Closed-Loop CFD Analysis of the Fontan Cardiovascular Circulation

Marwan Hameed
Closed-Loop CFD Analysis of the Fontan Cardiovascular Circulation

by

Marwan Hameed

A Thesis Submitted to the College of Engineering Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
March 2016
Closed-Loop CFD Analysis of the Fontan Cardiovascular Circulation

by

Marwan Hameed

This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Eduardo A. Divo, Associate Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Jean M. Dhainaut, Associate Professor, Daytona Beach Campus, and Dr. Victor Huayamave, Visiting Assistant Professor, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Thesis Review Committee:

Eduardo Divo, Ph.D.
Committee Chair

Jean-Michel Dhainaut, Ph.D.
Committee Member

Jean-Michel Dhainaut, Ph.D.
Graduate Program Chair,
Mechanical Engineering

Victor Huayamave, Ph.D.
Committee Member

Charles F. Reinholtz, Ph.D.
Department Chair,
Mechanical Engineering

Maj Mirmirani, Ph.D.
Dean, College of Engineering

Christopher Grant, Ph.D.
Associate Vice President of Academics

Date 05/04/2016
Acknowledgements

I would first like to thank my thesis advisor Dr. Eduardo Divo of the. The door to Prof. Divo office was always open whenever I ran into a trouble or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

This journey would not have been possible without the support of my family. To my family, thank you for encouraging me in all of my pursuits and inspiring me to follow my dreams. I am especially grateful to my parents, who supported me emotionally and financially. I always knew that you believed in me and wanted the best for me. I am grateful to my mother, father and my siblings for all of the sacrifices that you’ve made on my behalf. Your prayer for me was what sustained me thus far.

I would also like to thank friends in the US and back home for their support and encouragement throughout the thesis work.
Abstract

Researcher: Marwan Salah Hameed

Title: Closed-Loop CFD Analysis of the Fontan Cardiovascular Circulation

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science in Mechanical Engineering

Year: 2016

One out of 150 newborn babies born with congenital heart disease, approximately 7.5% of those infants have a single ventricle (SV). The Fontan operation, which is a procedure to create a harmonious circulation in SV patients, has been performed for a long time to save the newborn patients. In this procedure the superior vena cava and inferior vena cava, which carry the oxygen-poor blood from the upper and lower body back to the heart, are linked directly to the pulmonary arteries, bypassing the atrial connection. Even though this operation has been around for years, the patients who have undergone this operation have experienced chronic illnesses and their surviving probability is about 50% by age twenty. To reduce this risk, an Injection Jet Shunt (IJS) is presented to connect the single ventricle to the Fontan pulmonary arteries and effectively improve blood flow circulation. In this study, two closed-loop models of the simplified Fontan circulation system, with and without IJS, were built using Catia V5 and fluid flow simulations were performed using Star CCM+ to find out the influence of using the IJS. Results of the aortic, atrial, and caval pressures as well as flow rates for both models were compared to determine the effectiveness of the IJS.
# Table of Contents

THESIS REVIEW COMMITTEE: .......................................................................................................................... i

ACKNOWLEDGMENT ........................................................................................................................................ ii

ABSTRACT .......................................................................................................................................................... iii

TABLE OF CONTENTS ........................................................................................................................................ iv

TABLE OF FIGURES ........................................................................................................................................ vi

TABLE OF TABLES ........................................................................................................................................... vii

Chapter 1 INTRODUCTION .............................................................................................................................. 1

1.1 Background ................................................................................................................................................. 1
1.2 HLHS procedures ....................................................................................................................................... 2

Chapter 2 MODELS ......................................................................................................................................... 6

2.1 Models .......................................................................................................................................................... 6
2.2 Injection Jet System .................................................................................................................................... 11
2.3 Equations .................................................................................................................................................... 14

Chapter 3 GRID STRUCTURE ......................................................................................................................... 15

Chapter 4 Computational Fluid Dynamics Analysis instead of CFD ............................................................ 19
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5 RESULTS AND DISCUSSION</td>
<td>22</td>
</tr>
<tr>
<td>CONCLUSION AND RECOMMENDATIONS</td>
<td>44</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>45</td>
</tr>
<tr>
<td>FIGURES REFERENCES</td>
<td>47</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>48</td>
</tr>
<tr>
<td>A. Figures</td>
<td>48</td>
</tr>
</tbody>
</table>
Table of Figures

