Numerical Model of the Univentricular Fontan with Mechanical Cavopulmonary Assist

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Motivation

- The treatment of single ventricle defects represents a formidable challenge for clinicians caring for patients with congenital heart disease.
- These patients must undergo three major heart surgeries for palliation, and the final surgery is called the Fontan conversion where passive flow is achieved in the pulmonary circulation (**Figure 1**).
- Overall survival through these operations is only 50-70% and those who survive have prolonged, complicated, and costly hospitalizations.
- Those having a univentricular Fontan circulation are at high risk of developing complications of systemic venous hypertension, thromboembolism, and congestive heart failure.
- Approximately 25% of the first generation of Fontan recipients will develop heart failure within 15 years postoperatively.
- The implementation of mechanical assist, such as extracorporeal membrane oxygenation (ECMO) or ventricular assist devices (VADs), has improved hospital survival and simplified postoperative management in a small number of patients with single ventricle physiology.
- Alternative treatment strategies to conventional circulatory assist include the development of a new category of blood pumps to augment pressure in the cavopulmonary connection.
- This study aims to assess the interactive biofluid dynamics of a percutaneously-inserted collapsible axial flow pump and an idealized cavopulmonary circulation.

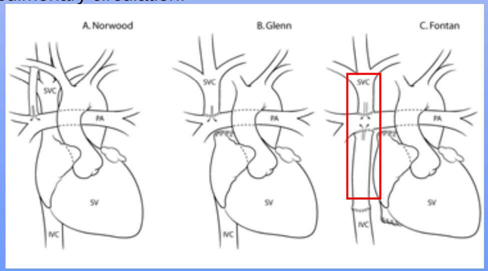
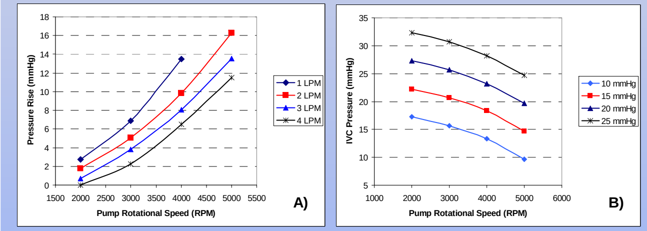


Figure 1: Staged surgical repair of single ventricle. **A.** Stage-1 Norwood. Blood flow to the lungs is supplied by a systemic-to-pulmonary artery shunt. **B.** Stage-2 Glenn. The SVC is connected to the PA as the only source of pulmonary blood flow. IVC flow enters the common atrium and is ejected back out to the body. **C.** Stage-3 Fontan. IVC flow is diverted to the PA. **SV**, single ventricle; **PA**, pulmonary artery; **SVC**, superior vena cava; **IVC**, inferior vena cava.

Numerical Results

- The axial flow pump has three impeller blades that would be flexible and constructed of biologic material. The impeller blades would fold to allow the rotor to be fed through a catheter-based self-expanding sheath assembly.
- The folding cage serves as touchdown surfaces to protect the vessel wall from the rotating components. For this initial analysis, the cage was not included.
- No suction or negative pressures were achieved on the inlet of the pump.
- This configuration led to an approximate 50:50 split in flow through the LPA and RPA due in large part to the equal pressure conditions in both branches.
- As expected, the pressure rise values dramatically increased at higher speeds. In addition, for a particular rotational speed, the pressure rise across the pump was found to increase with a decrease in flow rate, as also expected.
- The IVC pressure (inlet side of the pump) decreased with increasing speeds and did not become negative during these simulations.



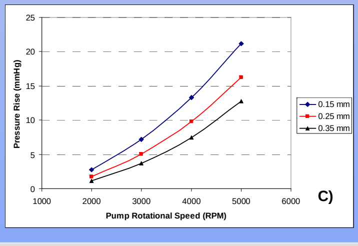


Figure 2: Numerical Predictions using an Axial Pump having a 0.25 mm tip clearance and 8 mm SVC offset. A) Pressure Generation of Pump; B) IVC Pressure as a function of increasing RPM with constant LPA and RPA pressures; C) Pressure Rise across the pump as a function of increasing RPM for each tip clearance (0.15 mm, 0.25 mm, and 0.35 mm)

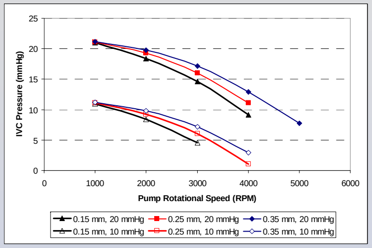


Figure 3: Numerical Predictions with a 8 mm SVC offset, 10 and 20 mmHg pressures for the LPA and RPA, and tip clearances of 0.15, 0.25, and 0.35 mm as a function of increasing RPM at 1 LPM.

