A MULTI-SCALE CFD ANALYSIS OF THE HYBRID NORWOOD PALLIATIVE TREATMENT FOR HYPOPLASTIC LEFT HEART SYNDROME: EFFECT OF REVERSE BLALOCK-TAUSSING SHUNT DIAMETER

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Hypoplastic left heart syndrome (HLHS) is a complex cardiac malformation in neonates suffering from congenital heart disease.

1 in 5000 infants with HLHS are born each year.

The Norwood is the most commonly widely implemented first stage palliative treatment of HLHS.

Despite improvements in surgical techniques, the mortality rate in early post-operative palliation is 25%.
Background

Hybrid Norwood Anatomy

Procedure:
- Stenting of the ductus arteriosus
- Branched pulmonary artery banding
- Balloon atrial septostomy

Avoids:
- Cardiopulmonary bypass
- Cardioplegic and circulatory arrest
Immediate or delayed obstruction in the aortic isthmus after stent deployment may occur

The reverse BT shunt may prevent myocardial and cerebral ischemia due to stenosis of the aortic isthmus

HN with reverse BT hemodynamics are complex
Objectives

- Create a representative or patient-specific anatomical model of the Hybrid Norwood circulation.

- Develop a multi-scale CFD model that accurately represents the local and global hemodynamics.

- Study the hemodynamic effects on major arterial perfusion of various degrees of distal aortic arch obstruction proximal to the ductus arteriosus stenting, as well as the effects of shunt diameter.
Below is a representative 3D model of the Hybrid Norwood anatomy with reverse BT-shunt (RBTS).

- Subclavian arteries
- Carotid arteries
- Reverse BT-shunt
- Ductus Arteriosus
- Pulmonary arteries
- Coronary arteries
Discrete Stenosis Model

- Two levels of stenosis were modeled to examine the effect of distal arch obstruction on the hemodynamics.

  - Severe Obstruction (90% Reduction in Lumen)
  - Moderate Obstruction (70% Reduction in Lumen)
Six Anatomical CAD Models

Twelve anatomical models were analyzed:

1) Nominal
2-4) Nominal + 3, 3.5, 4mm RBTS
5) Stenosis 90%
6-8) Stenosis 90% + 3, 3.5, 4mm RBTS
9) Stenosis 70%
10-12) Stenosis 70% + 3, 3.5, 4mm RBTS
Volume Mesh for CFD Simulation

Sever Stenosis

Right Coronary

Banded Pulmonary

Pulmonary Root
• Blood was modeled as Newtonian and incompressible, with typical density and viscosity values of $\rho=1060 \text{ kg/m}^3$ and $\mu=0.004 \text{ Pa-s}$.

• An unsteady, implicit Navier-Stokes equations solver STARCCM+ (k-Epsilon Turb.)

\[ \nabla \cdot \vec{V} = 0 \quad \text{and} \quad \rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \cdot \nabla) \vec{V} = -\nabla p + \mu \nabla^2 \vec{V} \]

• 2\textsuperscript{nd} order upwinding of convective derivatives

• A time step of $\Delta t=4.62\text{ms}$ provided time-independent solution for a 130 bpm.
Lumped Parameter Model

\[ \Delta P = QR \]
\[ Q = C \frac{d(\Delta P)}{dt} \]
\[ \Delta P = I \frac{dQ}{dt} \]
\[ Q = \frac{\Delta P}{R_{\text{vessel}}} - H(\Delta P) \]

Coupled ODE’s solved by 4th order explicit adaptive Runge-Kutta Fehlberg method

Hybrid Norwood Circuit model

CFD Adjusted Parameters

Elastance Function

\[ \gamma = \begin{cases} 
\Delta P & \rightarrow \text{at capacitors/valves} \\
Q & \rightarrow \text{at resistors/inductors} 
\end{cases} \]
Lumped Parameter Model
The circuit model imposes the flow-split boundary conditions at the outlets of the 3D model.

The input to the circuit model is the pulmonary root pressure waveform along with the targeted flow-rates at the AO, CA, … the outlets of the 3D CFD model.

Iteration is used to couple the two solutions.
The current coupling scheme involves data transfer between Starccm and the user code through file sharing.
A Lumped-Parameter Model of the circulatory system is controlled by Starccm through Java code. Starccm manages the iterative process. Output tables are in Text format, and input tables are also in Text format. C-code performs the cardiac cycle and provides boundary conditions for Starccm.
Circuit constants were tuned to achieve representative pressure and flow waveforms and to balance $Q_p/Q_s \sim 1$ as well as target flow-rates to branching and coronary arteries.
Composite of driving pressures at outlets from the circuit model

- Nominal and Sten 90% cases, w/o RTBS

![Composite of driving pressures at outlets from the circuit model](image)
Model Outputs: Flow Comparison
Model Outputs: Flow Comparison

![Graph showing pressure and volumetric flow rate over time for different conditions: Nom Carotid Avg Press, Nom-RBTS Carotid Avg Press, Sten 90% Carotid Avg Press, Sten 90%-RBTS Carotid Avg Press, Sten 70% Carotid Avg Press, Sten 70%-RBTS Carotid Avg Press for both pressure and flow rate.](image-url)
# Model Outputs: Flow Comparison

