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Hepatic blood flow distribution and performance in conventional and novel Y-graft Fontan geometries: A case series computational fluid dynamics study

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Objectives: A novel Y-shaped baffle has been proposed for the Fontan operation with promising initial results. However, previous studies have relied either on idealized models or a single patient-specific model. The objective of this study is to comprehensively compare the hemodynamic performance and hepatic blood flow distribution of the Y-graft Fontan baffle with 2 current designs using multiple patient-specific models.

Methods: Y-shaped and tube-shaped grafts were virtually implanted into 5 patient-specific Glenn models forming 3 types of Fontan geometries: Y-graft, T-junction, and offset. Unsteady flow simulations were performed at rest and at varying exercise conditions. The hepatic flow distribution between the right and left lungs was carefully quantified using a particle tracking method. Other physiologically relevant parameters such as energy dissipation, superior vena cava pressure, and wall shear stress were evaluated.

Results: The Fontan geometry significantly influences the hepatic flow distribution. The Y-graft design improves the hepatic flow distribution effectively in 4 of 5 patients, whereas the T-junction and offset designs may skew as much as 97% of hepatic flow to 1 lung in 2 cases. Sensitivity studies show that changes in pulmonary flow split can affect the hepatic flow distribution dramatically but that some Y-graft and T-junction designs are relatively less sensitive than offset designs. The Y-graft design offers moderate improvements over the traditional designs in power loss and superior vena cava pressure in all patients.

Conclusions: The Y-graft Fontan design achieves overall superior hemodynamic performance compared with traditional designs. However, the results emphasize that no one-size-fits-all solution is available that will universally benefit all patients and that designs should be customized for individual patients before clinical application.
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The impact of geometry on Fontan hemodynamics is now widely accepted in the engineering and clinical communities.[1–4] Recent advances in computational fluid dynamics, computer-aided design, magnetic resonance imaging (MRI), and fluid structure interaction methods for blood flow modeling have led to studies of Fontan hemodynamics and surgical design progressing from idealized to patient-specific models, steady to unsteady flow, and trial and error to optimal design.[5–9]

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In the earlist extracardiac Fontan procedures, the inferior vena cava (IVC) was anastomosed to the pulmonary arteries (PAs) via a straight polytetrafluoroethylene graft (Gore-Tex graft; W. L. Gore & Associates, Inc, Flagstaff, Ariz) forming a T-junction. An offset design derived from simulations[5] was then adopted by surgeons to reduce energy losses and remains standard of care in most extracardiac procedures.

Recently, 2 research groups [7,10] proposed a new Y-shaped connection to replace current designs. First, Soerensen and coworkers[10] bifurcated both the superior vena cava (SVC) and IVC. Simulations using an idealized model with steady inflow conditions demonstrated lower energy loss. Given the technical difficulties and need for increased synthetic material, this modification was not pursued in clinical practice. Marsden and coworkers[7] introduced an IVC-only bifurcated Fontan modification. A detailed comparison of energy efficiency, Fontan pressures, and hepatic flow distribution demonstrated superior Y-graft performance.[7] An optimization process was then used to systematically explore design parameters and hemodynamics for an idealized Y-graft model.[8] Although the preliminary studies showed the Y-graft design to improve hemodynamics overall, it has not yet been confirmed that the superiority of the Y-graft is universal.

Abbreviations and Acronyms

IVC = inferior vena cava
LPA = left pulmonary artery
MRI = magnetic resonance imaging
PA = pulmonary artery
RPA = right pulmonary artery
SVC = superior vena cava
WSS = wall shear stress

Complications after the Fontan procedure, including diminished exercise capacity, thromboembolic complications, protein-losing enteropathy, arteriovenous malformations, ventricular dysfunction, and arrhythmias, continue to present serious clinical challenges despite postoperative survivals upwards of 90%.[11] Among these, the development of pulmonary arteriovenous malformations is known to be linked to hepatic flow distribution and is therefore an obvious target for improvement via simulation-based design. Although the pathogenesis of pulmonary arteriovenous malformations is unknown, several studies have revealed a clear link between the absence of hepatic venous return and the development of pulmonary arteriovenous malformations, and reversal of pulmonary arteriovenous malformations has been achieved by correcting the uneven hepatic flow distribution.[12] Although the energy dissipation of different Fontan geometries has been investigated in numerous studies[1-3,5,6] only a few studies[4,7,13-16] have quantified the hepatic flow distribution in in vitro or simulation studies.

