Computational Modeling for Single Ventricle Surgery

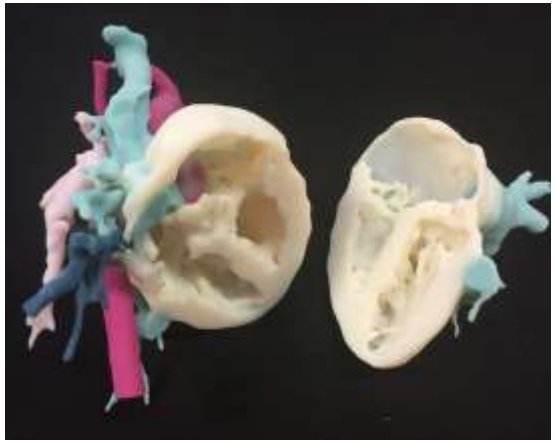
T-Y Hsia, MD

Chief, Pediatric Cardiac Surgery, Arnold Palmer Hospital for Children
Professor of Surgery, University of Central Florida

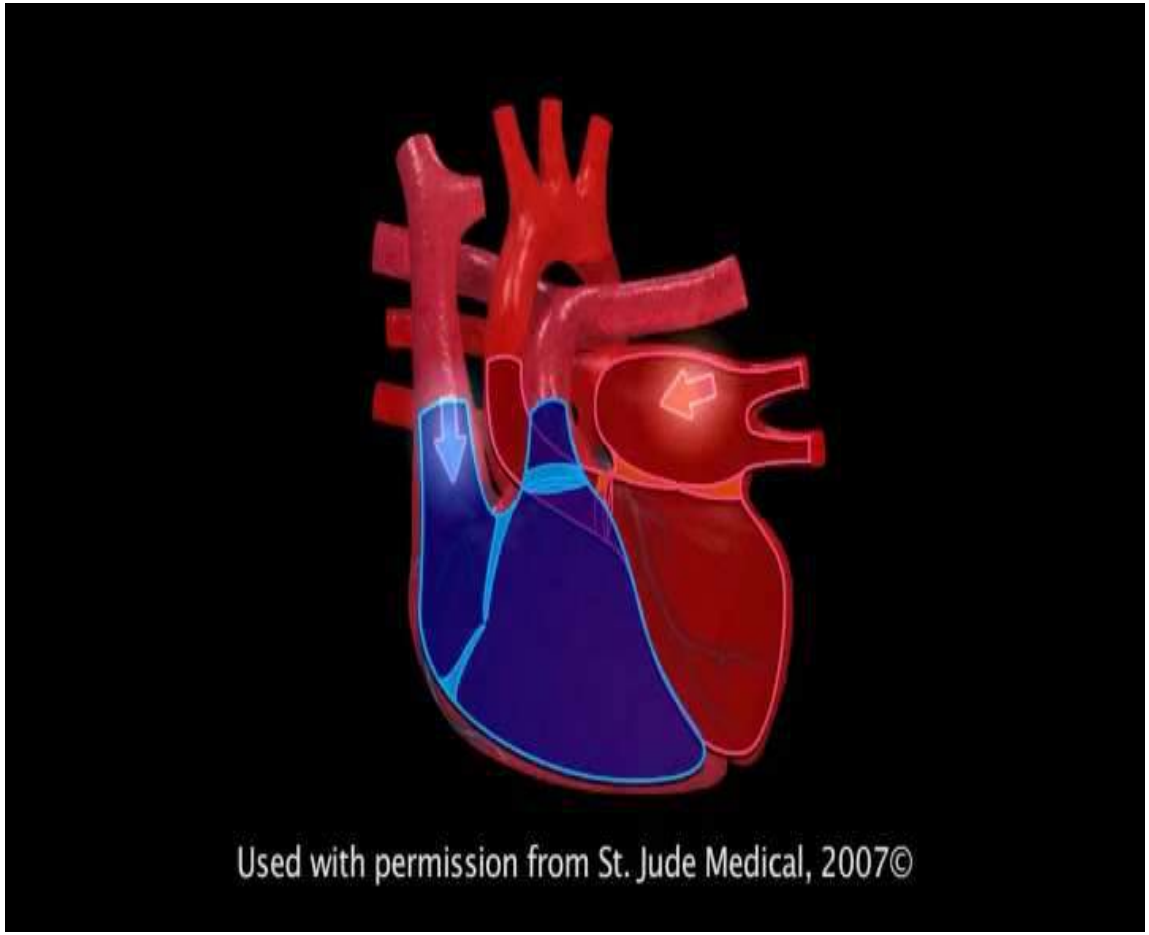
Arnold Palmer Hospital
For Children

No Disclosures

3D Printing / Virtual Reality



Where is the blood?