Figure 1.1 Healthy Heart Anatomy [1] ................................................................. 2
Figure 1.2 Normal Heart, HLHS, Norwood Operation and Fontan Operation[2-3] .......... 4
Figure 2.1 The first base model design .................................................................... 7
Figure 2.2 The second baseline model without tapering ........................................... 8
Figure 2.3 The baseline model with the Aorta on the side ........................................ 9
Figure 2.4 The final baseline used shows the Aorta placed on the top of the ball ...... 10
Figure 2.5 The first model with the IJS ................................................................. 11
Figure 2.6 The first IJS design ............................................................................... 11
Figure 2.7 The second IJS design .......................................................................... 12
Figure 2.8 The balanced flow IJS ........................................................................... 12
Figure 2.9 The third design of the IJS attached to the model ................................. 13
Figure 2.10 The Third IJS ..................................................................................... 13
Figure 2.11 Shows the last model used with the IJS placed on the Aorta .......... 13
Figure 2.12 The last IJS design ............................................................................ 13
Figure 3.1 Shows the mesh of the final model with the IJS attached to the Aorta ...... 15
Figure 3.2 Shows a close view for the IJS mesh .................................................. 16
Figure 3.3 Shows the mesh of the Aorta, Pas and the IJS ....................................... 17
Figure 3.4 Shows different mesh element sizes .................................................... 18
Figure 3.5 Shows the mesh of the two branches .................................................... 18
Figure 5.1 a scalar scene shows pressure contour of the baseline model for the first design .... 23
Figure 5.2 scalar scene shows pressure contour for the first model with the IJS .......... 23
Figure 5.3 a scalar scene for the baseline model .................................................. 24
Figure 5.4 vector scene for the baseline model ...................................................... 25
Figure 5.5 shows a close vector scene for the baseline model ................................ 25
Figure 5.6 mass flow averaged pressure report for the aorta right after leaving the ventricle .... 26
Figure 5.7 mass flow rate plot of the Aorta .......................................................... 26
Figure 5.8 scalar scene of the second model design with the 4mm IJS .................. 28
Figure 5.9 vector scene of the second model design with the 4mm IJS .................. 28
Figure 5.10 a close vector scene of the second model design with the 4mm IJS ........ 29
Figure 5.11 scalar scene for baseline model without PAs tapering ...................... 30
Figure 5.12 vector scene for the baseline model without tapering ....................... 31
Figure 5.13 close picture for the vector scene show how the blood flow directions .... 32
Figure 5.14 scalar scene for the 4mm IJS model without PAs tapering .................. 32
Figure 5.15 close picture for the 4 mm IJS model ............................................... 33
Figure 5.16 vector scene for the 4mm IJS ............................................................. 33
Figure 5.17 a close picture for the 4mm model shows the flow direction .............. 34
Figure 5.18 scalar scene of the baseline model .................................................... 36
Figure 5.19 vector scene of the baseline model .................................................... 37
Figure 5.20 close picture for the vector scene show the blood flow directions ....... 37
Figure 5.21 the Residual plot of the baseline model .............................................. 38
Figure 5.22 Aorta mass flow rate plot ................................................................. 38
Figure 5.23 a scalar scene for the 4mm IJS .......................................................... 39
Figure 5.24 close picture of scalar scene for the 4mm IJS ..................................... 39
Figure 5.25 vector scene for the 4mm IJS ............................................................ 40
Figure 5.26 close picture of vector scene for the 4mm IJS ................................... 41
Table of Tables

Table 1 Results Analysis from CFD for Baseline model and IJS models for the second design...... 29
Table 2 Results analysis from CFD for with and without IJS models for the third design............35
Table 3 Results analysis from CFD for with and without IJS models for the same mass flow for the
third design.............................................. .............................................................. ........35
Table 4 Results analysis from CFD for with and without IJS models for the final design ............ 42
Table 5 Results analysis from CFD for with and without IJS models for the same mass flow for the
final design.......................................................... .......................................................... .42
Chapter 1

Introduction

1.1 Background

Infants who are born with a single working heart ventricle (Hippoplastic Left Heart Syndrome or HLHS) undergo a chain of surgical operations to obtain the best pumping performance from the single working ventricle [1-11]. Usually, patients undergo their first surgery at birth (Norwood procedure), the second within six months (Glenn Procedure), and the third one when they become one year old (Fontan Procedure) [12-13]. A French cardiac surgeon, Francis Fontan, was the one who developed the first Fontan Procedure in 1971 as a treatment for Tricuspid Atresia [14]. In 1980 the Fontan was developed as one of the stages of the treatment for HLHS [14].

Having this syndrome means that the left ventricle, the mitral valves, the aortic valve and the ascending portion of the aorta are underdeveloped and or too small [15]. That means that the right pump will be the only pump in the heart. Before explaining HLHS surgery stages, it is important to explain how a normal heart works. The heart works to pump blood thought the body. There are two separate circulations: the first circulation, which the right side of the heart is responsible for, takes the flow to the lunges, and the second pumps the blood to the body. The journey starts when the blood comes back by veins from the body to the right side of the heart, specifically to the right atrium and the color of the return blood is blue because it was deoxygenated by the body. The blue blood, then, moves though the Tricuspid valve to the right ventricle to be pumped to the lunges to oxygenate the blood. After that, the red blood will pass to the left Atrium and, then through the Mitral valve to the Left pump (Left Ventricle). Finally, the Left Ventricle will pump the blood thought the Aortic valve to the body. The body will use the oxygenated blood and turn it to blue and the journey start over [16].
1.2 The three stages of HLHS

- **Norwood Procedure**
  
  Usually done after two weeks of an infant’s life. Doctors will connect aorta with the main pulmonary artery and, also, will implement a shunt to connect the pulmonary arteries and the aorta to provide blood to the lungs. Therefore, the right ventricle now is able to pump blood to both the lungs and the rest of the body [13].

