IN VITRO PATIENT-SPECIFIC STUDY OF THE NORWOOD PROCEDURE

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Introduction

The Norwood procedure is the first of a sequence of three cardiovascular operations for the palliative treatment of infants born with a single functioning heart ventricle to covert to the Fontan circulation: a circulation in which the single ventricle supplies blood to both the body and to the lungs. The Norwood is performed within days after birth.

Norwood Procedure | Glenn Procedure | Fontan Procedure

Because of the underdeveloped ventricle, blood flow to the neonate's body is not well oxygenated. The goal of Norwood procedure is to allow mixing between blood in the systemic circulation with blood in the pulmonary circulation. To accomplish this, an alternative path is created by inserting a shunt between the aorta and the pulmonary arteries. The dimensions of the shunt are critical to attain proper balance of flow in the two circulations but because of the congenital deformations each patient is different.

Normal ventricle | Rudimentary ventricle

Objectives

Fontan Facts: Complicated surgery, Multiple complications, Low survival rate.

Fontan circulation is known for chronic complications which increase pulmonary vascular resistances and decrease vascular compliance which lead to liver disease and heart failure. The 10 year survival rate of Fontan procedure is reported 83.8% in 2002. Since every heart is different, the best strategy for one child may not work as well for another.

Our objectives: Simulate the surgery, Evaluate its effectiveness, Develop therapies.

The Leducq Foundation Transatlantic Network is focused on Single Ventricle Heart Defects, which involves 8 engineering and clinical centers in the US and Europe. We conduct experimental and computational studies of a child's heart to allow doctors to visualize the anatomy and to perform virtual operations to see the outcome of differing surgical strategies for a particular patient.

Study purpose: Replicate Norwood circulation, Study shunt and aorta geometry

The goal of this study is to replicate the hemodynamics phenomenon in Norwood circulation using an in vitro model and to validate system function against the analytical model. Each patient-specific study involves investigating the geometry of the aorta and shunt, often in the presence of coarctation, and how it effects the hemodynamics phenomenon in circulation.

Methods

Patient specific aorta test section and pulmonary shunt

The anatomy of aorta is reconstructed in 3D from the magnetic resonance (MR) data (Fig. 1) and then manufactured by 3D printing using a clear polycarbonate-type resin. Each patient has a unique anatomy and test section.

Build lumped parameter network model

A mock circulatory system is built around a lumped parameter model to the circulation and the 3D aortic teats section with shunt. Figure 2 shows a full lumped parameter (LPN) model of the Norwood circulation. This model is reduced to a lab model (Fig. 3) by using Thevenin equivalents (Giovanni Biglino et al, 2012). The equivalent mock circulatory system shown in Fig. 4 is the physical realization of reduced LPN model.

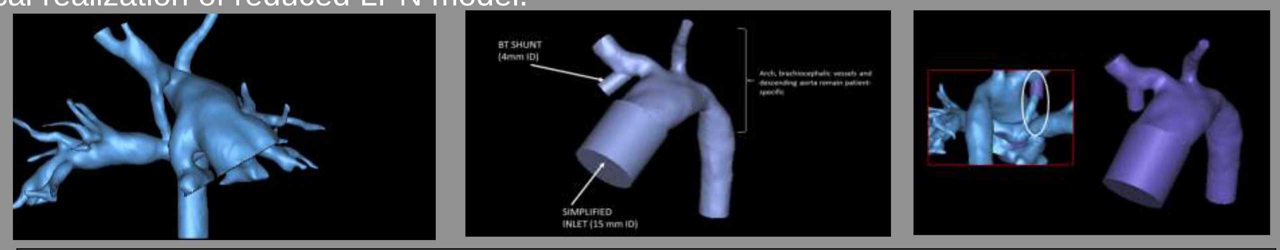

FIGURE 1. Geometry of patient specific pulmonary shunt and aorta with aortic coarctation.

