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Closed-loop CFD Model of the Self-Powered Fontan Circulation for the Hypoplastic Left Heart Syndrome

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ABSTRACT

The Fontan operation is the definitive step in creating a compatible circulation in SV patients. This type of procedure may fail due to the known decrease survival rate, and the inability of the systemic venous blood to pass through the lungs, which leads to further complications in the patient. To improve the Fontan circulation an injection jet shunt (IJS) from the single ventricle to the Fontan pulmonary arteries, is incorporated into the closed-loop circulation model to determine if the energy and momentum will effectively be transferred to the pulmonary artery circulation. Using ANSYS Fluent two models, a baseline and an IJS model, were compared in a steady state solution to determine the effectiveness of the IJS velocity outflow and energy transfer. After the analysis was performed it was determined that a vacuum pressure is created at the exit of the IJS, and that indeed the energy and momentum transfer to the pulmonary arteries, improves the Fontan circulation.

INTRODUCTION

Congenital heart disease (CHD) occurs in 1/150 newborn babies, 7.7% of whom have only a single chambered (single ventricle, SV) heart [1]. The complication of this physiological anomaly is responsible for a high mortality rate near 50% by age of 20. The Hypoplastic Left Heart Syndrome (HLHS) consists of patients that have an underdeveloped left heart. Their aorta and left ventricle are too small and septum did not mature correctly, as shown in Figure 1 [2]. The alternative to treat single-ventricle (SV) types of heart defects is surgical, by creating a compatible circulatory system [2]. This type of surgery is performed through a surgical staging process that leads to the Fontan circulation. This surgery allows venous blood to flow passively, without a pump, through the pulmonary arteries into the lungs. Even though this type of procedure seems as a solution for SV patients, it may fail due to the inability of the systemic venous blood to pass through the lungs, which leads to further complications of high systemic venous pressure and low cardiac output [1].

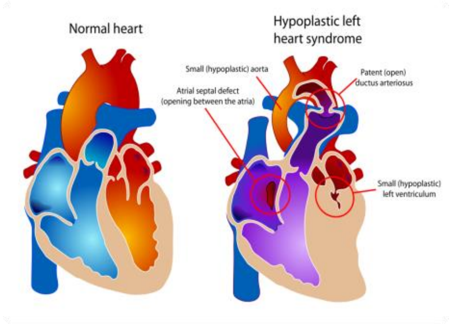


Figure 1: Difference between normal heart and HLHS heart [2]

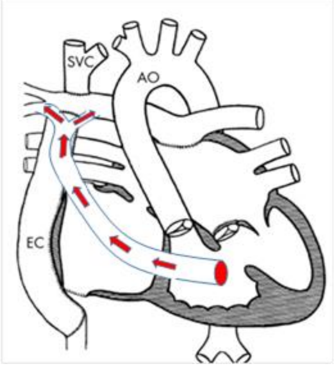


Figure 2: Sketch of "IJS" functionality [3]

Due to the failures experienced with the Fontan circulation, researchers have suggested to incorporate an assisted mechanism that can help level the systemic circulation pressure and cardiac output by using a pump. Incorporating an external pump has complications, such as reliability of mechanical moving parts and thrombus formation [3]. Others have proposed developing a synthetic pump with ideal flow characteristics and without intravascular device complications, which seems to be an ideal solution but it is still under development [4]. As an alternative to the synthetic and external powered pump, this research proposes a modified Fontan loop circulation model, where an injection jet shunt (IJS) is positioned from the single ventricle to the pulmonary arteries directly. The objective is to determine if incorporating an IJS from the single ventricle to the Fontan pulmonary arteries will effectively increase the energy and momentum transfer to improve the Fontan Circulation (i.e. increased pulmonary flow and decreased inferior caval pressure), shown in Figure 2.

In order to demonstrate that the proposed IJS solution achieves most of the objectives of the idealized synthetic pump, a steady-flow analysis will be performed using computational fluid dynamics (CFD) with the ANSYS Fluent solver. This research paper seeks to present the methodology, mesh analysis, and fluid analysis to demonstrate the conceptual effectiveness of the surgical modification to the Fontan operation with the goal of preventing or treating the failing Fontan to increase the survival rate of the patients with SV.

