Benchtop Study of Autoregulatory Response Mechanism for Injection Jet Shunt Assisted Fontan Circulation

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Abstract

Although the Fontan procedure is effective in what it aims to accomplish, it is a short term, fragile solution that is prone to imperfections which may compromise quality of life and can only guarantee a 50% survival rate. In response, we propose to augment energy in the Fontan circulation with an injection jet shunt (IJS) drawing flow directly from the aortic arch, balanced by a conduit-to-atrial fenestration to approximately preserve the ratio of pulmonary flow (Qp) to systemic flow (Qs). Preliminary results show that pressure relief in the IVC is closely related to fenestration orifice diameter which validates detailed in-silico findings. Addition of an IJS with an enlargement of the fenestration to 7mm delivers significant IVC pressure drop along with total systemic oxygen saturation drop all while there is no substantial increase in ventricular volume load.

Introduction

The treatment of hypoplastic left heart syndrome (HLHS) continues to be a critical concern in the field of pediatric heart care. Occurring in approximately 1 out of every 3,841 births, HLHS leaves infants with a severely underdeveloped left heart, requiring immediate and complex medical intervention.

Fontan Procedure (Stage III Surgical Palliation):

The Fontan operation involves the diversion of the inferior vena cava flow into the pulmonary artery, either through a lateral tunnel in the atrium or an extracardiac conduit. This results in all systemic venous blood passively flowing into the pulmonary arteries, allowing oxygenation but potentially leading to chronic issues like ventricular dysfunction or arrhythmias.

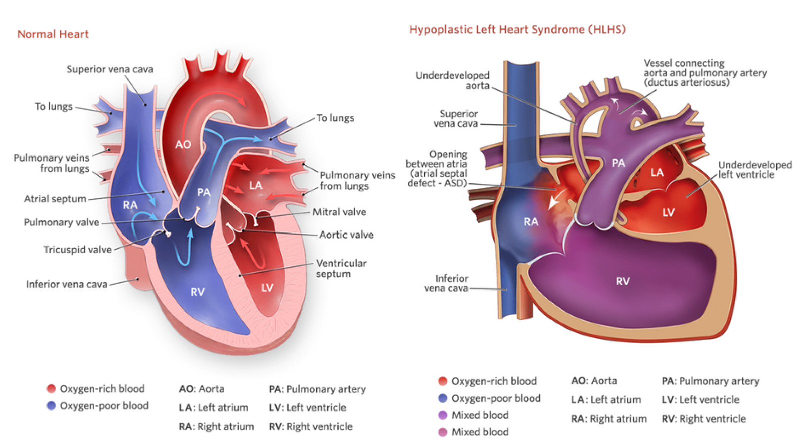


Figure 1: This figure shows a comparison between normal and single ventricular heart

Methodology

Importance:

The experimental jet proposed greatly increases the effectiveness of the Fontan procedure and serves as a more permanent solution for children with congenital heart conditions such as Hypoplastic Left Heart Syndrome (HLHS). The addition of an injection jet shunt (IJS) paired with an enlarged fenestration mitigates IVC pressure buildup while keeping systemic oxygen saturation low.

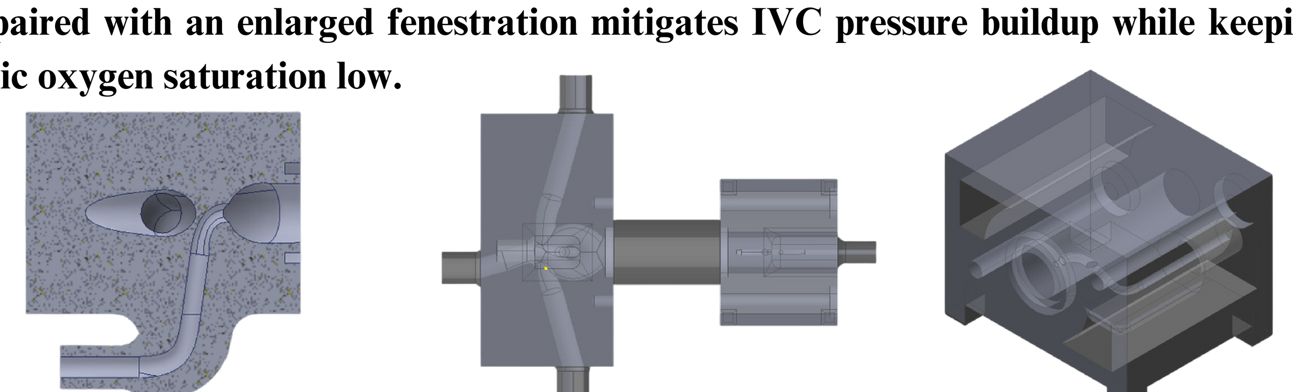


Figure 2: Torus Model

To ensure that patient-specific Fontans with the added IJS are effective, a series of comprehensive experimental tests must be performed that validate the results obtained from CFD. This requires the implementation of a representative Mock Flow Loop (MFL) in conjunction with an auto-regulatory response control system that accurately models blood flow through the Fontan in various conditions.