- **Bi-directional Glenn Shunt Procedure**
  
  After four to six months from the first surgery, the superior vena cava will be disconnected from the right side of the heart and reconnected directly to the pulmonary artery to prevent the oxygen-poor blood coming from the upper body from mixing with the red blood. This reduces the work the right ventricle has to do but still the patient suffers from hypoxia because the inferior vena cava (IVC) blood still going back to the right ventricle [17].
Fontan Procedure

It is also called Kreutzer procedure. At age of 2 or 3 years old the final stage is usually performed. In this surgery the inferior vena cava, which is responsible of carrying the oxygen-poor blood from the lower part of the body to the heart, will be connected to the pulmonary artery and by the end of this stage no more blue blood coming back from the body to the heart [18].

Figure 1.2 Normal Heart, HLHS, Norwood Operation, Bidirectional Glenn and Fontan Operation
Although these three stages have helped and saved a lot of infants’ life, just around 50% of the patients survive at age of 20 because of chronic illnesses, which happens because the systemic venous blood is unable to pass through the lungs and that leads to further complications of high systemic venous pressure and low cardiac output [19]. To reduce this risk, scientists suggested using a device, a pump, which will increase the systemic circulation pressure and cardiac output [20]. However, using a foreign pump may lead to other problems, like thrombus formation.

Recently, researchers suggested developing a synthetic pump with ideal flow characteristics and without complications of intravascular devices. This propose may be the best solution but still need years of development [21]. Another solution came up by other researcher as a substitute to the external pump. The idea was to connect the aorta (or the single ventricle) to the Fontan pulmonary arteries by a graft called Injection Jet System (IJS). After implementing the IJS, the pulmonary blood pressure and flow will be increased and the inferior vena cava pressure will drop down. Computational fluid dynamics (CFD) is used to show how effectively attaching the IJS might be on the Fontan circulation and the pressure of the blood flow.
Chapter 2

Models

2.1 Base Line Model

A synthetic model was built by using CATIA v5 and it includes the pulmonary arteries, left and right pulmonary arteries, Descending Aorta (DA), Inferior Vena Cava (IVC), Superior Vena Cava (SVC) and finally the upper and lower body circulations were constructed to close the loop. The dimensions of this model are not as same as what a human’s blood circulation has since it is not possible to build and model hundreds of kilometers of various size vessels.

The IJS, then, was created to achieve the desired energy and momentum transfers. The two branches of the IJS were built carefully so their flow enters PAs in a parallel way to the PA blood flow. To achieve satisfied results, the design was changed many times as can be seen in the results section.

Both the anatomical model and the IJS had different designs as shown in figure 2.1 to figure 2.4 for the model and from figure 2.5 to figure 2.12 for the IJSs to achieve the best circulating flow in the Pulmonary Arteries. Figure 2.1 shows the first baseline model that was created. After running the simulation, the results were not close to what was expected, as will be shown later in results chapter, and that due to the inconstant diameter for the vessels like what happens in the Inferior vena cava before connected the PAs. This flaw increased the flow velocity, which led to a high drop in pressure in small area.
After that the simulation carried out but another flaw came out after examining the results of the simulation and that was the tapering in the Pulmonary Arteries. That defect was doing as same as what the first flaw did but severely. The pressure drop was 10 mmHg from the area that connects the SVC and IVC with the PAs to the atria and that was not logic. So, modifying that part, PAs, by building it with one constant diameter, as shown in figure 2.2 was necessary to proceed with the simulation. This modification helped getting better results by decreasing the pressure loss as well as the velocity of the flow going back to the ventricle.
Although of all these modifications the results of the flow coming out through the Aorta was not satisfactory enough and that happened because the Aorta was placed on the side of the ball (ventricle), as shown in figure 2.3. So, another change in the baseline model was done by moving the aorta vessel from the side of the ball and place it on the top, as shown in figure 2.4, and that has increased the blood flow significantly as shown in the tables.
Figure 2.3 Shows the baseline model with the Aorta on the side
Figure 2.4 The final baseline used in this paper shows the Aorta placed on the top of the ball.
2.2 IJS

The IJS had also some changing and modification in its design to achieve the desired energy and momentum transfers as will be shown in figures below.

The problem with this design was that more flow goes to right lung than the left lung and that because the left branch was going out of the main IJS vessel with an angle that didn’t allow it to get enough flow while the right side was quite the opposite.