Set-up, Measurements and Data Analysis

The system elements are set to patient-specific values. A pediatric (Berlin) ventricular assist device operates as the single functioning ventricle. Pressures and flow rates are measured throughout the model. The resulting waveforms are analyzed for consistency with the predictions of the full LPN model and to clinical measurements for that particular patient.

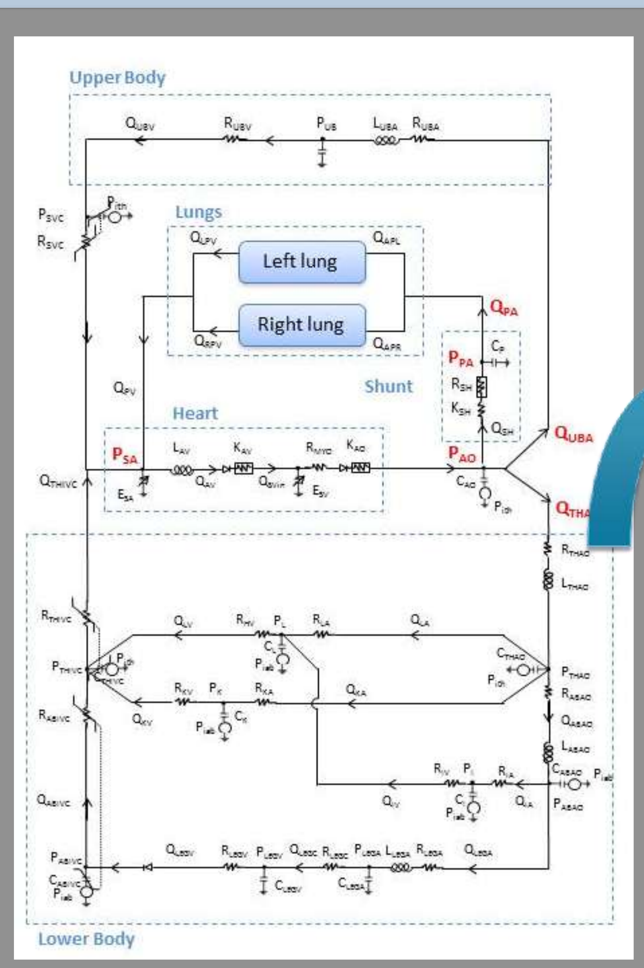

FIGURE 2. Full Norwood LPN model (Baretta et al, 2012)