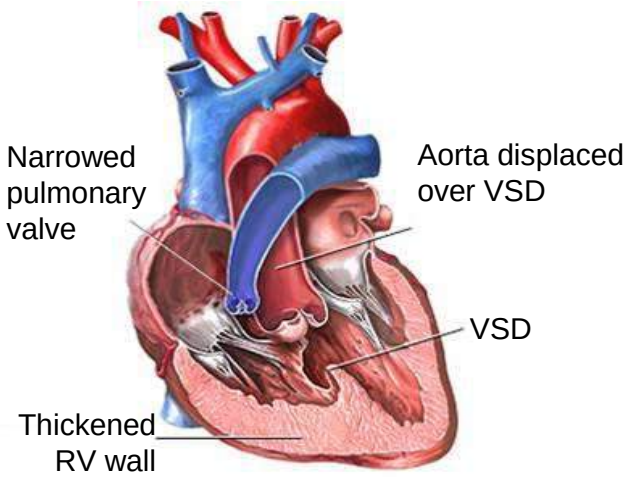
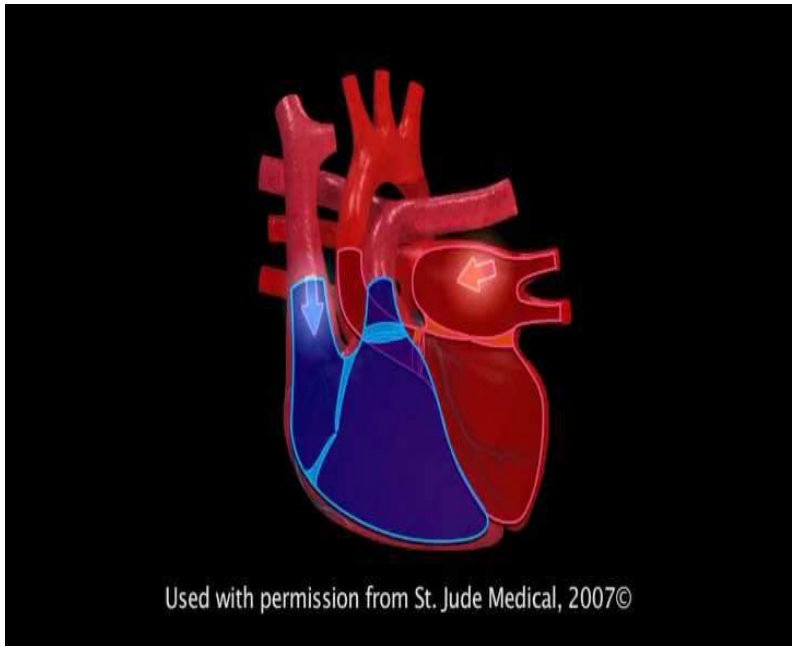


Image from: ncbi.nlm.nih.gov



Form ⇄ Function

What is Computational Modeling?

Math, Lots of Math, and Blood Flow

All fluid flow is governed by Newton's Laws of Conservation of Mass and Momentum.

