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Hemodynamics of patient-specific aorta-pulmonary shunt configurations

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ABSTRACT

Optimal hemodynamics in aorta-pulmonary shunt reconstruction is essential for improved post-operative recovery of the newborn congenital heart disease patient. However, prior to *in vivo* execution, the prediction of post-operative hemodynamics is extremely challenging due to the interplay of multiple confounding physiological factors. It is hypothesized that the post-operative performance of the surgical shunt can be predicted through computational blood flow simulations that consider patient size, shunt configuration, cardiac output and the complex three-dimensional disease anatomy. Utilizing only the routine patient-specific pre-surgery clinical data sets, we demonstrated an intelligent decision-making process for a real patient having pulmonary artery atresia and ventricular septal defect. For this patient, a total of 12 customized candidate shunt configurations are contemplated and reconstructed virtually using a sketch-based computer-aided anatomical editing tool. Candidate shunt configurations are evaluated based on the parameters that are computed from the flow simulations, which include 3D flow complexity, outlet flow splits, shunt patency, coronary perfusion and energy loss. Our results showed that the modified Blalock-Taussig (mBT) shunt has 12% higher right pulmonary artery (RPA) and 40% lower left pulmonary artery (LPA) flow compared to the central shunt configuration. Also, the RPA flow regime is distinct from the LPA, creating an uneven flow split at the pulmonary arteries. For all three shunt sizes, right mBT innominate and central configurations cause higher pulmonary artery (PA) flow and lower coronary artery pressure than right and left mBT subclavian configurations. While there is a trade-off between energy loss, flow split and coronary artery pressure, overall, the mBT shunts provide sufficient PA perfusion with higher coronary artery pressures and could be preferred for similar patients having PA overflow risk. Central shunts would be preferred otherwise particularly for cases with very low PA overflow risk.

1. Introduction

Pulmonary atresia with ventricular septal defect (PA-VSD) accounts for 1% to 2% of children born with a congenital heart defect. This complex condition differs from the standard tetralogy of Fallot due to its obligatory extra-cardiac pulmonary blood flow sources. For patients with diminished pulmonary blood flow, an artificial systemic-to-pulmonary artery shunt is surgically reconstructed. Several templates have been used to create aorta pulmonary conduits, including the modified Blalock-Taussig (mBT), central, right ventricle-to-pulmonary artery, Potts, Waterston/Cooley and reverse BT (Baba et al., 2013) shunts, even though some of them are very rarely used (van Doorn and de Leval, 2006).

Hospital mortality of mBT and central shunt operations are 10.2% and 14.2%, respectively (European Association for Cardio-Thoracic Surgery, 2015), which is significantly higher than other more complex or simpler pediatric pathologies (European Association for Cardio-Thoracic Surgery, 2015). While it is widely accepted that the outcome depends on the balance between the pulmonary and systemic flows (Q_P/Q_S ratio) (Erek et al., 2006), the prediction of the post-operative hemodynamic state is challenging due to the complex relation between the shunt design, patient-specific anatomy, hemodynamics and cardiac output. The state-of-the art surgical decision-making process is founded on experience and constitutes a qualitative trade-off between the confounding performance objectives. For example, the conduit size should be large enough to supply sufficient blood to the pulmonary vascular bed for adequate oxygenation; but in the case of excessive

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pulmonary blood flow, pulmonary edema and heart failure may develop. There are other potential complications directly associated with the shunt hemodynamics, including the risk of stenosis or thrombosis of the shunt, distortion of the pulmonary artery, poor coronary perfusion and asymmetric growth of the pulmonary arteries (Waniewski et al., 2005). Customized vascular simulations based on the three-dimensional (3D) reconstruction of the patient-specific vascular anatomy and flow conditions may allow improved flow physics-based decision-making (Marsden, 2013; Pekkan et al., 2008; Piskin et al., 2015). With this in mind, the objective of the present study is to conduct a real-life pre-surgical planning effort for a neonatal patient case, prior to *in vivo* execution.

Computational fluid dynamics (CFD) has been increasingly used to study the effects of the diameter, curvature and angle of the conduits, and the hemodynamics of mBT procedures (Malota et al., 2007; Migliavacca et al., 2000; Sant'Anna et al., 2003; Waniewski et al., 2005). These studies were exclusively conducted on idealized anatomies and only a few incorporated the real neonatal arterial anatomy. Jinlong et al. (2013) and Qian et al. (2010) presented the post-surgery hemodynamics of one specific shunt type (right ventricle to pulmonary artery conduit) without offering any comparison to other possible shunt templates in the context of surgical planning. On the other hand, Bove et al. (2008) compared *idealized* mBT and right ventricle-pulmonary artery shunt configurations. There are studies utilizing advanced boundary conditions assigned to 3D vascular geometries that have shunt connections, lead by MOCHA investigators (Esmaily-Moghadam et al., 2015a, 2015b; Schiavazzi et al., 2015). Among those, studies with patient specific outlet boundary conditions (Arbia et al., 2015) and a model that predicts the growth of the patient anatomy (Corsini et al., 2015) could be highlighted. To our knowledge, this present manuscript describes the first patient-specific case where the entire anatomical data is acquired from a real patient and a large number of shunt configurations are compared prior to surgery.