EQUATIONS

The "injector jet" that is proposed works on a combination of the Venturi effect and direct momentum transfer. To demonstrate that the required energetics are achievable, we performed the following analytic calculation assuming a single orifice, or "nozzle": If one wishes to reduce the gradient, Δ(Δp), between the inferior vena cava (IVC) and atrium by an amount Δp by interposing a high velocity jet in the pulmonary artery (PA) flow direction, then the power provided by this jet must be ΔQpΔp + QsΔ(Δp), where Qs and Qp are the systemic and pulmonary blood flows, respectively [5]. The first term is the power required to drive the excess (jet) flow, and the second term is the supplemental power required to drive the baseline Fontan (venous) flow at the reduced IVC-atrial pressure gradient. The jet energy comes from the ventricle, producing a left-to-right "shunt fraction", f = Qp/Qs. The jet power is thus ρ(f-1)Qsv2, where v is the jet velocity. Setting this equal to the required power, we get is shown in Equation 1.

$$(f-1)Q_s\Delta p + Q_s\Delta(\Delta p) = r\,(f-1)Q_s v^2 \tag{1}$$

In cgs units, r = 1 and if pressure is in mmHg, we obtain Equation 2, below.

$$v = 36.5\sqrt{\Delta p + \Delta(\Delta p)/(f-1)} \quad cm/sec \tag{2}$$

Suppose, for example, Δp = 8mmHg, and we want Δ(Δp) = 5mmHg (the reduction in Fontan pressure) and an "acceptable" shunt fraction f= 1.4. Then v = 165 cm/sec. If Qs = 4.5 l/min the required nozzle orifice diameter would be 4.8mm.—a very reasonable requirement.

The Multidisciplinary Bioengineering Lab at Embry-Riddle Aeronautical University maintains a license for commercial CFD with ANSYS Fluent [6] that will be utilized in this study. ANSYS Fluent CFD software is capable of modeling 2D and 3D flows, steady-state and transient simulations, viscous, laminar and turbulent flows, subsonic, transonic and supersonic flow, among other capabilities. Codes such as ANSYS Fluent use numerical algorithms to solve the mass and momentum conservation equations governing fluid mechanics. That is, they solve the Navier-Stokes equations (NSE):

$$\nabla\cdot\vec{V} = 0 \quad and \quad \rho\frac{\partial\vec{V}}{\partial t} + \rho\left(\vec{V}\cdot\nabla\right)\vec{V} = -\nabla p + \nabla\cdot\sigma \tag{3}$$

Here, $\vec{V}$ is the velocity vector, p is the pressure field, ρ is the blood density (1060 kg/m3), and μ is the blood viscosity typically taken as 0.004 Pa-s. It is generally acceptable to treat blood as a Newtonian fluid in large vessels where the shear rates are high.

METHODOLOGY

For the research, the patient-specific solid model was rendered utilizing CT scan/MRI data and medical segmentation software Mimics to construct the test section joint of the Inferior Vena Cava (IVC) and the Superior Vena Cava (SVC). The synthetic solid model was generated using CATIA V5 [7]. Figure 3 shows the baseline model geometry of the closed-loop circulation and the IJS added geometry. The junction of the IVC, SVC, left pulmonary artery (LPA) and right pulmonary artery (RPA) are modeled using dimensions obtained directly from the MRI scan data. The upper and lower circulations as well as the pulmonary circulations were modeled as a simplified loop with relative constant cross sectional areas, as it would be impossible to run computational analysis in a model that has hundreds of miles of vessels on it.

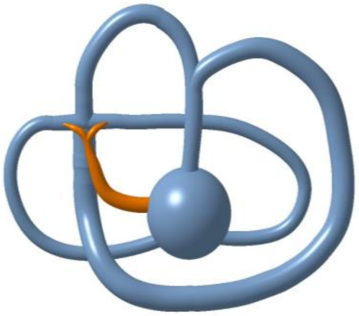
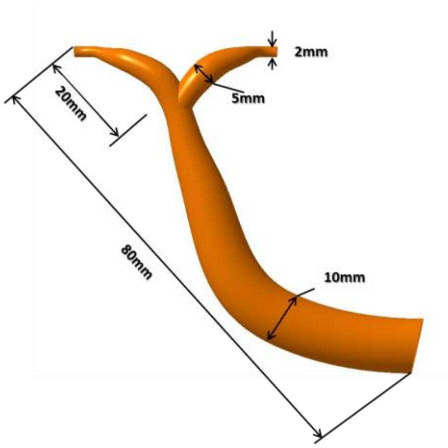


Figure 3: IJS Model Geometry of Closed-Loop Circulation



The IJS was created based on jet velocity requirement for energy and momentum transfers, used in Equation 2. This design provides the V_{JET} required to achieve the desired energy and momentum and to minimize its power losses. A rough design is detailed in Figure 4, where the diameter of the conduit is 10mm and 8cm-long, and bifurcates forming two 2cm-long arms tapering to 5mm-diameter nozzles, and 2mm of entrainment diameter.

