PRIMES Final Research Paper

January 15, 2022

Computational Fluid Modeling for Surgical Planning of Single Ventricle Congenital Heart Defects

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Introduction:

Single ventricle defects (SVD) refer to the collection of congenital heart defects in which one chamber of the heart remains weak or underdeveloped. The most common palliative treatment for SVD physiologies involves a 3-stage surgical intervention, ending with the Fontan procedure. The Fontan reroutes deoxygenated blood from the upper and lower body directly to the lungs, allowing the single functioning ventricle to pump blood for systemic circulation. Though lifesaving, the Fontan physiology produces a non-natural pathway for venous return of the blood to the lungs thus producing a non-physiological blood flow. A successful Fontan flow requires three main components: 1) well-balanced overall and hepatic flow return to lungs to prevent pulmonary arteriovenous malformations (PAVMs) that can lead to poor gas exchange, 2) minimal energy loss, and 3) minimal thrombosis risk[1]. Complications such as PAVMs and thrombosis post-surgery can result in a Fontan takedown[2].

For patients with bilateral Superior Vena Cavae (SVC), the bilateral bidirectional Glenn (BBDG) procedure is typically employed, connecting the Left SVC directly to the Pulmonary Arteries (PA). Unsuitable resistance from the abnormal left SVC increases the risk of hepatic venous flow (HVF) maldistribution in Fontan connections in BBDG physiologies.

Considering the physiological intricacies of Fontan procedures, Computational Fluid Dynamics (CFD) solvers are useful tools for surgical planning. At Boston Children's Hospital,

patient-specific CFD and other simulation techniques are used to improve predictability of a given Fontan surgical approach and determine the best surgical strategy for a patient. The clinical workflow used by this lab for flow simulation involves three major steps: 1) conversion of clinical MRI data into 3-D CAD interface, 2) CFD processing to calculate pressure and velocity solutions, and 3) post-processing. Nevertheless, a separate goal, which is the focus of this study, is to identify patterns in CFD flow results, allowing us to make predictions about patient flow profiles without performing CFD. This process would not only improve the general understanding of factors that increase risk of complications, but also to avoid unnecessary computational analysis when data-driven predictions are possible.

The primary goal of this study was to examine the effects of various physiological factors, such as vascular sizes, hepatic vein angle, curvature and position of the Fontan conduit, and the construction of a neo-innominate vein on the distribution of hepatic flow to the lungs in BBDG geometries.

Methods:

A dataset of 30 past patients with BBDG physiologies were collected and MRI data was analyzed to determine realistic ranges for vascular sizes and flow ratios. Once consistent measurements were obtained, idealized geometries were developed using Fusion 360 CAD software to model patient physiologies, assuming cylindrical vessels and uniform diameter. The geometries were varied with a collection of parameters, including vascular diameter, positioning of the Fontan conduit with respect to the vena cavae, and curvature of the Fontan

conduit. Each of these parameters was varied at regular intervals, with all other variables constant. Additionally, a model was created for the construction of a neo-innominate vein by directing all LSVC flow to the RSVC. CFD simulations were executed on the idealized models, assuming incompressible, laminar flow, consistent with conventional understanding of venous flow, as well as no-slip boundary conditions. Massless particles were injected into hepatic veins using a Discrete Phase Model (DPM) with varied velocity boundary conditions. Custom subroutines were written to quantify the distribution of hepatic and overall flow to the lungs. The results were collected and analyzed.

Results:

Of all the parameters tested, the position of the Fontan conduit relative to the SVC demonstrated the most significant effect on HVF distribution. Figure 1 shows the percent flow to the LPA at various distances from the center of the RSVC, with negative distances indicating a rightward position of the Fontan conduit with respect to the RSVC. The results demonstrate a significant increase in HVF to the right lung as the Fontan was placed farther to the right. When the Fontan conduit was located directly below the RSVC, a 60% imbalance of HVF toward the right lung was noticed. These results suggest that Fontan connections in BBDG physiologies produce high levels of HVF maldistribution and are highly sensitive to the positioning of the Fontan conduit.

Figure 2 shows the effect of constructing a neo-innominate vein with various positions and flow boundary conditions, compared to the traditional BBDG. Our results demonstrate that

this construction produces a more balanced hepatic flow distribution at nearly all positions and conditions. Nevertheless, when the Fontan is placed very far leftward, the traditional BBDG demonstrates more balanced flow than the neo-innominate vein.