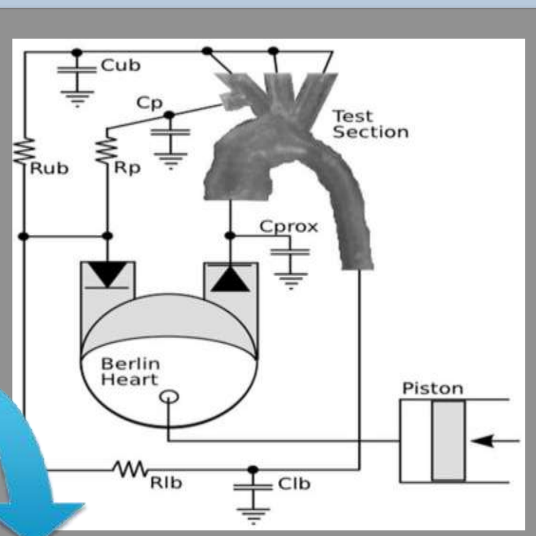

FIGURE 3. Reduced LPN model

FIGURE 4. Mock Norwood circulation

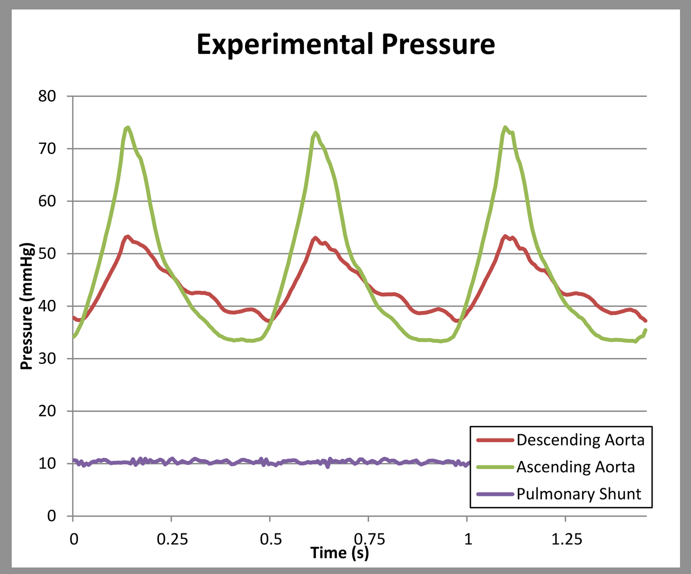

FIGURE 5. Experimental pressure measurements in the descending aorta, ascending aorta, and pulmonary shunt. To accommodate for the non-compliant test section, a lumped aortic compliance is added with a proximal compliance chamber.

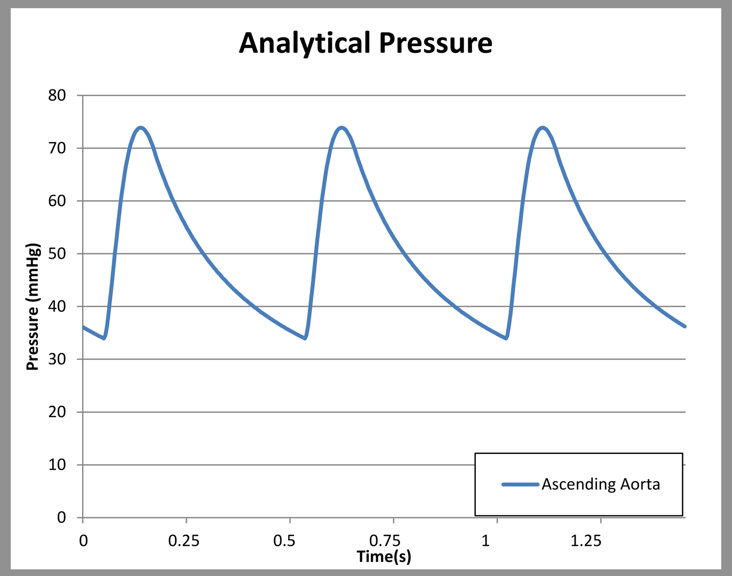

FIGURE 6. Analytical LPN result for ascending aorta pressure. To accommodate for the non-compliant test section, a lumped aortic compliance is added with a proximal compliance chamber.

	Ascending aorta	Pulmonary shunt
Experimental mean pressure (mmHg)	54	10
Analytical mean pressure (mmHg)	52	12

Table 1. Analytical vs. experimental results for ascending aorta pressure and pulmonary pressure. The analytical model has been validated against clinical data.

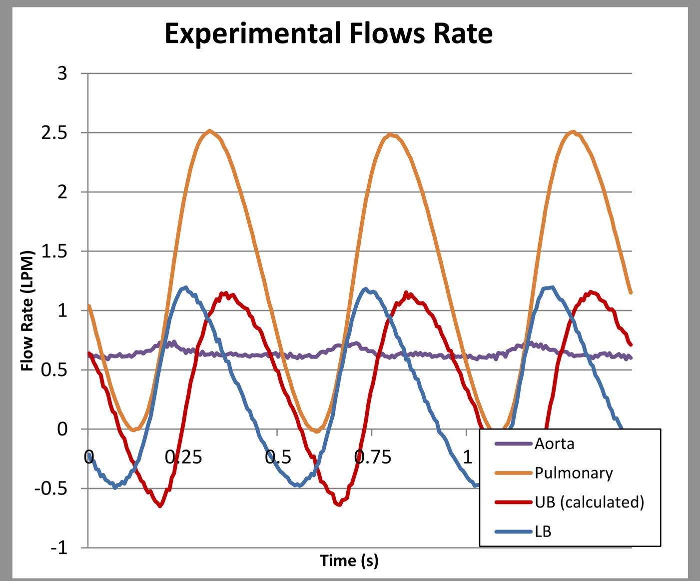

FIGURE 7. Experimental flow rate measurements for aorta, upper body, lower body and pulmonary shunt.