Two medium unstructured mesh models with TRex grid enhancement were created using PointWise: baseline (without IJS) and IJS models. PointWise is a mesh generation software capable of generating structured, unstructured and hybrid meshes into various Computational Fluid Dynamic solvers, such as ANSYS Fluent [8]. Figure 5 and 6 show the baseline model mesh and detail of the quality of its mesh, which was built using 713,584 cells, 30 domains and 3 blocks. Figure 7 and 8 show the IJS model mesh and detail of the quality of its mesh, which was built using 1,040,155 cells, 37 domains and 4 volume block.

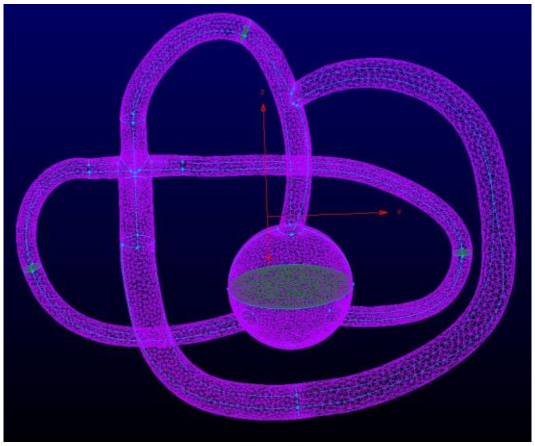


Figure 5: Mesh of Base Model

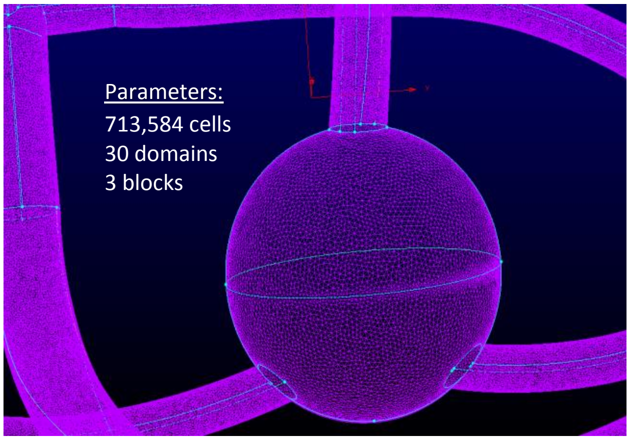


Figure 6: Detailed Mesh of Base Model

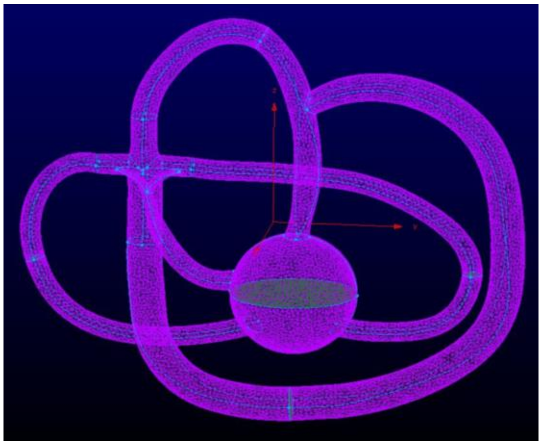


Figure 7: Mesh of IJS Model

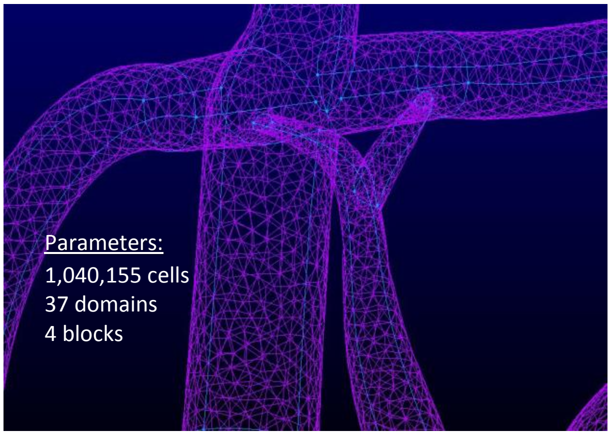


Figure 8: Detailed Mesh of IJS Model

The CFD simulation of the two models was evaluated using ANSYS Fluent as an analysis tool. The use of porous jumps to simulate the pressure drops was implemented in four intermediate media on inflow-outflow conditions: upper circulation, lower circulation, left pulmonary circulation, and right pulmonary circulation, that account for the viscous loss over hundreds of miles of vessels. Several trials were performed until the calibrated baseline model was obtained (one that matched physiological values of pressures and flows). Once the baseline model was calibrated, the IJS was introduced to study its effects. The target outcome is to maintain a pulmonary to systemic volume flow rate,

$Q_P/Q_S < 1.5$, and to decrease baseline inferior caval pressure so that the pressure in the IVC (P_{IVC}) is less than 17mmHg (2266.5 Pa) to avoid organ failure.

RESULTS AND DISCUSSION

Figures 9 through 11, detail the CFD results for the baseline model, while Figures 12 through 14 show the results with the IJS added to the calibrated baseline model. Table I shows the results obtained during this research.