Navier-Sto  **onian Fluids:**

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial}{\partial}\right)$$

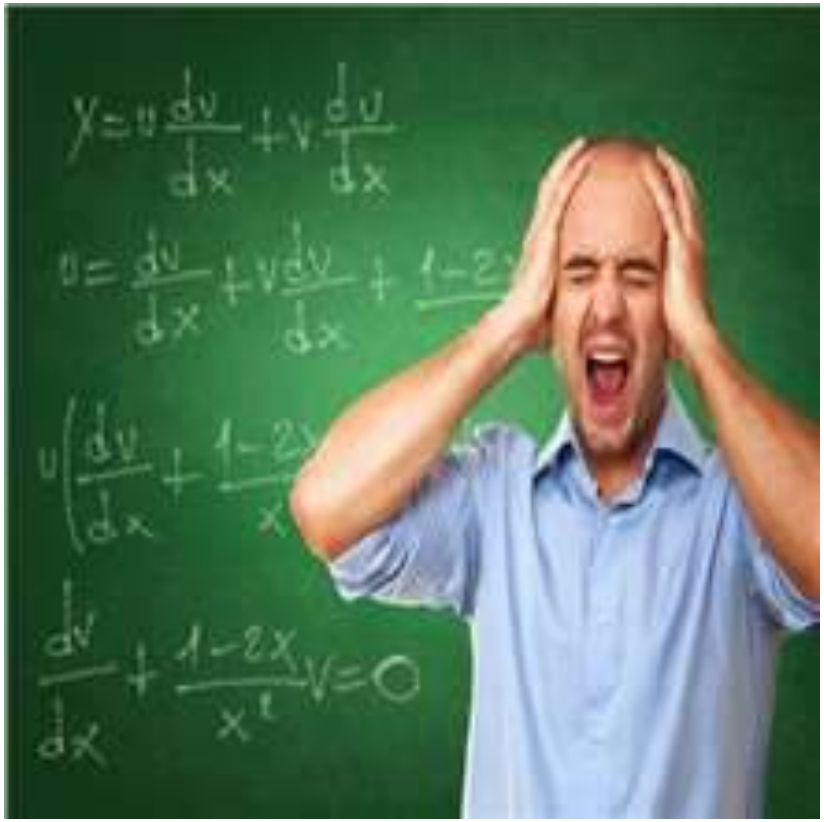
$$\rho g_x - \frac{\partial p}{\partial x} + \left[\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right]\Bigg]$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial}{\partial}\right)$$

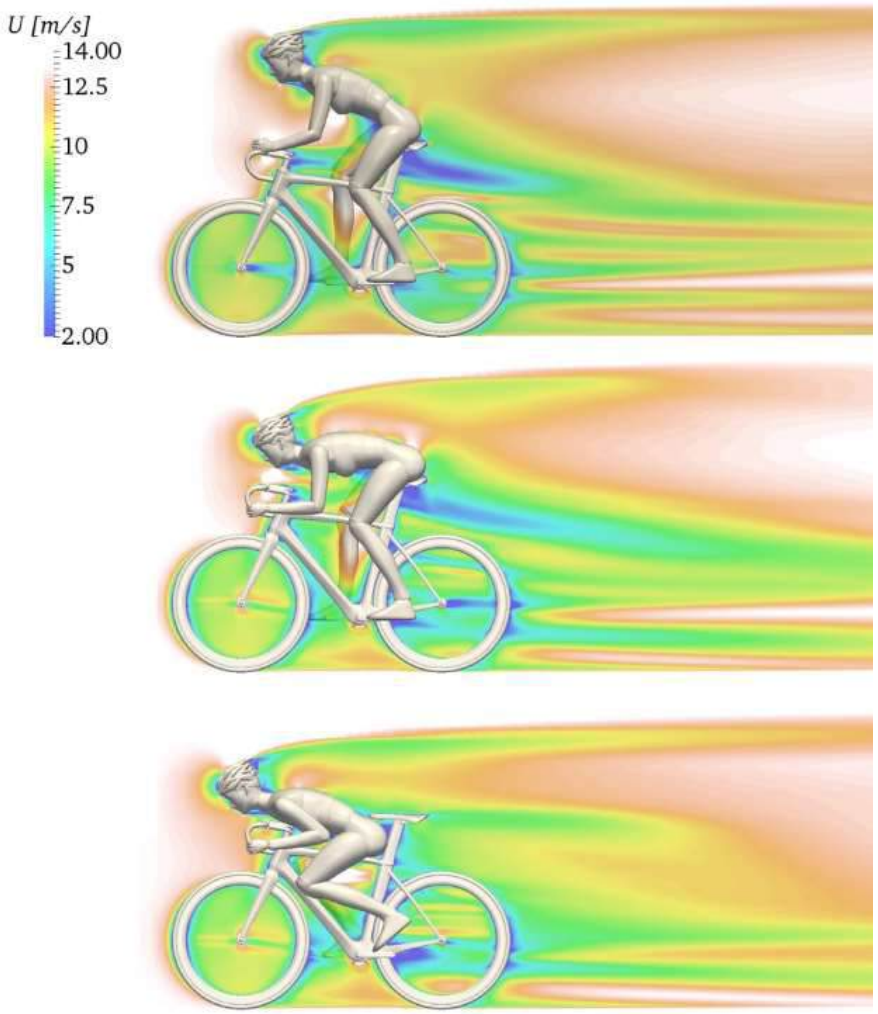
$$\rho g_y - \frac{\partial p}{\partial y} + \left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right]\Bigg]$$