Since this flaw has a big impact on the simulation results another design was created to make balance in the flow going into these two branches as we can see in figure 2.8.
Even after making the IJS more efficient and equal flow going to each side of it, the IJS was not doing the job that has to do and that can be seen in the results of simulation conducted by using this IJS. The flow was coming from the Ventricle through the main IJS vessel was coming in a right angle before it splits to two ways and that was causing a lot of swirls and pressure loss as will be shown in the results section.

To get more efficient flow and decreasing the energy lost, another change in the IJS was done by building the new branches in a way that both of them come with an angle that is aligned to the main vessel and then smoothing the angle of the branches so the flow does not lose much energy and to prevent creating swirls. That changes led to better results as can be seen in the results table (3).
The last modification on the IJS was done to increase the shallow angle of the two branches so they can be as parallel as possible to the Pas flow and the IJS position was changed from the top of the ventricle to be on the aorta as can be seen in figure 2.12 below.

Figure 2.9 The third design of the IJS

Figure 2.10 the IJS with better branches flow angle

Figure 2.11 Shows the last model with the IJS placed on the aorta.

Figure 2.12 the last IJS design
2.3 Equations

The IJS uses a combination of the Venturi effect and momentum transfer. To explain how to achieve the required energetics, a calculation assuming a single orifice was performed. So, to reduce the gradient, \( \Delta p \), between the Inferior Vena Cava (IVC) and atrium by an amount \( \Delta(\Delta p) \) by using a high velocity jet in the PA flow direction, then the power provided by this jet must be \( \Delta Q_p \Delta p + Q_s \Delta(\Delta p) \), where \( Q_s \) and \( Q_p \) are the systemic and pulmonary blood flows, respectively. 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”, \( f = Q_p/Q_s \). The jet power is thus \( \rho(f-1)Q_s v^2 \), where \( v \) is the jet velocity. Setting this equal to the required power, we get

\[
(f - 1)Q_s \Delta p + Q_s \Delta(\Delta p) = r(f - 1)Q_s v^2 \tag{2.1}
\]

In cgs units, \( r = 1 \) and if pressure is in mmHg,

\[
v = 36.5 \sqrt{\frac{\Delta p + \Delta(\Delta p)}{(f - 1)}} \text{ cm/sec} \tag{2.2}
\]

Suppose, for example, \( \Delta p = 8 \text{ mmHg} \), and we want \( \Delta(\Delta p) = 5 \text{ mmHg} \) (the reduction in Fontan pressure) and an “acceptable” shunt fraction \( f = 1.4 \). Then \( v = 165 \text{ cm/sec} \). If \( Q_s = 4.5 \text{ l/min} \) the required nozzle orifice diameter would be 4.8 mm.—a very reasonable requirement.
Chapter 3

Grid Structure

For CFD the geometry mesh was generated by using Star CCM+ meshing tools. The, Surface Remesher, Polyhedral mesher and Prism Layer modules of Star CCM+ were the meshers used in this simulation. The Surface Remesher module repairs the geometry and improves the quality to obtain good quality mesh elements. Polyhedral mesher in complex problems gives a balanced solution, also, it has a lower number of cells compared with tetrahedral, nearly five times. Prism Layer allows the user to refine the mesh by changing the size of the elements as well as the element growth rate in order to capture the boundary layer [22].

Figure 3.1 Shows the mesh of the final model with the IJS attached to the aorta.
As can be seen in the figure above, some areas in the model have more element, more density, than others and that because STAR CCM+ mesh tools give more element to the areas where there is a change in the geometry which will lead to a higher flow velocity as in the area where the two IJS branches meet with pulmonary arteries. While in area where the dimensions are not having big changes the mesh is coarser and that would not affect the accuracy of the solution but could save computational resources. Figure 3.1 below shows some close pictures of the mesh for different areas.
Figure 3.3 Shows the mesh of the aorta, PAs and IJS
Figure 3.4 Shows different mesh elements sizes

Figure 3.5 Shows the mesh of the two branches
Chapter 4

Computational Fluid Dynamics Analysis instead of CFD

StarCCM+ from the CD-Adapco was used and it is a multi-physics CFD software that models 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 StarCCM+ use numerical algorithms to solve the mass and momentum conservation equations governing fluid mechanics. That is, they solve the Navier-Stokes equations (NSE):[13]

\[
\nabla \cdot \vec{V} = 0 \quad \text{and} \quad \rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \cdot \nabla) \vec{V} = -\nabla p + \nabla \cdot \sigma 
\]

(4.1)

Here, \( \vec{V} \) is the velocity vector, \( p \) is the pressure field, \( \rho \) is the blood density (1060 kg/m\(^3\)), and \( \mu \) 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.