The results for Fontan curvature demonstrated no significant change in relative LPA hepatic flow as curvature increased (Figure 3). For both 1:1 and 1:1.5 SVC:IVC flow ratios, hepatic flow to the LPA ranged between 45% and 55%, and no consistent trend was observed.

Discussion:

The results of the CFD ideal geometry analysis were generally consistent with clinical predictions. The effect of Fontan positioning on flow distribution can be explained by streaming and resistance effects: when the conduit is positioned to right of the SVC, the path of minimal resistance of IVC flow is achieved when more flow from the lower body drains to the RPA, while more upper body flow drains to the LPA. The CFD solver predicted that hepatic flow to the RPA increased significantly with increasing rightward distance of the Fontan conduit from the RSVC. In contrast, the curvature of the conduit and the angle of the connection are less significant than the position of the conduit.

The results of CFD analysis also suggest that the construction of a neo-innominate vein using the LSVC can be an effective alternative to the traditional BBDG construction to reduce hepatic flow maldistribution. When the conduit is placed within **5** mm of the RSVC, the neo-innominate vein cases demonstrated significantly more balanced flow, likely due to the absence of LPA-directed LSVC flow.

One limitation to this study was that it was performed exclusively on ideal geometries, instead of patient-specific geometries. The purpose of this approach was to isolate variables, considering that each patient has unique conditions and surgical approaches that serve as confounding variables for this targeted study. Nevertheless, since all the calculated results are based off of simplified models, it is possible that features specific to this model influenced the result. In order to measure this error, experiments were executed to measure the sensitivity of the observed result to the type and size of lofts used to connect vessels, the greatest source of uncertainty. The results showed a negligible difference (less than 2% hepatic flow) between the flow results when these variables were adjusted, suggesting that the observed trends are likely consequences of real fluid dynamic factors. Furthermore, virtual surgery can be done on Fontan positioning and neo-innominate vein construction to verify the findings of the idealized geometries. Through this process, geometries are imported from patient imaging and modified using virtual surgery based on specific metrics; CFD analysis can then be run on the original and modified models to evaluate the effect of the virtual surgical change.

Conclusion:

The results of this study demonstrate the power of CFD to answer theoretical questions about surgically relevant physiologies. While the method of virtual surgery will allow us to validate our predictions, the use of idealized geometries is effective at identifying crucial physiological trends. Considering the computational costs of running CFD, the methods used in this study can be an effective way to reduce the necessity for patient-specific CFD as well as to develop a mechanistic understanding of Fontan physiologies.

Figures:

Figure 1:

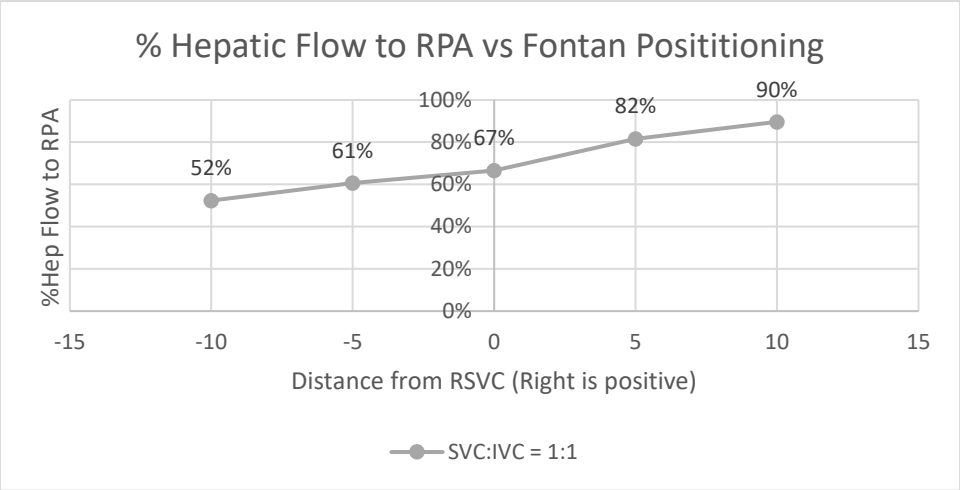


Figure 2:

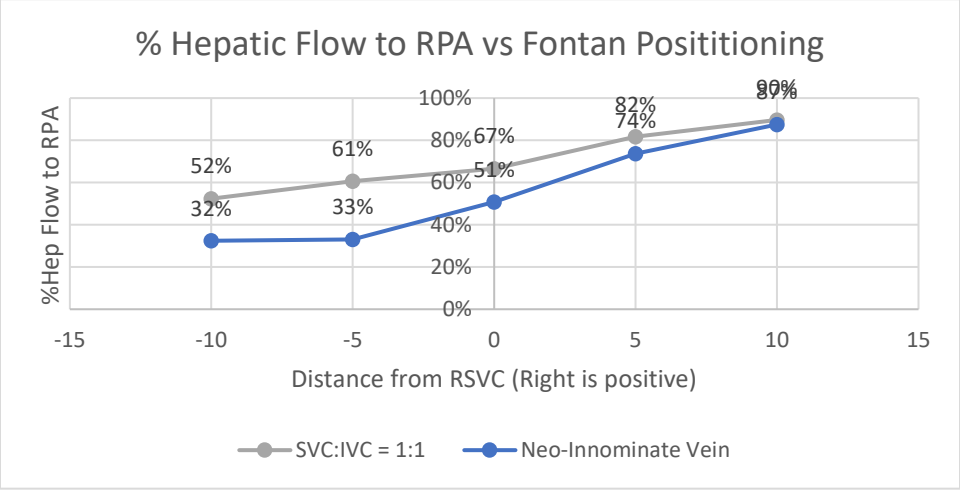
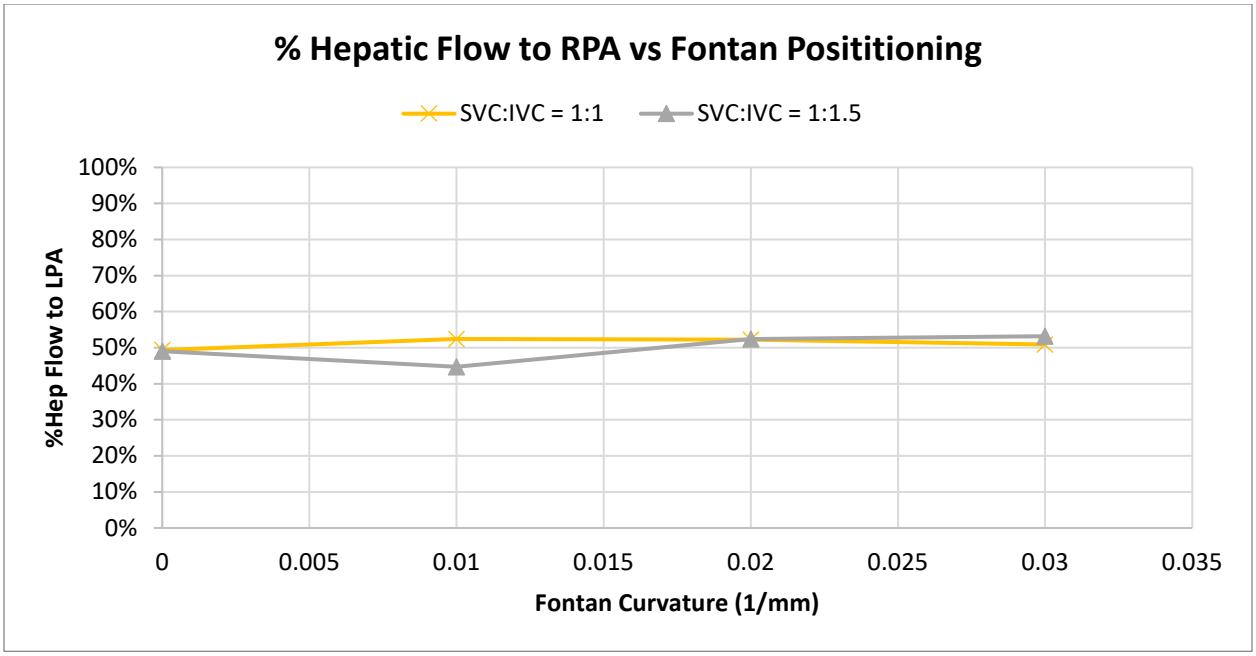


Figure 3:



References:

[1]Park, M. K. (2012, April 27). *Cyanotic congenital heart defects*. Pediatric Cardiology for Practitioners (Fifth Edition).

[2]Srivastava, D., Preminger, T., Lock, J.E., Mandell, V., Keane, J.F., Mayer Jr, J.E., Kozakewich, H. and Spevak, P.J., 1995. Hepatic venous blood and the development of pulmonary arteriovenous malformations in congenital heart disease. *Circulation*, *92*(5), pp.1217-1222.