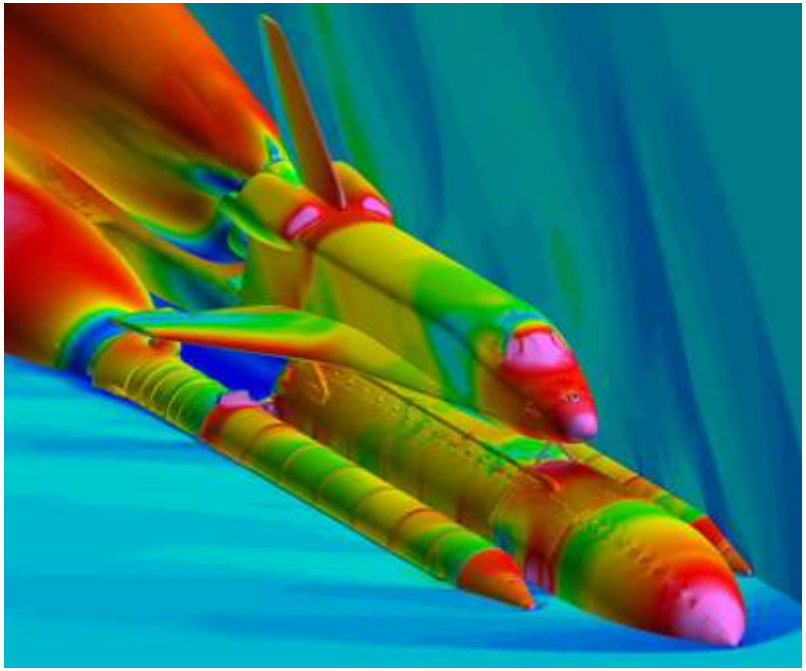
$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial}{\partial}\right)$$

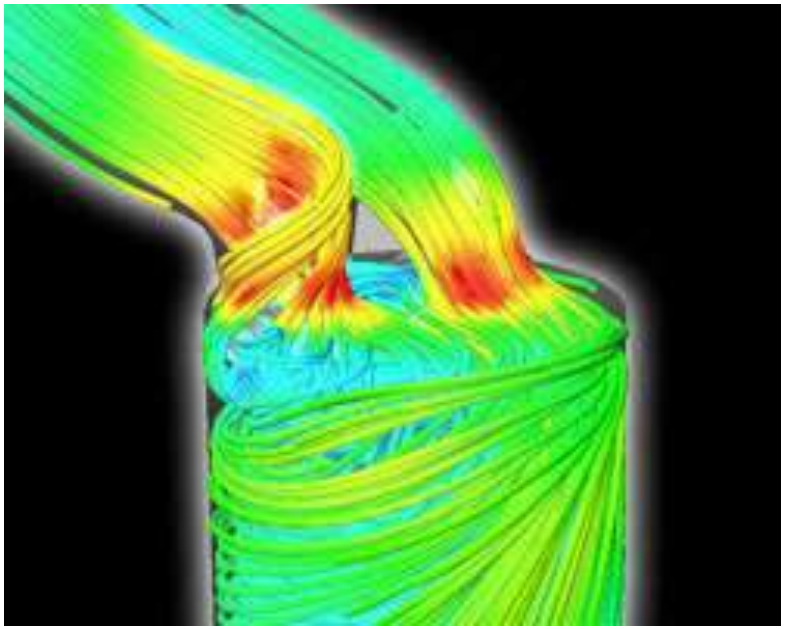
$$\rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left[2\mu\frac{\partial}{\partial z} + \lambda\nabla\cdot\mathbf{V}\right] + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial z}\right)\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)\right]$$




