In-Vitro Analysis of the Fenestration in the Injection Jet Shunt Assisted Fontan Circulation

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Abstract

In addressing the challenges of the Fontan circulation, which has survival rates below 50%, our focus is on managing increased inferior vena canal (IVC) pressure, a key factor in Fontan failure. We propose an injection jet shunt (IJS) from the aortic arch, combined with a conduit-to-atrial fenestration, to balance pulmonary and systemic flow. Traditional fenestration methods can lower systemic oxygen saturation while reducing IVC pressure. Our studies indicate that adding an IJS to the Fontan setup effectively lowers IVC pressure while preserving systemic oxygen saturation, without substantially increasing ventricular volume load.

Introduction

Hypoplastic Left Heart Syndrome (HLHS) represents a critical congenital cardiac anomaly characterized by the diminutive development of left-sided cardiac structures, including a hypoplastic left ventricle and stenotic aortic and mitral valves, leading to inadequate systemic perfusion. Management of HLHS requires a tripartite surgical strategy.

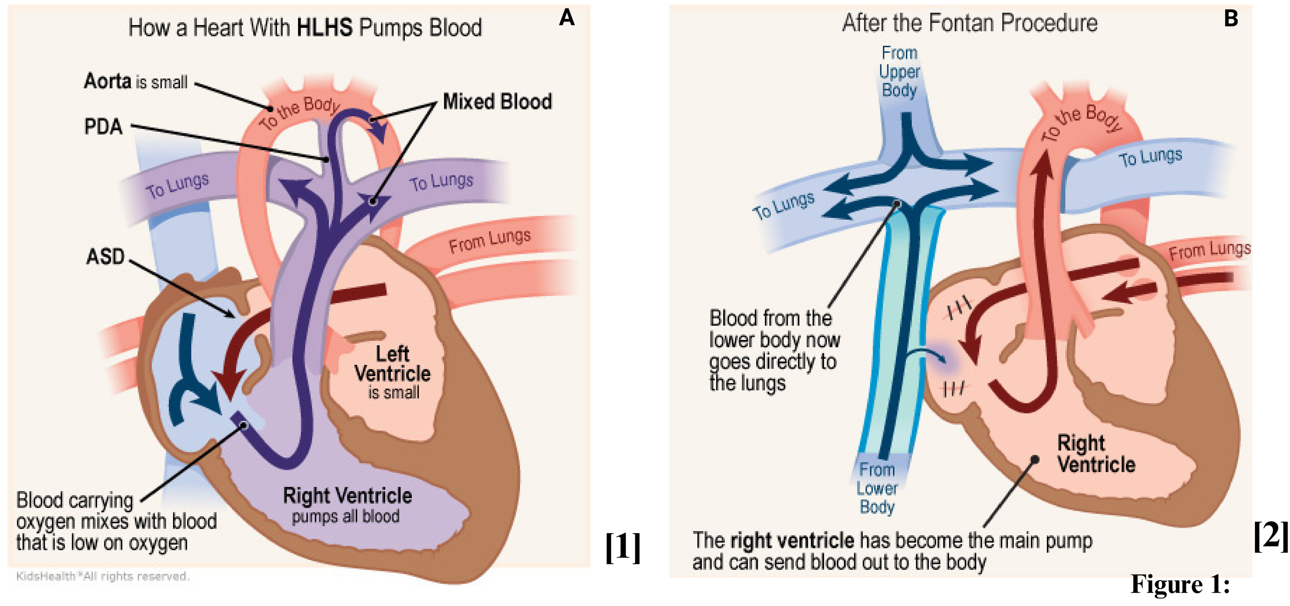


Figure 1:
A: HLHS circulation
B: Fontan circulation

Fontan Procedure (Stage III Surgical Palliation):

Usually executed between the ages of 2 and 4, this procedure completes the separation of the systemic and pulmonary circulations. 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.

