IN VITRO PATIENT-SPECIFIC STUDY OF THE NORWOOD PROCEDURE

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Introduction

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

Objectives

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

Fontan procedure is known for chronic complications which increase pulmonary vascular resistance and decrease vascular compliance which lead to liver disease and heart failure. The 10 year survival rate of Fontan procedure is reported 83.6% in 2000. Since every heart is different, the best strategy for each child may not work as well for another.

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

We conducted 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 different 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 is performed on a virtual model of the patient. 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 different surgical strategies for a particular patient.

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 aortic test 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 Trementino equivalents (Giovanni Biglioli et al, 2012). The equivalent mock circulatory system shown in Fig. 4 is the physical model of intrinsic LPN.

Set-up, Measurements and Data Analysis

The system elements we will test are patient-specific values. A pediatric (Bent) ventricular assist device operates as the single functioning ventricles. 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 critical measurements for the particular patient.

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 shown 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 pressure value in Table 1. Difference between experimental and analytical mean pressure is within 2 mmHg, which is within the clinical relevance. Using the side-by-side raw flow 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 5%. Percent agreement with clinical measurements. Given measured data, assuming 95% probability level, uncertainty analysis on pressure and flow fits well with analytical, the uncertainty of pressure and flow rate measurement is 0.3 mmHg and 0.01 Lpm respectively.

Future Work

In order to use a mock circulatory system to predict patient outcomes, to understand the underlying factors that cause variations in the surgical outcomes, to test new surgical techniques 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.

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 advanced digital imaging, and predictions from experimental and numerical modeling tools (Fig. 8). Concurrent to this study, our research 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 post-surgical scenarios can also be simulated.

Conclusion

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

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Reference


Appendix A. Summary of patient heart anatomy and surgical techniques.

Appendix B. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix C. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix D. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix E. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix F. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix G. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix H. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix I. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

Appendix J. Analytic vs. Experimental Pressure and flow rate for right aorta, left pulmonary artery, body, and lower body.

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