The baseline model, first, was evaluated in Star CCM+. The first approach to run this simulation was by using momentum source option in five intermediate media: Ventricle, upper circulation, lower circulation, right pulmonary circulation and left pulmonary circulation. Using the momentum source options in these five places to simulate the pressure rise/drops that happens in the cardiovascular system due to the long journey through hundreds of miles of vessels. Each of these sections has their own momentum source and which is defined by a vector field function that points the desired forces in the proper direction. The input for the momentum source is a force/volume value. To calculate the magnitude of these vectors you simply calculate:
F / V = dp * A / (A * L) \quad \text{for a cylindrical section with constant area} \quad (4.2)

Here, $F$ is the force, $V$ is the volume, $A$ is the area of disks used, $L$ is the thickness of each disk and $dp$ is just a random number calibrated until the right rise/drop pressure were right.

To use this approach, a disk with a thin thickness in each of the five media mentioned earlier was built. Having a disk instead of a face is necessary to make sure that each one has at least three cells through the thickness so the pressure gradient caused by the momentum source can be resolved.

1. **To Iterate to Get Pressure at Effector Locations**

Step 1. Making assumptions about what the pressure drops/rise should be at each of the effector locations. In this case is the difference between your high and low pressures.

Step 2. Run the analysis. Check flow rate and check the pressures on the downstream faces as well as the upstream faces of the effector disks by using mass flow averaged reports of total pressure. After figuring out the results, calculate a new force/pressure drop that will give the correct pressure rise/drop value.

Step 3. Repeat step 2 until the momentum source gives you the correct pressure rise/drop value.

Unfortunately this solution approach has some disadvantages:

1. It was taking a long time to converge.
2. Too much iterating to the momentum source value to get the desired pressure.
3. There were swirls close to the area were the disks are created.

Because of number 3, using mass flow averaged reports of total pressure didn’t give the accurate values of the pressure rise/drop.

Another approach was used to run the simulation and that was by using a Fully Developed Interfaces on each place where the pressure rise/drop needed. Using this approach by sitting a
positive value where the pressure rise needed and a negative value where the pressure drop needed was easier and the simulating converging time was less with more accurate value and no swirls.

2. To get the pressure needed at Effector locations

Step 1: setting the exact pressure rise/drop needed instead of making assumption since this approach gives instant pressure change.

Step 2: Run the simulation and check the pressure before and after each effector to make sure the values are correct.

Numerous attempts were performed by either using the first approach (momentum sources options) or the second approach (Fully Developed Interface) to get the desired baseline model calibration solution. After that, the Injection Jet System was attached to the baseline model to validate and verify how efficient it is. In addition, different diameters for the IJS branches will be used to compare their results and choose the best among them. The diameters used were 4 mm, 3 mm and 2 mm and table and pictures of each case will be shown below for the last model design used and also for the old designs to show effect of each design on the results Decreasing inferior vena cava pressure and make it less than 17mmHg and to get a pulmonary to systemic volume flow rate $l, \frac{Q_p}{Q_s}$, less than 1.5 were the targets of this study.
Chapter 5

Results

As mentioned earlier, there are two models one without the IJS and one with the IJS. So, the simulation will be carried out first to get the desired results (pressure and flow rate) from the baseline mode. Then, after getting the desired results, the IJS will be implemented to the base line model with the exact same input values used for the base line model to find out the effect of the IJS on the blood circulation flow and the pressure. Different IJS branches dimensions used in this study 2 mm, 3mm and 4 mm. In this chapter, scalar scenes and vector scenes for all the IJS branches dimensions used will be shown. Figure 5.1 shows the scalar scene for the first simulation was conducted and as mentioned earlier this model was rejected due to some flaws in the design.
For this geometry the simulation wasn’t carried out to find the other results since it was found that more flow is going to the right branch of the IJS than the left side as mentioned earlier.

Figure 5.1 A scalar scene shows pressure contour of the baseline model for the first design

Figure 5.2 A scalar scene shows pressure contour for the first model with the IJS
The next design was used gave very acceptable results but there was a problem with the IJS as mentioned above and can be seen in figure 5.3 below.

![Figure 5.3 A scalar scene for the baseline model](image)

There was a big loss in the pressure because of the tapering in the pulmonary arteries and that allowed the flow to gain a very high speed. As a result of that speed the flow pressure dropped drastically below the 7 mmHg that the blood should have when return to the ventricle. All of that happened without even using the momentum sources on both right and left lungs.
Figure 5.4 Vector scene for the baseline model

Figure 5.5 Shows a close vector scene for the baseline model
Figure 5.6 Mass flow averaged pressure report plot for the aorta

Figure 5.7 Mass flow rate plot of the aorta
Figures 5.6 and 5.7 show the pressure and mass flow rate values of the blood right after it leaves the ventricle. These reports and the residual report help to decide whether the simulation was converged or not. As can be seen in the figures above, the pressure and the mass flow rate started to fluctuate in the beginning of the simulation, then, these two values stopped changing and that helps to get a better understanding about the simulation. More reports for different models used will be shown below as well as in the Appendix. Figure 5.8 shows a scalar scene for the second IJS design. After running the simulation, the results were somehow accurate but there was not a big effect for the IJS and that because the blood was coming from the ventricle through the main tube of the IJS in a 90 degree angle. The blood was hitting the wall of the two branches with a very high speed as can be shown in figure 5.6 and the led the flow to lose a lot of its energy and velocity.
Figure 5.8 Scalar scene of the second model design with the 4mm IJS