SUPERCOMPUTER
5
+5
12


U [m/s]
14.00
12.5
10
7.5
5
2.00



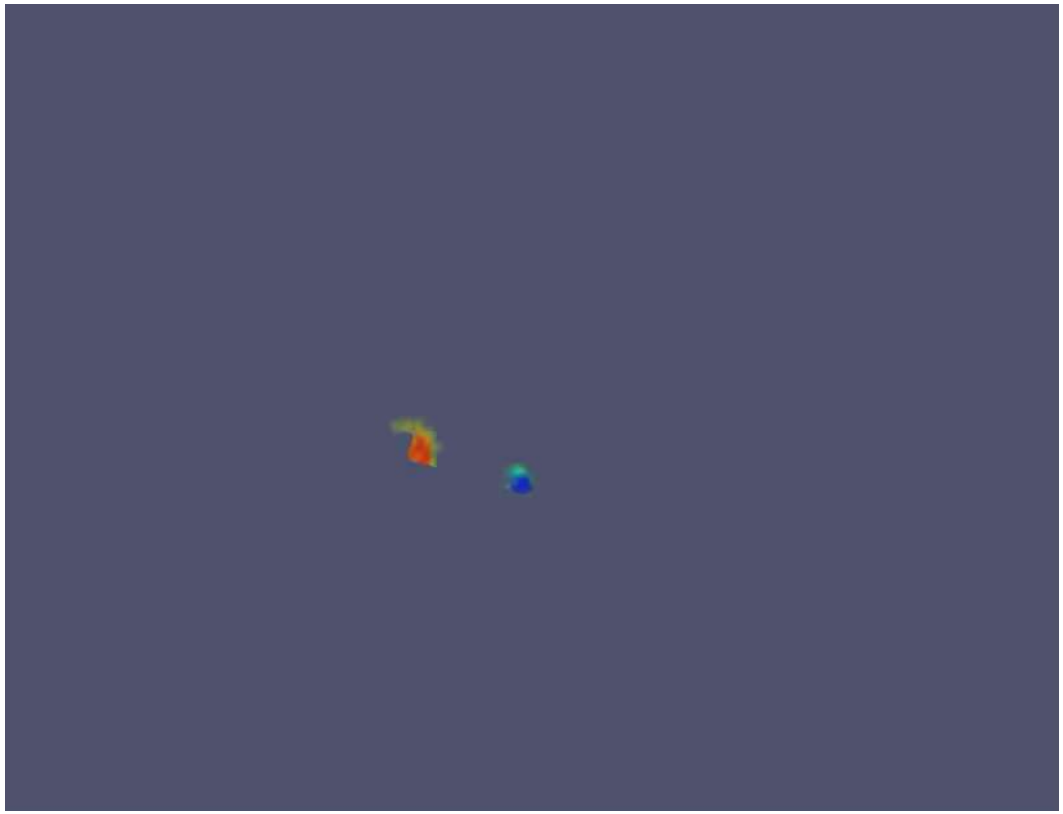


Computational Simulation

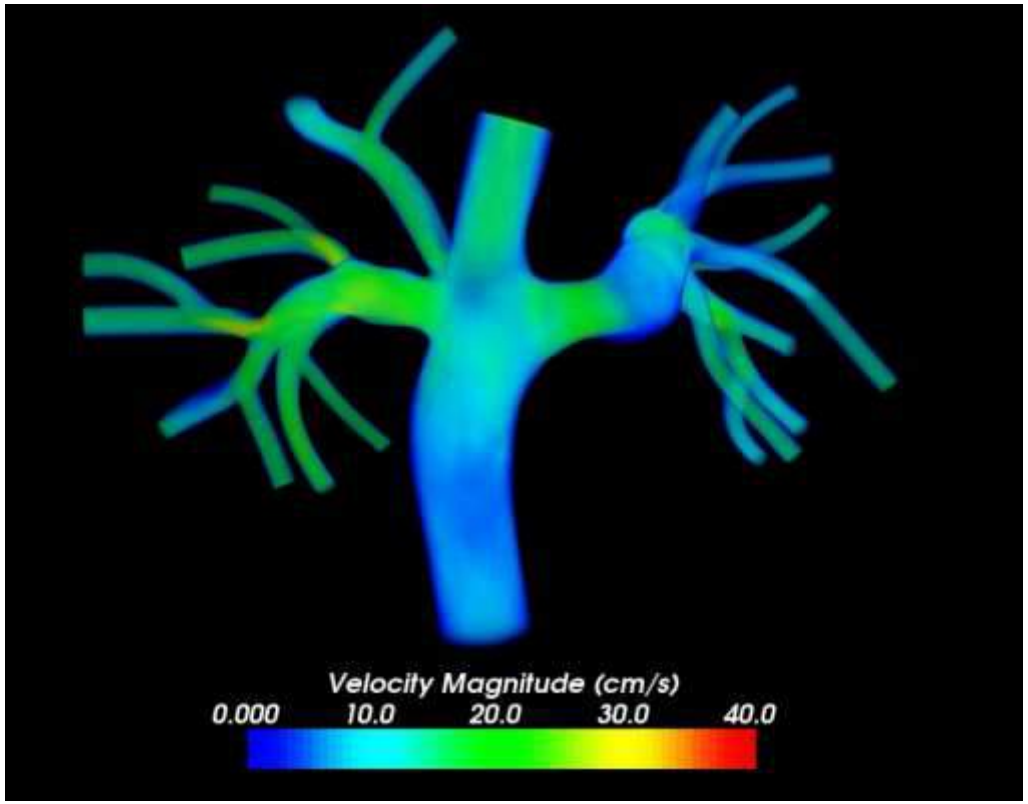
Blood flow = Fluid dynamics

Solves Equations

Flow and Pressure



Computational Simulation



Complex Geometry

Patient-specific

Manipulate Anatomy/physiology

Virtual Surgery

3 Ways Computational Modeling Helps Us

Improve/Modify Surgical Operation