The purpose of this article is to evaluate the potential performance of the Y-graft Fontan procedure in simulation as a step toward clinical implementation. Multiple virtual patient models are used, and multiple parameters[4] are evaluated for each, with particular attention paid to the hepatic flow distribution.

METHODS

Geometric Model Construction

Virtual surgery was performed on 5 models by implanting a Y- or tube-shaped graft into patient-specific Glenn models[17] constructed from MRIs. All patients gave consent as part of an institutional review board approved protocol at Lucile Packard Children's Hospital (Stanford University). Model construction was performed using a custom version of the open source Simvascular software package,[18] as in our previous work.[7]

Geometric parameters were chosen on the basis of our previous optimization study.[8] A Y-graft with a 20-mm diameter trunk and 15-mm diameter branches was chosen for all patients. The T-junction and offset models were constructed with a 20-mm diameter tube-shaped graft following common clinical practice, and resulting models are shown in Figure 1.

In the virtual implantation, the centerline paths of the SVC and PA anatomy of the original Glenn models were left unchanged. The space created by the deflation of the right atrium during the Fontan procedure was accounted for in IVC placement during virtual surgery. In addition, the PA segmentations were enlarged to match the baffle size to avoid creating unrealistic stenoses. Although this is purely a simulation study, all models were constructed under guidance of a surgeon to replicate as closely as possible a realistic surgical implementation of the intended design.

Patient B has a left PA (LPA) stenosis, which is commonly observed in Fontan patients owing to aortic arch override. Three potential Y-graft designs were proposed for this patient model. In Y-graft I, the stenosis is relieved by placing the anastomosis of the left branch at the stenosis. In Y-graft II, the left branch is anastomosed distal to the stenosis, without relieving it. In Y-graft III, the left branch is also anastomosed distal to the stenosis, but the stenosis is relieved. Patient E has heterotaxy and a right PA (RPA) stenosis. Instead of an LPA offset connection, the baffle is anastomosed to the RPA in a mirror image of the other patients, denoted as offset I. The stenosis is relieved in the Y-graft I, T-junction, and offset I designs. An LPA–offset connection without relieving the stenosis (II) is also constructed. We redesigned the Y-graft for patient E, denoted as Y-graft II, by bringing the left branch closer to the SVC–PA junction and less anteriorly convex, based on the simulation results of Y-graft I.

Flow Simulation and Boundary Conditions

Flow simulations were performed with a stabilized finite element Navier-Stokes solver,[19] assuming rigid walls and Newtonian flow with a density of 1.06 g/cm^3 and viscosity of 0.04 g/(cm s). MeshSim (Simmetrix, Inc, Clifton Park, NY) was used to generate tetrahedral meshes automatically and anisotropic mesh adaptation was performed to ensure mesh convergence. Final meshes consisted of approximately 1 to 1.5 million elements.

During MRI, phase-contrast MRI slices were acquired in the SVC, IVC, LPA, and RPA for each Glenn patient. The SVC waveform from phase-contrast MRI was applied directly to the SVC inflow face by mapping it to a parabolic profile. Because the IVC flow waveforms were acquired in the Glenn patients before surgery, when the IVC was still connected to the right atrium, these waveforms exhibited higher cardiac pulsatility and less respiratory pulsatility compared with typical Fontan patients.[20] To account for this, the amplitude of the IVC waveform of each Glenn patient was scaled to match typical Fontan data using 4 patients from a previous study, while keeping the mean the same. Additionally, a respiratory model was superimposed on the scaled IVC waveform as done in our previous work.[6]

A 3-element Windkessel circuit model (resistor–capacitor–resistor)[21–23] was applied at each outlet. Predicting changes in pulmonary resistance after Fontan surgery remains an open question. However, inasmuch as this study aims to model immediate postoperative flow conditions, we have assumed that the downstream resistances do not change significantly in the short period after the surgery. Therefore, the same parameters for the Windkessel model were used for the Glenn and Fontan simulations in all patients, so that the comparison of postoperative states among patients remains consistent.

Exercise flow conditions were simulated by increasing IVC flow and decreasing outflow resistances, as done in our previous work.[6] The mean IVC flow rate was increased by 2 and 3 times (2×, 3×) to simulate exercise conditions, and the total resistances of each branch was decreased by 5% and 10%, respectively.

Determination of Performance Parameters

Mean SVC pressure, wall shear stress (WSS), and power loss were computed with standard methods.[7] Lagrangian particle tracking[15] was performed to quantify the hepatic flow distribution in different surgical designs (Figure 2).

It is widely known that the ratio of IVC/SVC flow and LPA/RPA resistances vary widely among patients. Although ideally one would like to