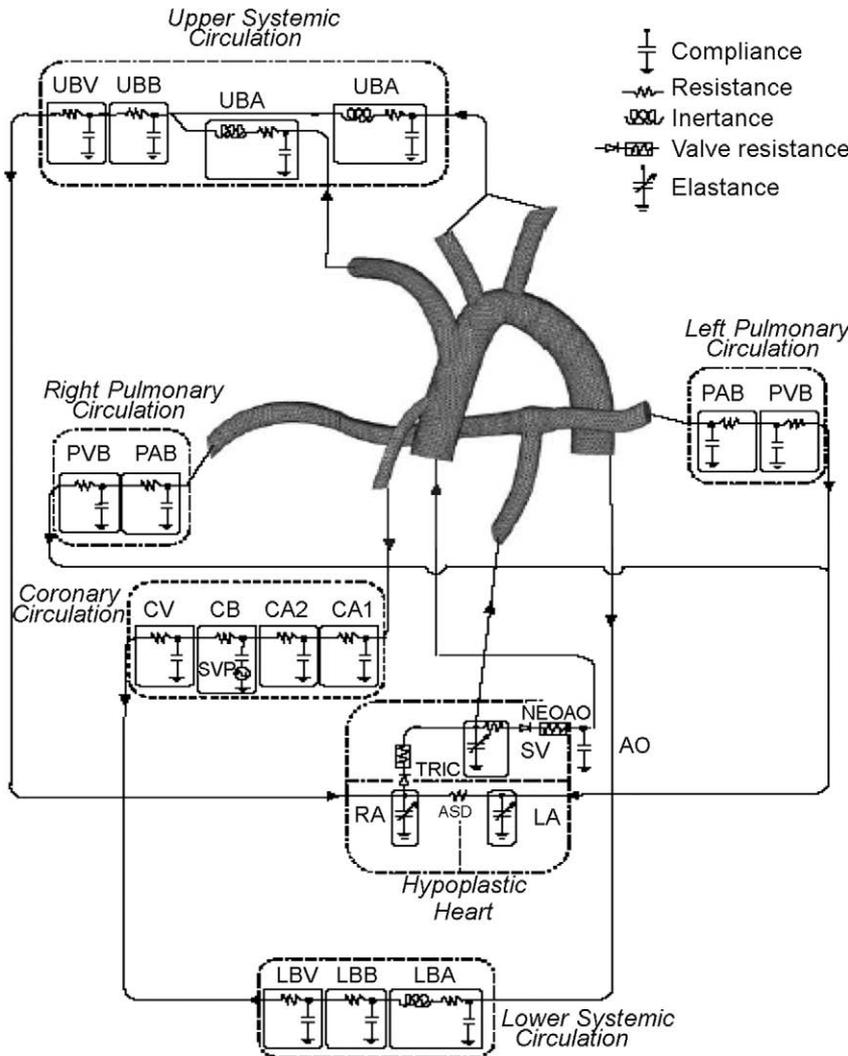


Fig 1. Schematics of the multiscale model of a 5-mm right ventricle to pulmonary artery shunt Norwood circulation that couples a 3-dimensional computational fluid dynamics model to the lumped parameter network of the entire circulation. (AO = aorta; ASD = atrial septal defect; CA1 = coronary artery 1; CA2 = coronary artery 2; CB = coronary bed; CV = coronary vein; LA = left atrium; LBA = lower body arteries; LBB = lower body bed; LVB = lower body veins; NEOAO = neo-aorta; PAB = pulmonary arterial bed; PVB = pulmonary venous bed; RA = right atrium; SVP = single ventricle physiology; TRIC = tricuspid valve; UBA = upper body arteries; UBB = upper body bed; UBV = upper body veins.)

shunt. The influence of either strategy on flow dynamics, such as diastolic runoff, and on systemic physiology, such as oxygen delivery and cardiac stroke work, is unknown.

This study was conducted to determine whether the stenotic RV-PA shunt should remain open as a source of pulmonary blood flow when a mBT shunt is used to remedy inadequate pulmonary blood flow early after a RV-PA Norwood operation. We used a recently introduced and validated multiscale computational modeling approach, where three-dimensional (3D) computational fluid dynamics (CFD) models of the Norwood reconstruction are coupled to a network description of the entire circulatory system, using clinical patient hemodynamic data [14, 15]. The multiscale computation quantifies the flow dynamics in the CFD model, such as pressures and flow in the Norwood circulation, as well as global variables such as systemic oxygen delivery [16, 17]. We studied various models of proximal RV-PA shunt stenosis, and their correction, by adding a mBT shunt or conversion to a mBT shunt as the sole source of pulmonary blood flow.

Material and Methods

The mathematic equations and computational methodologies applied in our previous multiscale modeling studies were used in this study [14, 15, 17-19]. Briefly, the multiscale approach couples a 3D CFD model of the Norwood procedure to a 0D lumped parameter or hydraulic network description of the entire circulation outside of the surgical domain. Figure 1 depicts a multiscale model of a Norwood procedure with a RV-PA shunt. The multiscale simulation solves the flow and pressure dynamics at any part of the surgical domain of the Norwood procedure, such as flow regurgitation in the RV-PA shunt and coronary perfusion pressure. At the same time, physiologic variables such as systemic oxygen delivery and right ventricular stroke work can also be calculated.

3D Models

Six different detailed 3D models of the Norwood procedure based on the finite volume method were developed.

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