	Aorta	Pulmonary Shunt	Upper Body	Lower Body
Experimental mean flow rate (LPM)	1.23	0.57	0.31	0.35
Analytical mean flow Rate (LPM)	1.22	0.58	0.32	0.32

TABLE 2. Analytical vs. experimental flow rate results for aorta, pulmonary shunt, upper body and lower body. The analytical model has been validated against clinical data.

Results

The circuit elements were tuned based on clinical measurements for this MUSC patient. Measured values are compared with the analytical model predictions, which were validated against patient data .

Experimental pressure curve showed in Figure 5 is compared with analytical pressure curve in Figure 6. Experimental systolic pressure value and diastolic pressure is in good agreement with analytical systolic and diastolic pressure. Using data in Figure 5, mean experimental pressure is obtained and is compared with analytical mean value in Table 1. Difference between experimental and analytical mean pressure is within 2 mmHg, which is within the clinical relevance.

Using the pulsatile flow rate shown in Figure 7, mean flow rate can be calculated and compared with analytical flow rate in Table 2. Difference between experimental and analytical mean pressure is within 0.03Lpm, which is within the clinical relevance.

Given measured data, assuming 95% probability level, uncertainty analysis on pressure and flow rate measurement can be performed, the uncertainty of pressure and flow rate measurement is 0.3mmHg and 0.02Lpm respectively.

Future Work

In order to use a mock circulatory system to predict patient outcomes, to understand the underlying factors that cause variations to the surgical outcome, to test new surgical technique and medical devices, and to compare with numerical models, a validation process is to be carried forward. A total of 5 patient specific cases will be studied in the near future.

FIGURE 8. Patient specific aorta test section with different geometry

As fully compliant test section is now under study, to achieve more realistic flow simulations and measurements.

Cardiovascular Procedure In The Future

We describe a new tool that can be used in planning surgical treatment, as well as for the training of physicians. We see one future of cardiovascular procedures that can be planned based on patient specific information, using highly accurate anatomical models based on advanced imaging, and predictions from experimental and numerical modeling tools (Fig. 8). Concurrent to this study, our Network has been developing imaging, catheterization, and numerical tools necessary for patient-specific virtual surgery.

Models permit studying patient response in different physiological states, such as crying, or stress, and their growth or postsurgical scenarios can also be simulated.

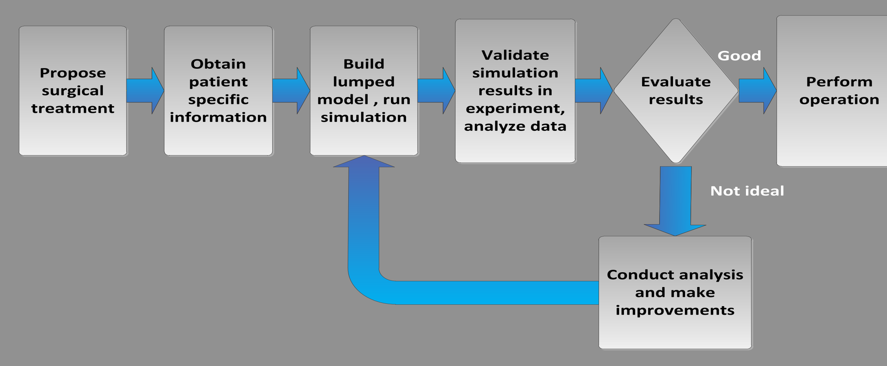

FIGURE 9. Flow chart of Cardiovascular procedure in the future.

Conclusion

An in vitro model of the Norwood circulation, the first stage in conversion to the Fontan circulation, has been constructed and tested. Under patient-specific tuning of each element, flow rate and pressure signals showed physiological features typically for this small infant patient and agree with results from an existing analytical LPN model .

Acknowledgments

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