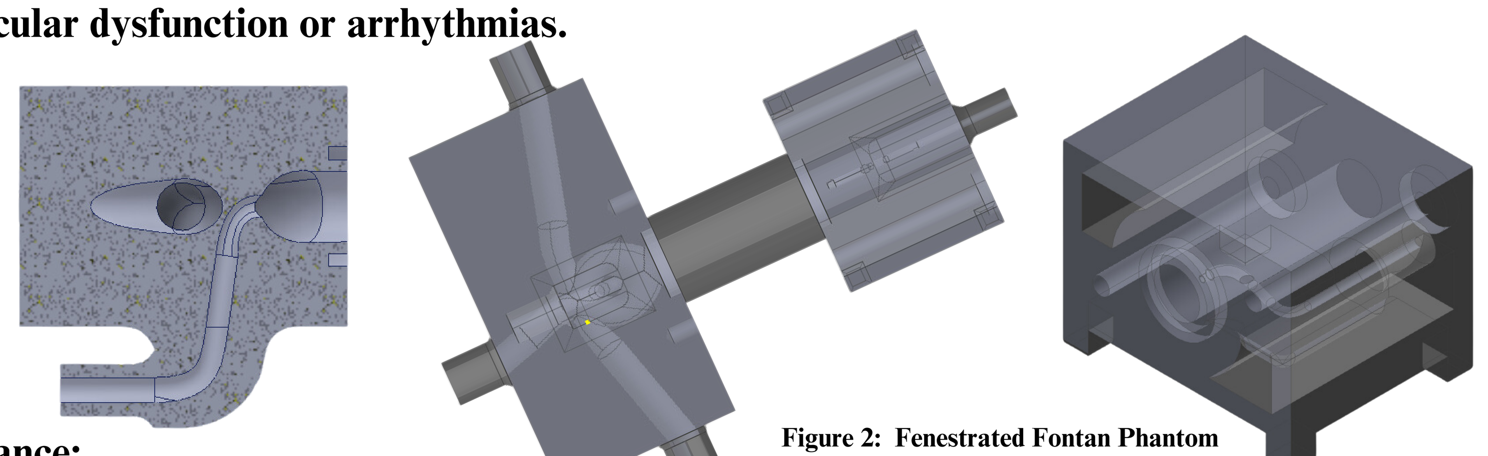


Figure 2: Fenestrated Fontan Phantom

Importance:

The experimental self-powered jet Fontan procedure offers a significant advancement in treating congenital heart conditions like Hypoplastic Left Heart Syndrome (HLHS). This novel approach aims to reduce systemic venous pressure, thereby decreasing the workload on the single-functioning ventricle and potentially reducing morbidity associated with the traditional Fontan procedure. By improving blood flow efficiency from the inferior vena cava to the pulmonary arteries, this technique could mitigate long-term complications common in post-Fontan patients, such as protein-losing enteropathy and liver dysfunction. The IJS component is a governing variable while tracking oxygen saturation.[3]

$$C_{aO2}\dot{Q}_s = C_{pvO2}CO\frac{1}{1+\frac{\dot{Q}_{ijs}}{\dot{Q}_s}} - C\dot{V}_{O2}\frac{(1-VF_{ijs})\,\dot{Q}_{fen}}{\dot{Q}_p}$$

This innovation signifies a crucial step in enhancing outcomes for HLHS patients. Oxygenated blood from the IJS combines with the pulmonary flow in the Total Cavopulmonary Connection (TCPC), impacting systemic oxygen saturation. Studying the volume fraction allows for the determination of systemic oxygen saturation levels, ultimately improving patient outcomes.