2. Materials and methods

2.1. Patient data and anatomical reconstruction

Beginning with a cohort of 140 patients who had aorta-pulmonary shunt surgery, a one-year-old male patient born with pulmonary artery atresia with ventricular septal defect (PA-VSD) was retrospectively selected as an adequate surgical planning case study through the approved IRB. Patients without a computer tomography (CT) scan and who did not have both VSD and pulmonary artery atresia were eliminated from this group before selecting our patient.

3D anatomical data from a 256 multi-slice CT detector (Siemens definition, Erlangen, Germany) with 0.6 mm slice interval was reconstructed as in our previous work (Dur et al., 2011; Pekkan et al., 2009; Sundareswaran et al., 2012, 2008). The final arterial geometry and vessel nomenclatures are presented in Fig. 1. Further details are provided in the Supplementary material, Table A.

2.2. In slico design of shunt configurations

Several candidate shunt location configurations were created in the computer using our in house anatomical editing tool (de Zelicourt et al., 2012; Dur et al., 2011; Piskin et al., 2015). Four configurations were selected for the detailed analysis, as illustrated in Fig. 1. Nomenclature and description of shunt types are provided in the caption for Fig. 1. Common shunts with 3.5, 4 and 5 mm diameters were generated for the selected configurations, resulting in a total of $12(=4\times3)$ simulation cases.

2.3. Numerical flow solver

Detailed description of numerical models and CFD methodology are presented in the Supplementary materials (Appendices A–C). We completed verification of the solver (Dur et al., 2011; Pekkan et al., 2008) and boundary conditions as in our previous studies (de Zelicourt et al., 2012; Piskin et al., 2015) and these results are presented in Appendix A. The vascular resistance values were calculated by verifying the pre-surgical patient specific Q_P/Q_S ratios obtained from the clinical echocardiography and catheterization data as detailed in Appendix B. Finally, Appendix C presents the configuration parameters of the 3D fluid dynamics solver.

The biomechanical parameters that quantify the post-operative surgical performance include graft wall shear stress level, moderate and robust directional trans-shunt flow with low gradients, balanced pulmonary artery flow split between the left and right lungs, higher coronary artery pressure level, Q_P/Q_S ratio, total systemic power loss and low vorticity level in the PAs. The surgical options evaluated in this study are based on these parameters that are computed through the simulations.

3. Results

3.1. Pulmonary flow and Q_P/Q_S ratio

Post-operative vital organ perfusion is considered to be the primary clinical performance parameter. For the selected patient, since the right ventricular outflow tract is totally blocked, the shunt flow is particularly critical as it supplies all of the PA flow. Table 1 presents the flow split ratios for different shunt configurations and sizes. These results suggest that RPA/LPA flow is not symmetric in almost all cases. In particular, the central shunt configuration causes non-symmetric pulmonary artery flow in favor of LPA for all shunt sizes studied. For mBT shunts, RPA and LPA flow differ by more than 20%, while it is around 40% for central shunt configurations. For the right mBT innominate shunt, the RPA/LPA ratio approaches to unity as the shunt size increases. As expected, the choice of larger shunt diameters increases the total pulmonary flow but does not alter the PA split significantly. The only exception is the right mBT subclavian shunt, where a 10–15% increase in RPA perfusion is recorded with respect to the smaller shunt diameters. As such, right mBT innominate shunt configuration resulted in a preferential RPA flow. In contrast, the flow favors LPA for the left mBT subclavian shunt. For shunt diameter sizes of 3.5, 4.0 and 5.0 mm, the Q_P/Q_S ratio ranges are 1.3–1.6, 1.4–2.1 and 1.7–3.0, respectively. These ratios are consistent with clinical findings (Driscoll, 1999) and qualitatively validate our CFD simulations. Finally, our results indicate that for a given cardiac output, anatomy and shunt template, a maximum PA flow limit exists, beyond which the PA flow does not increase further, even through larger shunts are employed.

3.2. Hydrodynamic energy loss

The total energy loss (Restrepo et al., 2015) is a quantitative, normalized (Yigit and Pekkan, 2016) index for the hemodynamic efficiency of the shunt configuration and the single-ventricle afterload. As shunt diameter increases, a significant decrease in energy loss is observed for all shunt types (Table 2). This decrease is dramatically high for the central shunt configuration, reaching $\sim$50% when the diameter is changed from 3.5 to 5 mm, whereas for other configurations (mBT), it is less than 30%.

Energy loss values for mBT shunts are higher than the central configurations as they inherently feature a T-shape anastomosis promoting stagnation and swirl. The difference between the shunt configurations is around 15% for the smallest shunt size (3.5 mm) but becomes more significant, reaching 45% for 4 and 5 mm shunts. For a shunt size of 3.5 mm, all mBT type shunt configurations have similar energy loss values. The improved efficiency of central shunts compared to mBT could be due to their shorter conduit length and their anastomosis curvature.

Larger diameter mBT shunts (4 and 5 mm) show significant variations in energy loss, in contrast to the smaller shunt size