The parameters in the MFL that need to be controlled are as follows:

- The cc per stroke of the Harvard Apparatus Pump (determines the amount of flow per stroke)
- The rpm of the Harvard Apparatus Pump (dictates heart bpm)
- The SVR or systemic valve resistance (Indicates how flow % is divided in the TCPC)

Simscape Modeling of Harvard Apparatus Pump

Harvard Apparatus Pump consists of a Cam Follower system which generates RPM that is connected to a Piston. This pump needs to be manually altered while doing the in-vitro analysis and experiments. To control the angular velocity of the Cam Follower system manually and to adjust the Systemic Valve Resistors is time-consuming.

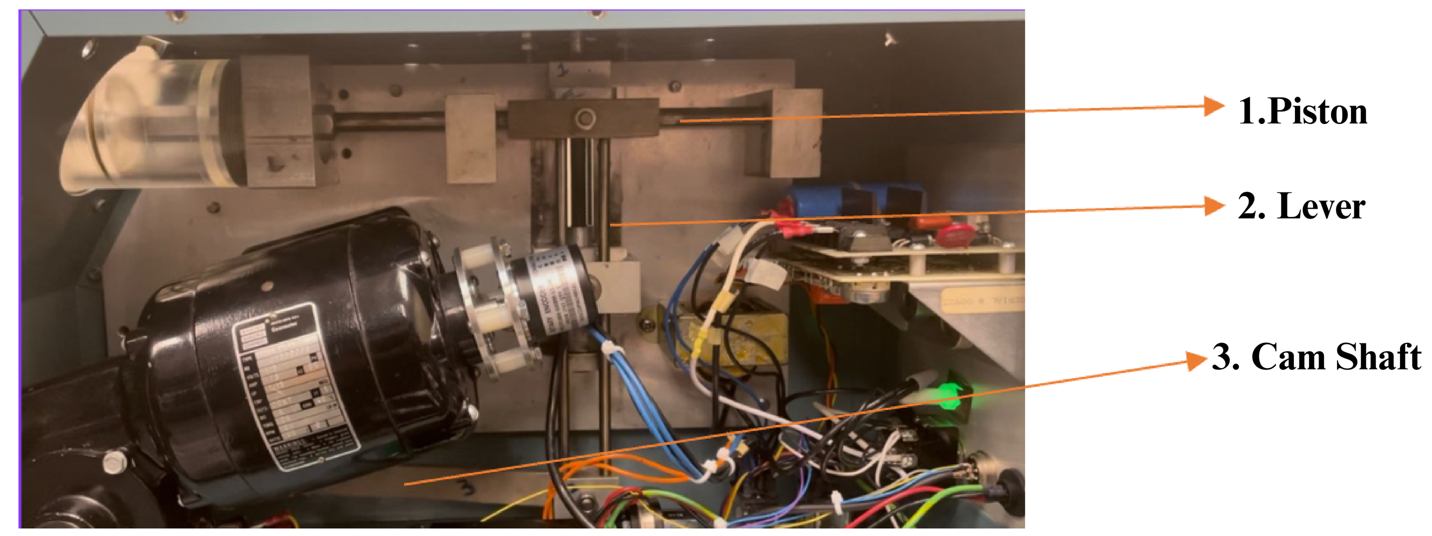
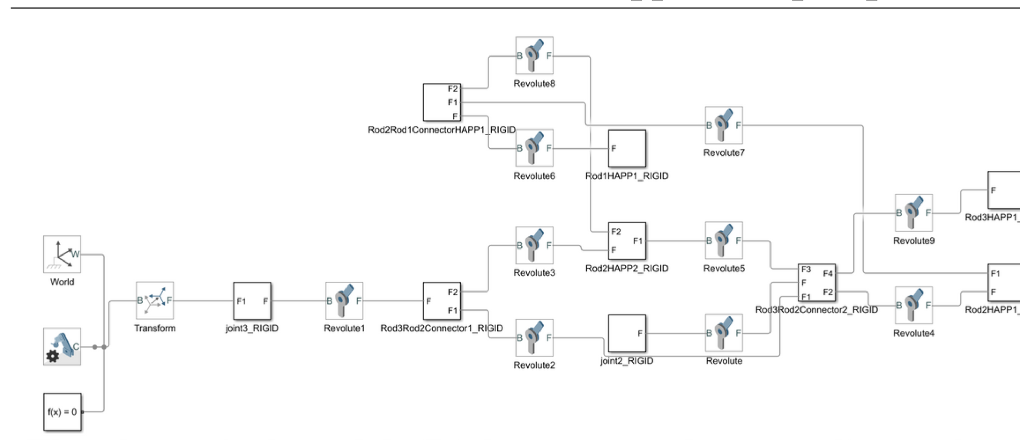