Methodology

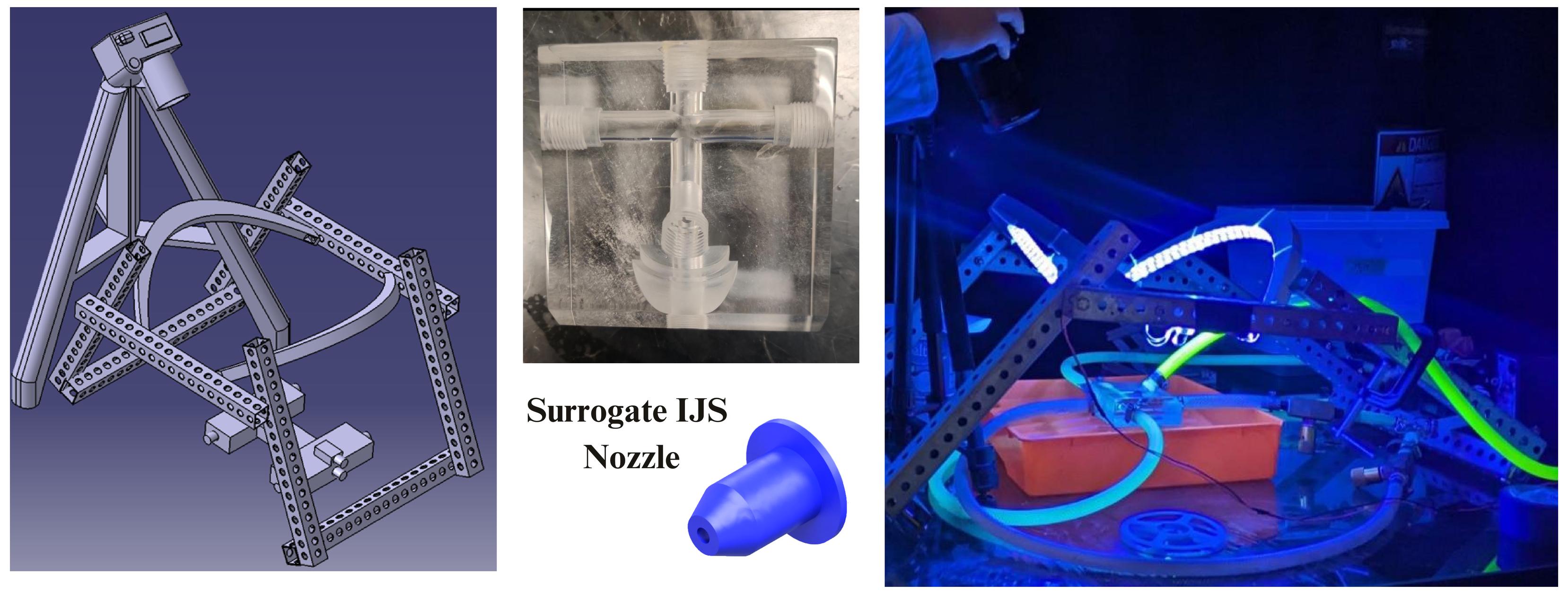


Figure 3: Experimental Setup

Modeling and Tracking (MATLAB)

RegionProps: An iterative process that calculates the centroid location of connected regions of a binary image.

imFindCircle: Identifies circular shapes within an image, then evaluates the gradients and curvatures within the images, tracking the center coordinates.

vision.BlobAnalysis: Identifies contiguous regions (blobs) in an image that share some common properties. Then calculates the blob's centroid and tracks it between frames.

Horn-Schnuck: Combines the squared difference in image brightness over time between neighboring points. Using the local gradient of brightness and the estimated flow vectors of neighboring points to update the flow vector in each frame.

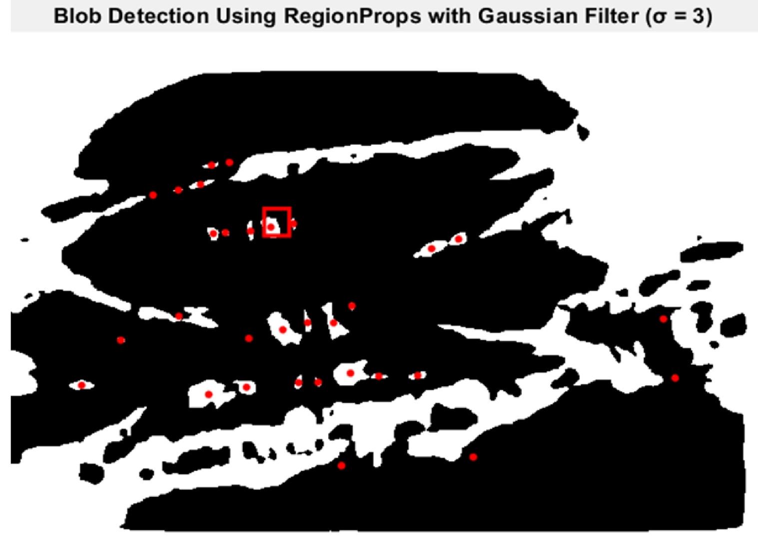
To determine pixel displacement using each method, numerical interpolation was used. A pre-determined ROI was used to target a specific pixel in order to accurately compare each method.

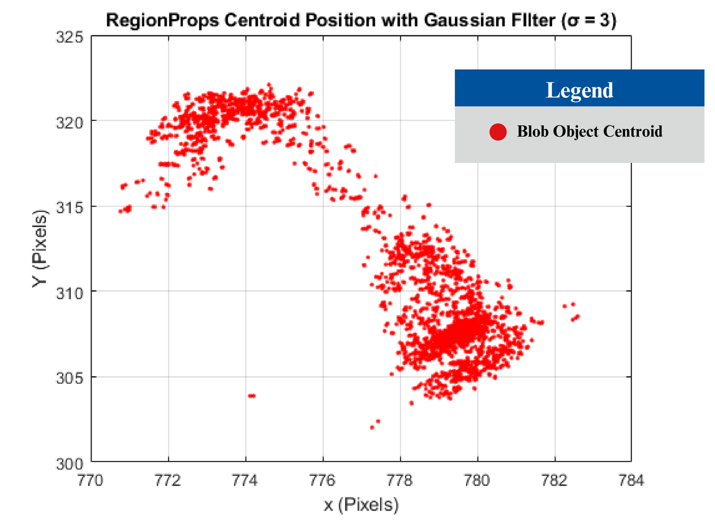
The four methodologies were applied to a video capturing a Baffle stent via an Otoscope. This acts as a nested surrogate model, facilitating the tracking of pixel displacement rather than fluid dynamics. Presented are the outcomes of these four methods, juxtaposed with three preprocessing video techniques employing Gaussian filtering and median filtering with a 3 x 3 kernel.