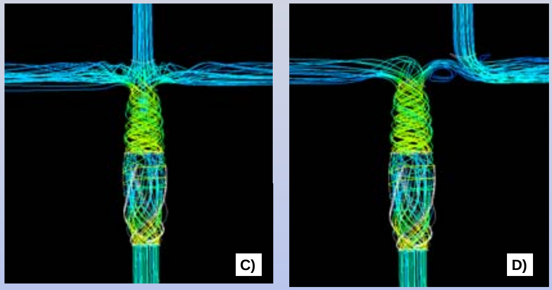


Figure 4: Numerical Predictions of Flow Streamlines using an Axial Pump having a 0.25 mm tip clearance for twp different SVC offset values of C) 0 mm and D) 16 mm. 3000 RPM, 3 LPM.

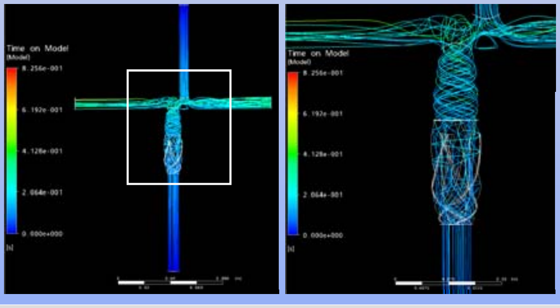
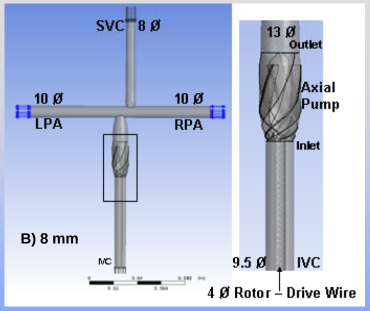


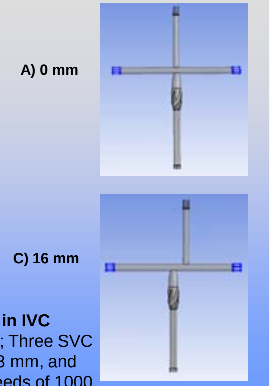
Figure 5: Flow Streamlines in the Model with a Maximum Residence Time of 0.8 Seconds. Through the pump and TCPC for LPA and RPA conditions of 15 mmHg, 3 LPM, and 5000 RPM.

Numerical Methods

Pump Design and Cavopulmonary Model

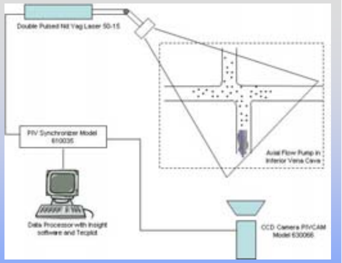
- Turbulent flow conditions expected in the pump and at the outlet.
- Standard k-ε turbulence model coupled with logarithmic wall function to characterize near-wall flow conditions.
- Grid quality and convergence study were completed.
- Blood Properties: Newtonian assumption; fluid viscosity of 3.5 cP (hematocrit of 33%); fluid density of 1050 kg/m^3.
- Steady flow with constant boundary conditions and velocities in time.
- No slip boundary conditions applied to stationary walls.
- Stationary wall boundary implemented along internal housing regions.
- Rotating walls specified for impeller in the counterclockwise direction according to blade orientation.
- Frozen rotor interface linked regions of differing reference frames.
- Uniform inflow mass flow rate and rotational applied with outflow pressure set at a constant 20,000 Pascal.
- A 2:1 ratio for the IVC / SVC flow rate respectively was applied. Pulmonary arterial pressures of 10 to 25 mmHg were also defined as outlet boundary conditions.





Cavopulmonary Circulation and Axial Pump in IVC
All diameters are in units of millimeter. 525K elements; Three SVC or caval offset positions were examined: A) 0 mm, B) 8 mm, and C) 16 mm. Flow rates of 1 to 4 LPM and rotational speeds of 1000 to 5000 RPM were modeled with axial pump designs having three different tip clearances of 0.15 mm, 0.25 mm, and 0.35 mm.

Conclusions



- This pump configuration in the IVC resulted in post-swirl at its outlet.
- Particle residence times through the pump, however, were less than 0.2 seconds.
- A small recirculation region appears to exist where the SVC inflow connects to the pulmonary artery.
- Optimization of the pump design may reduce such flow irregularities and improve energy transfer.
- Scalar stress estimations were also performed. The values remained below 350 Pascal, which suggests that acceptable shear stresses are present in this model.
- Next Step: Application of more physiological realistic boundary conditions, model pump in the SVC as well, include protective collapsible cage filaments around axial pump, transient simulations, and particle image velocimetry.

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