Figure 3: This figure shows the Harvard Apparatus Pump

Theoretical model of the Harvard Apparatus pump in Simscape



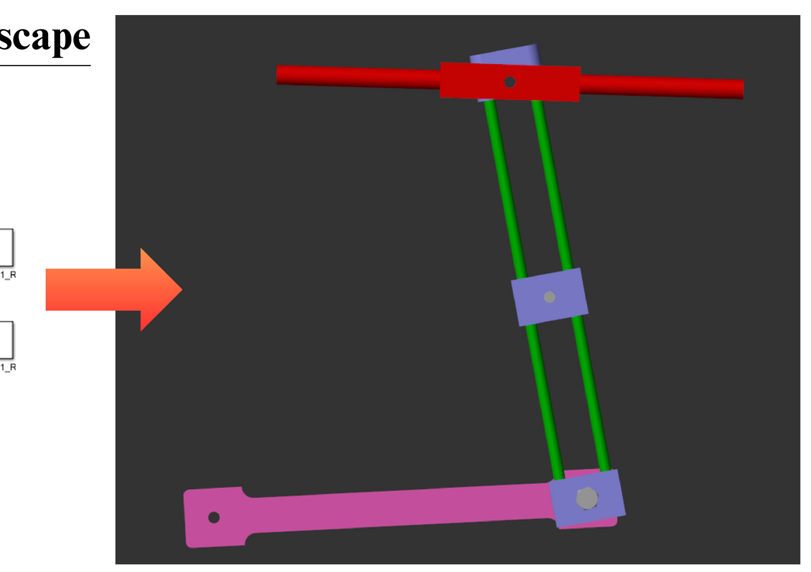


Figure 4: This figure shows the Harvard Apparatus Pump in Simscape MATLAB

The theoretical model (Right) was made to replicate the Harvard Pump. The red rod in the figure above is the piston, the green rods are the lever and the pink rod is the follower which is given an angular velocity.

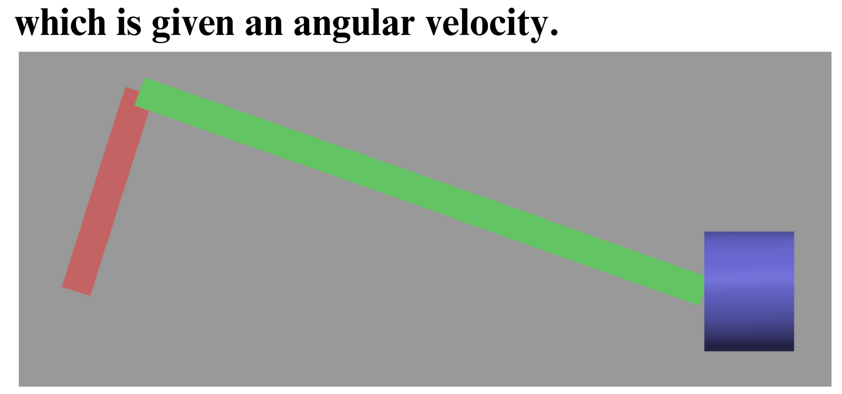


Figure 5: This figure shows the Piston movement of the Harvard Apparatus Pump in Simscape

The Dynamical model (Left) is to mimic the movement of the piston in the Harvard Apparatus Pump. The Red rod acts as a follower that is given an angular velocity which changes the cc/stroke of the piston.