Results

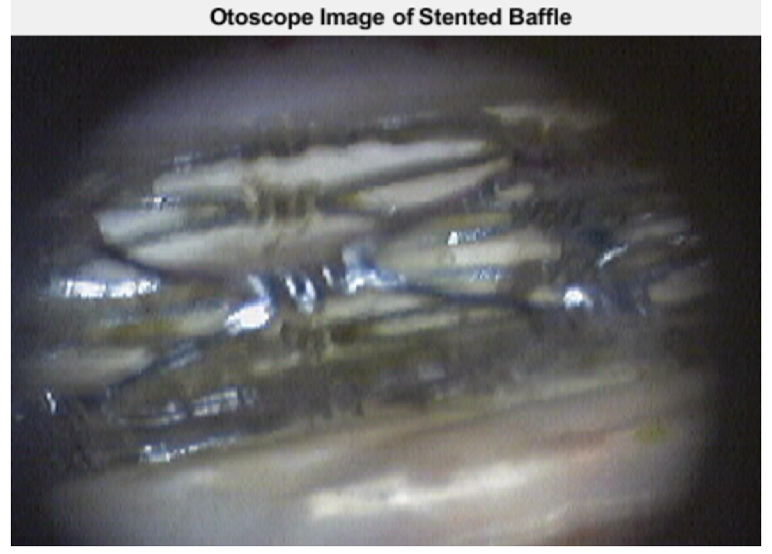
	Pixel Tracking and Numerical Interpolation			
Filter Type	regionProps	imFindCircle	vision.BlobAnalysis	Horn-Schunck
Gaussian (σ = 3)	15.49	16.11	15.49	17.31
Gaussian (σ = 5)	15.70	13.99	13.39	14.51
Median Filter [3 3]	12.71	11.22	15.00	26.25

Blob Detection Using RegionProps with Gaussian Filter (σ = 3)

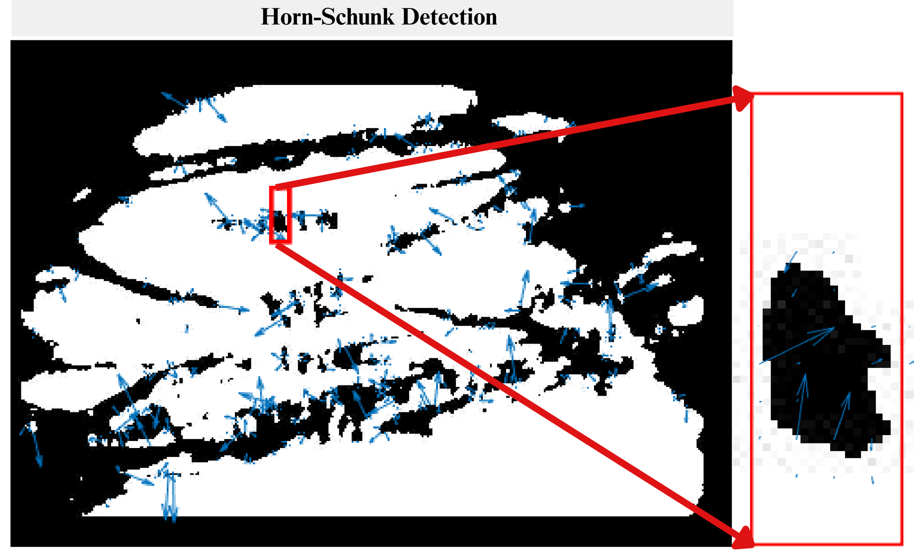




Otoscope Image of Stented Baffle



Horn-Schunk Detection



Ongoing Work

Volume Fraction Analysis

- **The volume fraction surrogate model's role is to facilitate the training of a Generative Adversarial Network (GAN). The GAN aims to predict the concentration of oxygenated blood exiting the IJS and the injected blood.**
- **Machine learning, particularly through the use of GANs, offers innovative solutions for enhancing video quality. This technique is use to infuse high-resolution frames into a video that has a higher frame rate but lower resolution, thereby achieving an optimal balance for optical flow analysis.**
- **By training on lower-resolution data, the GAN's generator learns to synthesize high-resolution details that are consistent with the existing frames, while the discriminator ensures the generated frames are indistinguishable from real high-resolution images. [4]**
- **This process effectively increases the spatial resolution without sacrificing temporal resolution, making the video more suitable for advanced optical flow methods.**