Figure 5.9 Vector scene of the second model design with the 4mm IJS
Figure 5.10 A close vector scene of the second model design with the 4mm IJS

Table 1 Results analysis from CFD for with and without IJS models

<table>
<thead>
<tr>
<th></th>
<th>Qs L/m</th>
<th>Qp L/m</th>
<th>Q ijs L/m</th>
<th>Qp/Qs</th>
<th>P atria mmHg</th>
<th>P aorta mmHg</th>
<th>P caval mmHg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>2.96</td>
<td>2.96</td>
<td>n/a</td>
<td>1</td>
<td>7</td>
<td>76.98</td>
<td>24.4</td>
</tr>
<tr>
<td>2 mm</td>
<td>2.47</td>
<td>3.15</td>
<td>0.67</td>
<td>1.275</td>
<td>7</td>
<td>77.055</td>
<td>24.84</td>
</tr>
<tr>
<td>3mm</td>
<td>1.95</td>
<td>3.43</td>
<td>1.49</td>
<td>1.758</td>
<td>7</td>
<td>77.07</td>
<td>25.59</td>
</tr>
<tr>
<td>4 mm</td>
<td>1.3</td>
<td>3.66</td>
<td>2.299</td>
<td>2.815</td>
<td>7</td>
<td>77.034</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Table 1 above shows the results for the base line model as well as the results for the simulation after attaching different IJS diameters. Qs, which is the flow rate value in liter per minute of the blood after leaving the ventricle and Qp is the flow rate of the blood after it returns to the ventricle from the lungs. Q ijs is the blood flow rate through the IJS. AS mentioned earlier the
Qp/QS is supposed to be less than 1.5 but the 3 mm and 4 mm is not even close to what is needed caval, which represents the IVC pressure, was, also, very high. All that happened because of the tapering and also the 90 degree angle of the IJS.

The third model used in this study was modified. Because of the Pulmonary arteries tapering, the flow was going to the lungs had a very high speed and that led to significant drop in the pressure before the flow goes back to the ventricle and the same problem was with the IJS design. So, both the PAs part and the IJS design were changed to solve the pressure lose issue.

Figure 5.11 scalar scene for baseline model without PAs tapering
Figure 5.10 shows the scalar scene for the baseline model after the tapering eliminated by building the pulmonary arteries with one diameter. That solved the problem of losing a lot of the blood flow pressure by decreasing the blood velocity that’s going to the right and left lungs as can be seen in figure 5.11 and figure 5.12. The results achieved from this model after the IJS was introduced were very accurate and showed a lot of progress. Figure 5.13 and figure 5.14 show the scalar scene for the 4 mm IJS. Better flow from the IJS to the Pulmonary arteries and that led to more reduction in the caval pressure as table 2 and table 3 show.

Figure 5.12 vector scene for the baseline model without tapering
Figure 5.13 Close picture for the vector scene show how the blood flow directions

Figure 5.14 Scalar scene for the 4mm IJS model without PAs tapering
Figure 5.15 Close picture for the 4 mm IJS model

Figure 5.16 Vector scene for the 4mm IJS
Figure 5.17 A close picture for the 4mm model shows the flow direction

Figure 5.16 and figure 5.17 represents the vector scenes which show the direction of the blood through the vessels. As shown in figure 5.17 the flow that’ coming through the main vessel of the IJS goes into the pulmonary arteries in a balanced way. That improved the results as shown in tables 2 and 3.
Table 2 shows Qs, Qp, Qij, Qp/Qs, P aorta and P caval results for the model showed up. The Qp values is higher comparing with the values of previous model and also P aorta in this table is more accurate than the old model. More reduction in P caval but in 4 mm IJs P caval was increase were it supposed to decrease. In table 3 the Qs for all the models with the IJs were changed to be three L/m by decreasing the pressure jump value of the pump and that because the patient heart can actually pump no more than three L/m. As can be seen Qp for 4 mm IJS is more than seven L/m which is impossible for the patient heart to pump. The results had some changes after making the Qs three L/m, especially, for the Qp/Qs values where they increased. For instance, the 4 mm IJS model’s results should be rejected because the Qp/Qs was 2.53 where it is supposed to be less than 1.5 and also there was no reduction in the caval pressure value.