<table>
<thead>
<tr>
<th>Cardiac Output (ml/min)</th>
<th>Flow Rate as Percentage of Cardiac Output</th>
<th>Percentage Change from Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Qp/Qs</td>
<td>DA</td>
</tr>
<tr>
<td>Nominal</td>
<td></td>
<td></td>
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<tr>
<td>2015</td>
<td>0.94</td>
<td>29.4</td>
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<tr>
<td>Nom-3mmBT</td>
<td>0.93</td>
<td>29.2</td>
</tr>
<tr>
<td>Nom-3.5mmBT</td>
<td>0.94</td>
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<tr>
<td>Nom-4mmBT</td>
<td>0.93</td>
<td>29.3</td>
</tr>
<tr>
<td>Sten 90%</td>
<td>1.10</td>
<td>31.9</td>
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<tr>
<td>Sten 90%-3mmBT</td>
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<tr>
<td>Sten 90%-3.5mmBT</td>
<td>0.95</td>
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</tr>
<tr>
<td>Sten 90%-4mmBT</td>
<td>0.95</td>
<td>29.2</td>
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</tr>
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<td>Sten 70%-3.5mmBT</td>
<td>0.94</td>
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</tr>
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<td>Sten 70%-4mmBT</td>
<td>0.95</td>
<td>29.2</td>
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<tr>
<td></td>
<td>Qp/Qs</td>
<td>DA</td>
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<tr>
<td>Sten 70%-4mmBT</td>
<td>0.92</td>
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</tbody>
</table>
Model Outputs: Flow Comparison

Nominal

Severe Stenosis

Nominal with rBT Shunt

Severe Stenosis with rBT Shunt
Model Outputs: Stenosis 90% + 4.0mm RBTS Flow Field

1. Peak systole
2. Early diastole
3. Mid diastole
4. Late diastole

Flow Rate (ml/s)

Time (s)

Volumetric Flow Rate (ml/s)

Nom-RBTS Shunt Flow
Sten 90%-RBTS Shunt Flow
Sten 70%-RBTS Shunt Flow

Velocity: Magnitude (m/s)

B
Model Outputs: Stenosis 90% + 4.0mm RBTS Flow Field

Peak Systole

Late Diastole
Model Outputs: Flow Comparison, Nominal + 4.0mm RBTS

1. Peak systole
2. Early diastole
3. Mid diastole
4. Late diastole
Model Outputs: Flow Comparison, Nominal + 4.0mm RBTS

Peak Systole

Late Diastole
Model Outputs: 3mm vs. 4.mm shunt

Peak Systole

3mm RBTS

4mm RBTS
Model Outputs: 3mm vs. 4.0mm shunt

Mid Diastole

3mm RBTS

4mm RBTS
WSS and OSI

- Cycle averaged Wall Shear Stress (WSS)

\[
WSS = \left| \frac{1}{T} \int_0^T \tau_w \, dt \right|
\]

- Another useful metric is the Oscillatory Shear Index (OSI), the cyclic departure of the wall shear stress vector from its predominant axial alignment

\[
OSI = \frac{1}{2} \left( 1 - \frac{\left| \int_0^T \tau_w \, dt \right|}{\int_0^T |\tau_w| \, dt} \right)
\]

- OSI = 0 unidirectional WSS
- OSI=0.5 purely oscillatory WSS
WSS Stenosis + RBTS

3mm

4mm

3mm

4mm

3.5mm

3.5mm

90% + RBTS

Nominal + RBTS
OSI Stenosis + RBTS

90% + RBTS

Nominal + RBTS
Summary remarks

- RBTS restores nominal flows and pressures to arch vessels and coronaries in presence of severe and moderate arch obstruction
- RBTS reduces retrograde arch flow
- RBTS does not exacerbate flow reversal in the carotids or coronaries, increases Qp/Qs slightly
- Results suggest that: (1) the 4.0mm shunt shunt diameter choice that may be problematic particularly when implemented prophylactically, and (2) the 3.0mm and 3.5mm shunts may be a more suitable alternative, with the latter being the preference since it provides similar hemodynamics at lower levels of wall shear stress. (3) RBTS may be problematic when implemented prophylactically – anticoagulation treatment
Ongoing and Future Work

- Patient specific applications (with Fluid Structure Interaction to account for vessel compliance).
- Aortic CT angiographic images of an HLHS patient are used to generate a 3D model.
Ongoing and Future Work

Four main models were created: (a). A nominal model, (b) a model with the reverse BT shunt, (c) a model with 90 percent stenosis, and (d) one with 90 percent stenosis and a reverse BT shunt.

The models with the reverse BT Shunt (b) and (d) have versions with a 3mm and a 3.5mm diameter shunt also (4 mm shunt shown).
Ongoing and Future Work

Severe (90%) stenosis

Nominal stenosis
Ongoing and Future Work

Severe (90%) stenosis with 4.0mm RBTS
Ongoing and Future Work
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Thank You