Auto-Regulatory Response Control Logic Diagram

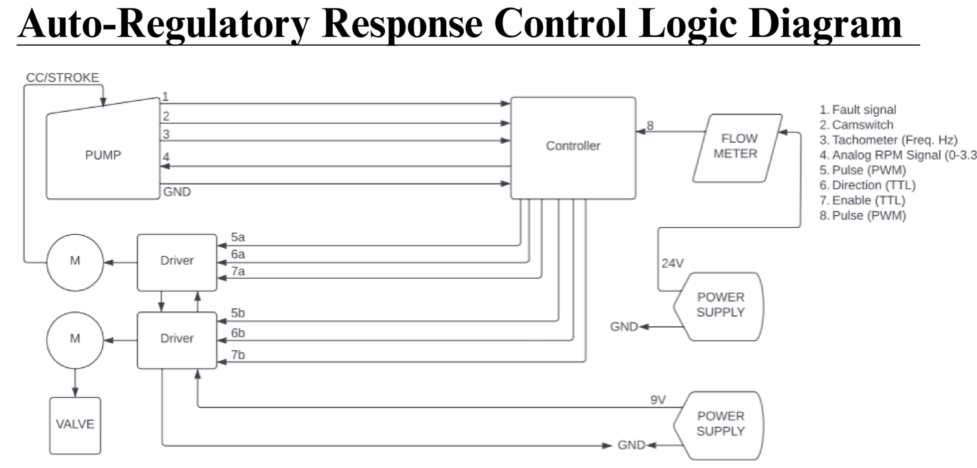
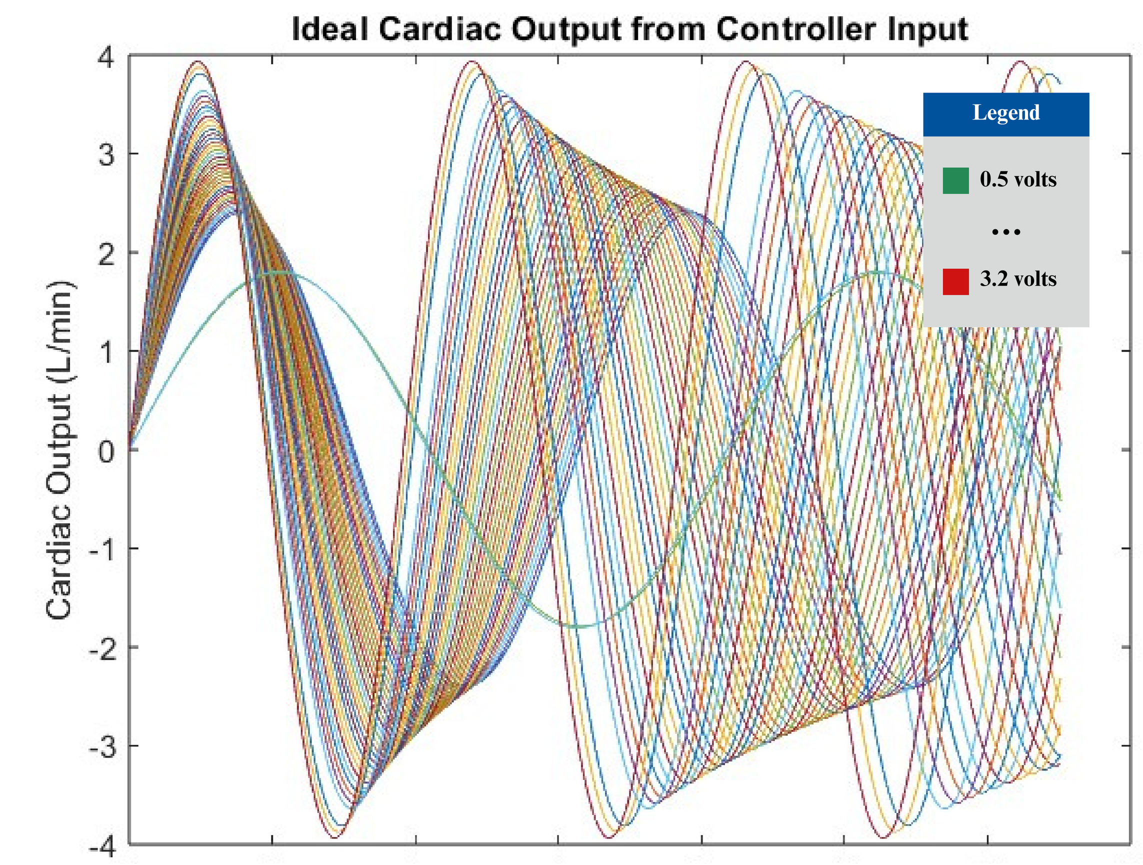