<table>
<thead>
<tr>
<th></th>
<th>Qs (L/m)</th>
<th>Qp (L/m)</th>
<th>Qij (L/m)</th>
<th>Qp/Qs</th>
<th>P atria (mmHg)</th>
<th>P aorta (mmHg)</th>
<th>P caval (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>2.973</td>
<td>2.97</td>
<td>n/a</td>
<td>1</td>
<td>7</td>
<td>67.395</td>
<td>18.203</td>
</tr>
<tr>
<td>2mm</td>
<td>3.139</td>
<td>4.264</td>
<td>1.123</td>
<td>1.358</td>
<td>7</td>
<td>67.457</td>
<td>18.21</td>
</tr>
<tr>
<td>3mm</td>
<td>3.233</td>
<td>5.71</td>
<td>2.618</td>
<td>1.766</td>
<td>7</td>
<td>67.746</td>
<td>18.2</td>
</tr>
<tr>
<td>4 mm</td>
<td>2.9</td>
<td>7.385</td>
<td>4.493</td>
<td>2.546</td>
<td>7</td>
<td>69.9</td>
<td>19.56</td>
</tr>
</tbody>
</table>

Table 3 lowered ventricular pressure to maintain the 3 l/m Qs

<table>
<thead>
<tr>
<th></th>
<th>Qs (L/m)</th>
<th>Qp (L/m)</th>
<th>Qij (L/m)</th>
<th>Qp/Qs</th>
<th>P atria (mmHg)</th>
<th>P aorta (mmHg)</th>
<th>P caval (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>2.973</td>
<td>2.97</td>
<td>n/a</td>
<td>1</td>
<td>7</td>
<td>67.395</td>
<td>18.203</td>
</tr>
<tr>
<td>2mm</td>
<td>2.973</td>
<td>4.089</td>
<td>1.116</td>
<td>1.375</td>
<td>7</td>
<td>66.698</td>
<td>17.393</td>
</tr>
<tr>
<td>3mm</td>
<td>3.01</td>
<td>5.618</td>
<td>2.603</td>
<td>1.866</td>
<td>7</td>
<td>67.118</td>
<td>17.487</td>
</tr>
<tr>
<td>4 mm</td>
<td>2.944</td>
<td>7.4505</td>
<td>4.507</td>
<td>2.53</td>
<td>7</td>
<td>70.34</td>
<td>20</td>
</tr>
</tbody>
</table>
The final modification done in this study to bet more better results was by increasing the IJS shallow angle to make its flow more parallel to the PAS flow and that would help getting more flow energy through the PAS. Also, the aortal position was transferred from the side of the ventricle (ball) to be on the top of it to get more flow through the aorta than before with the same pressure rise/drop used in the previous models. Finally, the IJS was displaced from the ventricle and attached to the aorta vessel right after it leaves the ventricle.

Figure 5.18 Scalar scene of the baseline model
Figure 5.19 Vector scene of the baseline model

Figure 5.20 close picture for the vector scene show the blood flow directions
Figure 5.21 The Residual plot of the baseline model

Figure 5.22 Aorta mass flow rate plot
Figure 5.23 A scalar scene for the 4mm IJS

Figure 5.24 Close picture of scalar scene for the 4mm IJS
Figure 5.23 and figure 5.24 show the scalar scene for the final geometry used in this study. Better flow was achieved in the pulmonary arteries since the IJS branches were more parallel to the pulmonary arteries and the let to better energy transfer to both lungs.

Figure 2.25 Vector scene for the 4mm IJS
Figure 2.25 and 2.26 show the vector scene for the simulation with the 4 mm IJS. In this model, more flow was produced from the ventricle since the aorta was moved from the side of the ventricle to be on the top and that produced what higher flow rate than all the old models used. Also, as it can be seen in figure 2.24 the blood was not gaining any more speed when it moves to both right and left lungs and that prevented the lose in the blood pressure that was happening in all of the previous models.
Table 4 Normal ventricular pressure

<table>
<thead>
<tr>
<th></th>
<th>$Q_s$ (L/m)</th>
<th>$Q_p$ (L/m)</th>
<th>$Q_{ijs}$ (L/m)</th>
<th>$Q_p/Q_s$</th>
<th>$P_{aorta}$ (mmHg)</th>
<th>$P_{caval}$ (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>3</td>
<td>3</td>
<td>n/a</td>
<td>1</td>
<td>70.9</td>
<td>17.18</td>
</tr>
<tr>
<td>2mm</td>
<td>3.65</td>
<td>4.6</td>
<td>0.947</td>
<td>1.26</td>
<td>70.9</td>
<td>16.85</td>
</tr>
<tr>
<td>3mm</td>
<td>4.32</td>
<td>6.58</td>
<td>2.26</td>
<td>1.523</td>
<td>71</td>
<td>16.62</td>
</tr>
<tr>
<td>4 mm</td>
<td>6.43</td>
<td>10.95</td>
<td>4.5</td>
<td>1.702</td>
<td>71.04</td>
<td>16.425</td>
</tr>
</tbody>
</table>