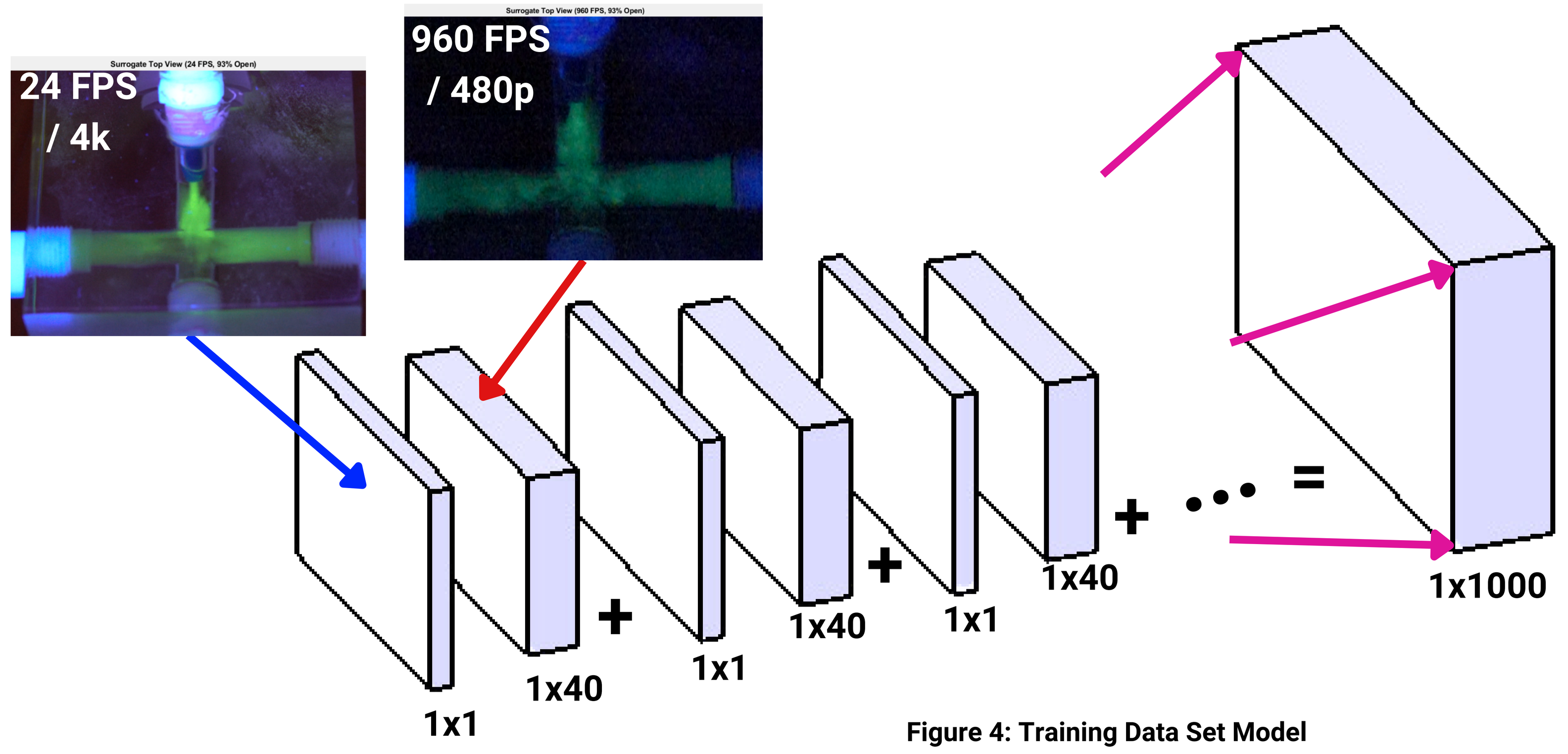


Figure 4: Training Data Set Model

- **GAN's capability can be extended to interpolate data across different planes in an optical flow study. Leveraging the multi-dimensional data from two distinct planes, the network can numerically interpolate the flow data at any desired angle between them.**
- **This facilitates a comprehensive understanding of the flow dynamics in three-dimensional space allowing for more detailed and accurate flow visualizations.**

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