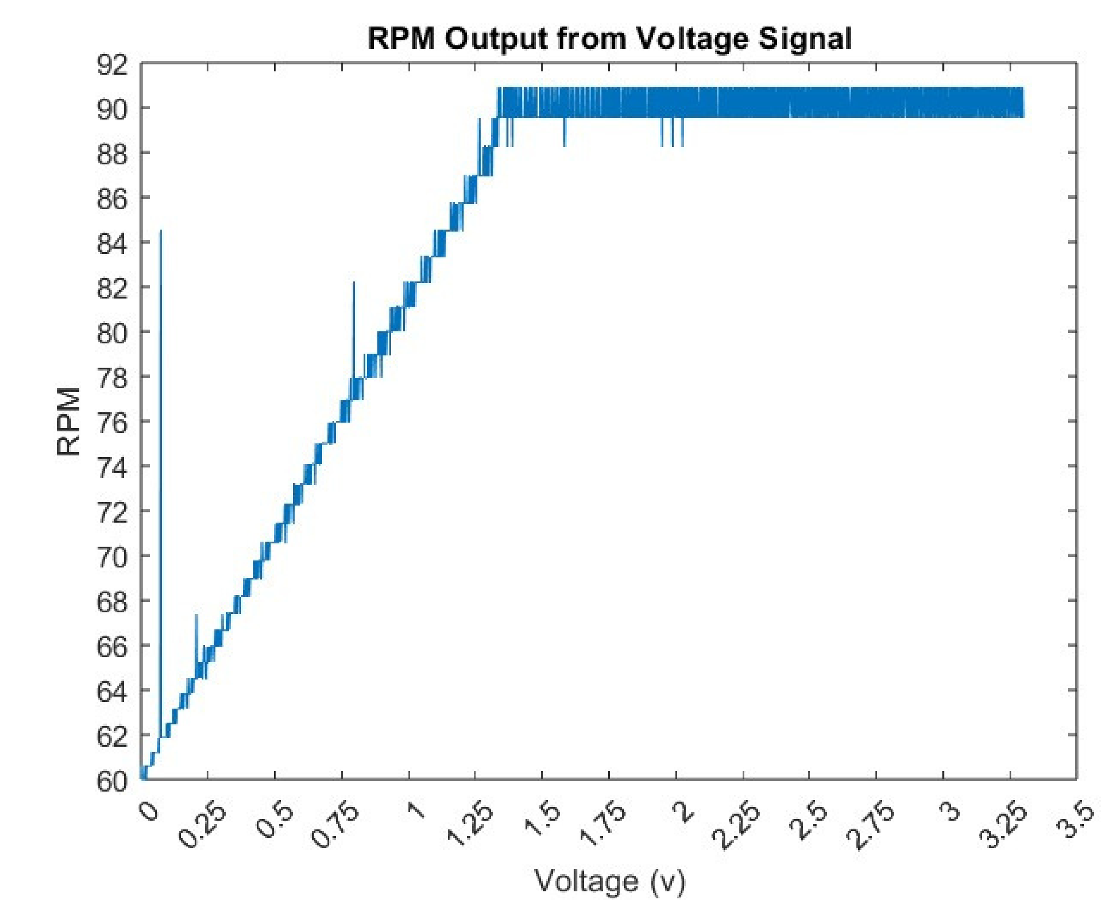
Figure 6: Logic Diagram

The Autoregulatory Response Control Logic diagram is representative of the connections between the controller and the hardware utilized within the system. The controller dictates the inputs to the Harvard Apparatus, the Systemic Vascular Resistance valves, and reads the outputs of the pump and flow measurements within the MFL.

Results

The figure (Top Right) displays the simulated Q~Cardiac Output (CO) of the Harvard Apparatus at each increment of signal from the controller. As the voltage increases incrementally, the Harvard Pump generates a higher simulated Q~Cardiac Output (CO) that is then passed through the function $y=A*\sin(\omega*t)$ which is indicative of an ideal response of the Harvard apparatus pump. A is the amplitude of the wave i.e., (mean CO), ω is the time period between strokes of the piston within the pump, and t is the time elapsed. The results display the ability of the controller to determine the appropriate target Cardiac Output by sending the respective signal to the Harvard Apparatus. The System Identification experiment provides the information needed to establish autonomous control of the Cardiac Output.





Future Works

In the future, the system identification and other collected data will be utilized to create a control algorithm that will allow the controller to operate fully autonomously when placed within the MFL. The Cardiac Output of the Harvard Apparatus will be measured within the MFL under the various pressures seen in an experiment to further match the autoregulatory response. In addition, the Harvard Apparatus will generate the appropriate outputs to train the Systemic Vascular Resistance response of the valves within the MFL.

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[2] Prather R, Das A, Farias M, Divo E, Kassab A, DeCampli W. Parametric investigation of an injection-jet self-powered Fontan circulation. Scientific Reports. 2022 Feb 9;12(1):2161.