The Assisted Bidirectional Glenn: An In Vitro and In Silico Study of a Surgical Approach for First Stage Single Ventricle Heart Palliation

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Background

Outcomes after the Norwood procedure and bidirectional Glenn procedure remain unsatisfactory, with high morbidity due to unbalanced pulmonary flow. The assisted bidirectional Glenn (ABG) concept, proposed by Esmaily-Moghadam [1], is an alternative option for stage 1 surgical palliation of single ventricle defects. In the ABG, the innominate artery and the SVC are connected by a shunt with a nozzle, and otherwise the circulation is the same as Bidirectional Glenn (BDG) circulation (Fig. 1). Motivated by the ejector pump concept in fluids engineering (Fig. 2), we attempt to improve pulmonary blood flow without increasing SVC pressure by exploring the potential hemodynamic advantages of the ABG.

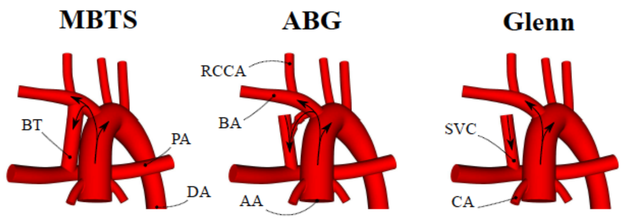

Figure 1:Assisted Bidirectional Glenn (ABG), in comparison with typical stage-1 Norwood with modified Blalock-Taussig shunt (mBTS) and stage-2 bidirectional Glenn (BDG)[1]

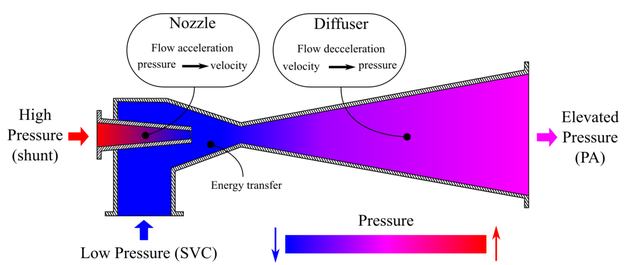

Figure 2: Schematic of an industrial ejector pump. This concept is utilized in the ABG, using systemic high-pressure flow to assist SVC low-pressure flow[1]

Methods

A multi-scale mock circulatory system (MCS), coupling a lumped parameter network (LPN) of the neonatal circulation with three dimensional models, was used to compare the hemodynamic performance in the ABG, Norwood and Bidirectional Glenn circulations (Fig. 3). A similar numerical model using the same geometries was previously reported [1]. The LPN (Fig. 4) was developed and tuned based on clinical measurements of 28 stage 1 patients[1]. For practical MCS realization, a reduced LPN was used as obtained by impedance matching [2]. Two levels of pulmonary vascular resistance (PVR) are considered to simulate neonatal (high PVR) and pre-stage two (normal PVR) conditions.

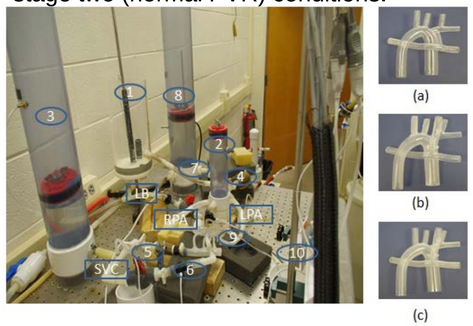

Figure 3: Photograph of system: (Left) 1, Atrium head tank; 2,3 and 8, compliance elements; 4, Berlin Heart VAD; 5 and 7, resistance elements; 6, flow meter; 9, Test section; 10, pressure transducers. (a) the mBTS Norwood circulation; (b) the ABG circulation; (c) the BDG circulation test sections.

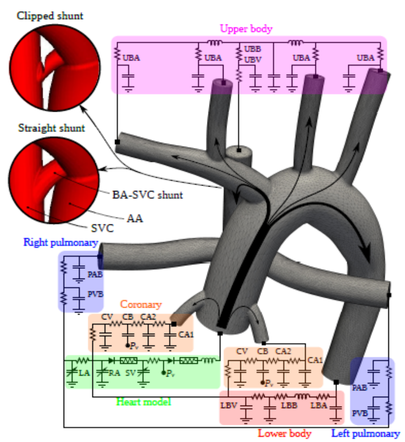

Figure 4: A schematic of coupled CFD simulation framework. The reduced-dimension LPN that contains separate blocks for modeling different organs is coupled to a 3D model, which represents the ABG surgical anatomy. Two possible systemic-to-SVC shunts, i.e. the clipped and straight shunts, are magnified in this figure.[1]

Results and Conclusions

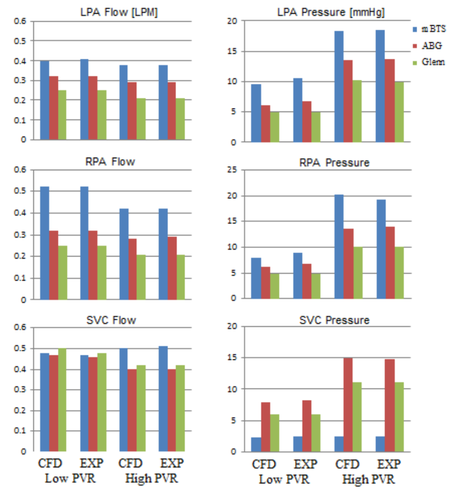

Figure 5: Comparison between numerical and experimental predictions of mean flow rate and pressure for the three circulations at normal and high PVR

From our results (Fig. 5), the ABG demonstrates : (1) 30% higher pulmonary blood flow compared with the BDG; (2) 14% higher systemic oxygen delivery compared to the Norwood with mBTS; (3) between 2 (normal PVR) to 5 mmHg (elevated PVR) increase in SVC pressure compared with the BDG.

We performed in-vitro experiments and multiscale simulations to explore the potential of adopting ABG instead of stage-1 Norwood surgery in single ventricle heart patients. In comparison with the conventional surgeries, the ABG presents an opportunity to combine two surgeries into one, while increasing oxygen delivery and pulmonary blood flow and reducing the heart load. However, elevated SVC pressure remains a concern in the ABG and is a subject of future exploration.

References

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2. Vukicevic, M ., Conover, T., Jaeggli, M., Zhou, J., Pennati, G.., Hsia, T.Y., Figliola, R.S. Control of Respiration-Driven Retrograde Flow in the Subdiaphragmatic Venous Return of the Fontan Circulation, ASAIO J, 60(4):391-399,2014.

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