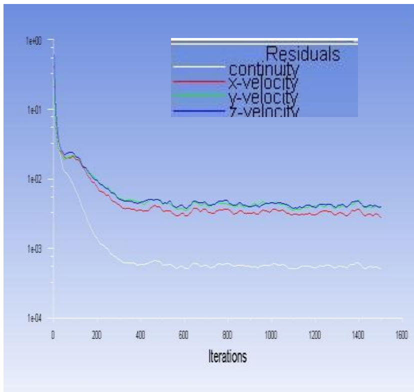


Figure 9: Baseline Model Residuals

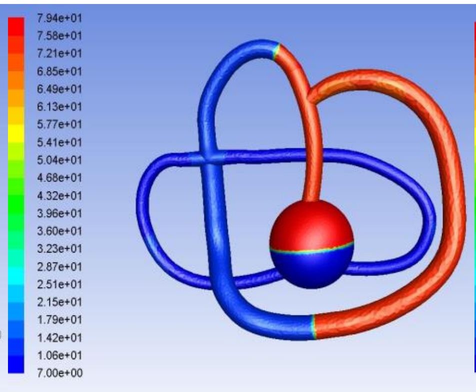


Figure 10: Baseline Model Pressure Contour

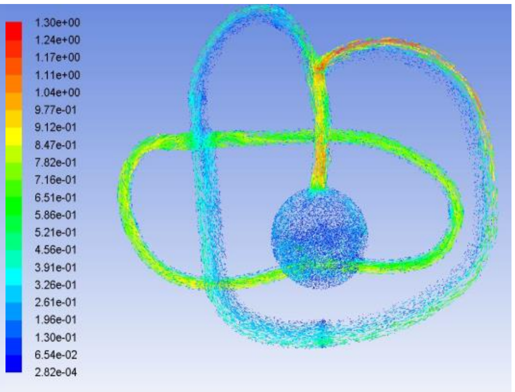


Figure 11: Baseline Model Velocity Vector Plot

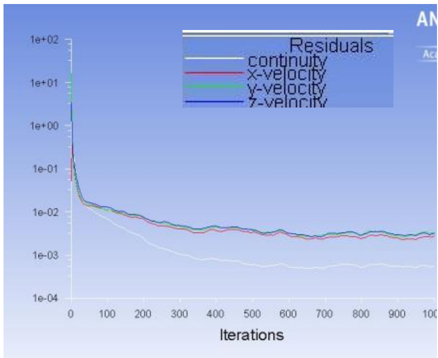


Figure 12: IJS Model Residuals

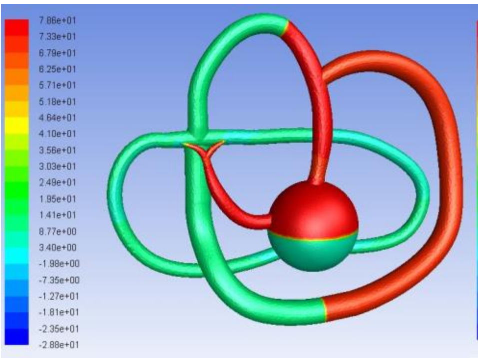


Figure 13: IJS Model Pressure Contour

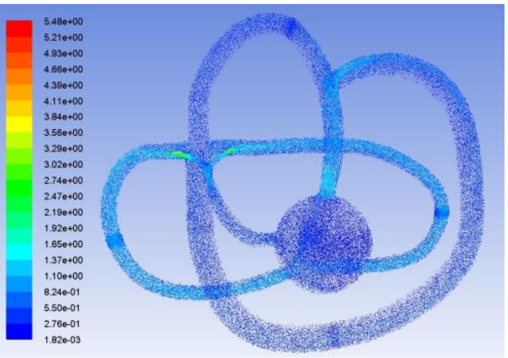


Figure 14: IJS Model Velocity Vector Plot

TABLE I – Result Analysis from CFD Baseline and IJS Models

PARAMETER	BASELINE MODEL	IJS MODEL
Q_P/Q_S	1	1.24
P_{IVC}	12.1 mmHg (1613.2 Pa)	11 mmHg (1466.5 Pa)
Heart Flow Rate	82.2 cm^3/s	90.67 cm^3/s
Lower Circulation Flow Rate	56.7cm^3/s	59.82 cm^3/s
Upper Circulation Flow Rate	25.8cm^3/s	31.64 cm^3/s
Max Velocity	1.3 m/s	1.1-1.37 m/s
Max Velocity at IJS Exit	-	5.48 m/s
Max Pressure	79.4 mmHg (10585.8 Pa)	78.6 mmHg (10479.1 Pa)
Min Pressure	7 mmHg (933.25 Pa)	7 mmHg (933.25 Pa)
Min Pressure at IJS Exit	-	-28.8mmHg (-3839.7 Pa)

CFD analysis (with appropriate intravenous pressure boundary conditions) on the closed-loop circulation problem with intermediate media on inflow-outflow conditions revealed the convergence of both models, as observed in the residual plots from Figure 9 (1700 iterations) and Figure 12 (1000 iterations). Figure 10 shows the baseline model calibrated to output roughly 70% to 30% on the lower and upper circulation blood flow, respectively, which complies with physiological data [4]. The maximum velocity, as shown in Figure 11 and Table I, is 1.3m/s, also close to clinical data [4]. For the IJS closed-loop model a vacuum pressure in the outlet of the IJS entering the Pulmonary