Table 5 lowered ventricular pressure to maintain the 3 l/m $Q_s$

<table>
<thead>
<tr>
<th>same</th>
<th>$Q_s$ (L/m)</th>
<th>$Q_p$ (L/m)</th>
<th>$Q_{ijs}$ (L/m)</th>
<th>$Q_p/Q_s$</th>
<th>$P_{aorta}$ (mmHg)</th>
<th>$P_{caval}$ (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>3</td>
<td>3</td>
<td>n/a</td>
<td>1</td>
<td>70.9</td>
<td>17.18</td>
</tr>
<tr>
<td>2mm</td>
<td>2.981</td>
<td>3.926</td>
<td>0.944</td>
<td>1.375</td>
<td>70.2</td>
<td>16.455</td>
</tr>
<tr>
<td>3mm</td>
<td>3.046</td>
<td>5.28</td>
<td>2.244</td>
<td>1.733</td>
<td>69.16</td>
<td>15.365</td>
</tr>
<tr>
<td>4 mm</td>
<td>3.06</td>
<td>6.91</td>
<td>3.85</td>
<td>2.258</td>
<td>68</td>
<td>15.382</td>
</tr>
</tbody>
</table>

Table (4) shows the systemic and pulmonary blood flows, which complies with physiological data, as well as the vacuum pressure of the aorta and the caval, which is the flow pressure of the inferior vena cava right before meeting the Pulmonary artery, for the baseline model. Table (4) shows, Also, the $Q_s$, $Q_p$, $Q_p/Q_s$, $P_{aorta}$ and $P_{caval}$ for the model after introducing the IJS. As expected the overall flow rate is higher than the baseline model flow rate since there is another resistance was added (IJS) which gives the ventricle more freedom to pump more flow to the heart. Also, it can be noticed that the Caval pressure was decreased for the 2mm, 3mm and 4 mm IJS diameters but in 4 mm model there was more reduction in the Caval pressure and also, the overall pressure, $Q_p$, was about 10.95 which is approximately three time than the $Q_p$ of the
baseline model. On the other hand the Qp/Qs value was more than 1.5, which is the maximum desired value, while in 2 mm case the Qp/Qs value was 1.26.

Since the heart can only pump 3 L/min, the Qs for the model with the IJS had to be reduced by lowering the pressure rise on the Ventricle interface till it produce a flow rate somewhere close to 3 L/min. Table (5) shows the new values for the mass flow rates and vacuum pressures and it can be seen that there are some noticeable changes .For example, Qp for the 4 mm model drops down from 10.95 to 6.91. The Qp/Qs values for 2 mm, 3mm and 4 mm were all increased especially in 4 mm case where the value jumped from 1.702 to 2.258.
Conclusion

The model used in this study shows how effective the use of the IJS in the blood circulation and how it may help significantly patient with the HLHS. Also, these type of study help surgeons to understand and predict the outcome of using of the IJS. Detailed scenes and tables were presented in results sections to demonstrate the benefits of introducing the IJS. The 2 mm IJs model gives a very good Qp/Qs result but less Inferior vena cava pressure reduction while the 4 mm IJS model gives an unacceptabe Qp/Qs results, which was more than two, with more Inferior vena cave pressure reduction. Using patient-specific anatomy can give more accurate results about using the IIJS and, also, building the IJS to go inside the PAs in a parallel way can add more momentum to the flow and that can lead to a better result.
References


[12] David J. Goldberg, MD Hypoplastic Left Heart Syndrome The Children Hospital of Philadelphia 2013 http://www.chop.edu/conditions-diseases/hypoplastic-left-heart-syndrome-hlhs/about#.VgCeX99VhBc


Figure References


[2] Fontan
http://www.heartbabyhome.com

[3] Norwood – Figure 2
http://www.severinbrenny.com/norwood_operation.html
Appendix

A. Figures

Figure 1 A close vector scene of the second model design with the 2mm IJS

Figure 2 A close vector scene of the second model design with the 3mm IJS
Figure 3 Scalar scene for the 2 mm IJS model

Figure 4 Scalar scene for the 3mm IJS model
Figure 5 A vector scene for the 3mm IJS model

Figure 6 A vector scene for the 2mm IJS model
Figure 7 The IJS mass flow rate plot for the 2mm model

Figure 8 Aorta mass flow rate plot for the 2mm model
Figure 9 Residual plot for the 2mm IJS model

Figure 10 Aorta pressure plot
Figure 11 IJS pressure plot

Figure 12 IJS mass flow rate plot
Figure 13 Scalar scene for the 3mm IJS

Figure 14 Close picture of scalar scene for the 3mm IJS
Figure 15 Vector scene for the 3mm IJS

Figure 16 Close picture of vector scene shows the blood flow directions
Figure 17: Aorta mass flow rate

Figure 18: IJS mass flow rate for the final model
Figure 19 Aorta pressure plot

Figure 20 Residual plot for the 3 mm IJS
Figure 21 Scalar scene for the 2mm IJS

Figure 22 Close picture of scalar scene for the 2mm IJS
Figure 23 Vector scalar scene for the 2mm IJS

Figure 24 Close picture of vector scene shows the blood flow directions
Figure 25 IJS mass flow rate plot

Figure 26 Aorta mass flow rate plot
Figure 27 IJS pressure report

Figure 28 Aorta pressure report