Arteries (PA) is produced, as observed in Figure 13, due to the generated jet velocity of 5.48m/s as the flow entrainment enters the PA, shown in Figure 14. This shows that the flow going into the pulmonary arteries effectively increases the energy and momentum in the Fontan circulation compared to the baseline model. As seen in Table I, the inferior caval pressure (P_{IVC}) decreases 1.1mmHg (146.65Pa) from 12.1mmHg (1613.2 Pa), in the baseline model, to 11mmHg (1466.5 Pa) in the IJS Model. This satisfies the target outcome of effectively reducing the caval pressure to avoid organ failure. It is expected that further reduction of the inferior caval pressure can be achieved by performing optimization of the IJS geometry and implantation.

CONCLUSION

This is a pioneering study of the application and conceptual advantage of the "injection jet" entrainment phenomenon to improve the Fontan circulation. This preliminary research study steady state results validate the hypothesis of the benefits of the IJS. The model could be improved by dimensional IJS changes of the outlet cross sectional areas (a_o) and ratio of nozzle to inlet areas (a_o/a_i), while maintaining a target flow ratio $Q_p/Q_s<1.5$. Future research include transient modeling and ventricular function programming using documented waveforms to approximate more realistic cases. This idea could facilitate future research opportunities that could eventually impact surgery procedures for patients with HLHS improving their survivability and quality of life.

CONTRIBUTION

This research was pursued due to the need to modify current surgical procedures in order to increase the survivability rates of patients with HLHS. There is a need to engineer new ways of solving the failing Fontan issue, and through CFD it is possible to prove the conceptual advantage of the "injection jet" phenomenon. This preliminary CFD analysis determined that the hypothesis is valid in steady state. This could contribute, optimize, and revolutionize the way surgery for HLHS patients is currently performed.

ACKNOWLEDGMENT

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