Insights/Clinical Decision Support

Innovation/Novel Concepts

3 Ways Computational Modeling Can Help Us

Modify/Guide Surgical Operation

Insights/Clinical Decision Support

Innovation/Novel Concepts

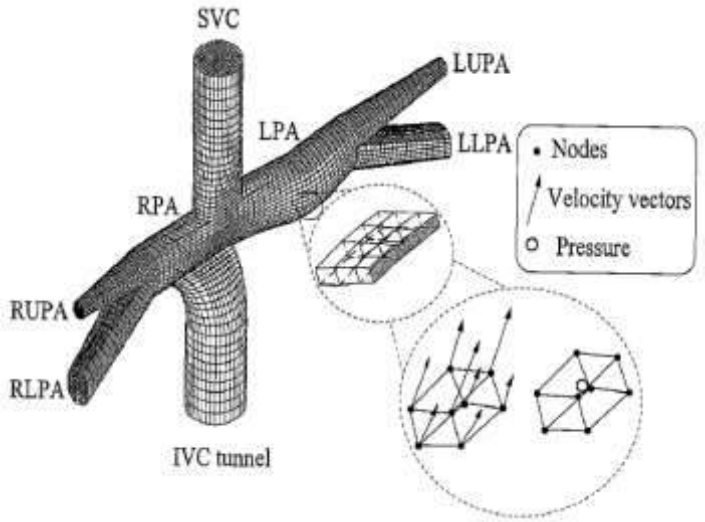
The Beginning

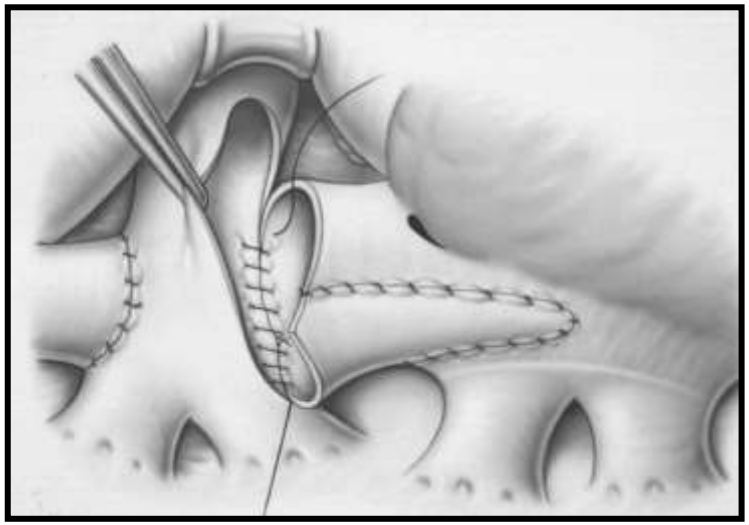
1996: Marc de Leval et al.

Modified Lateral Tunnel

Reduced power loss / Improve efficiency

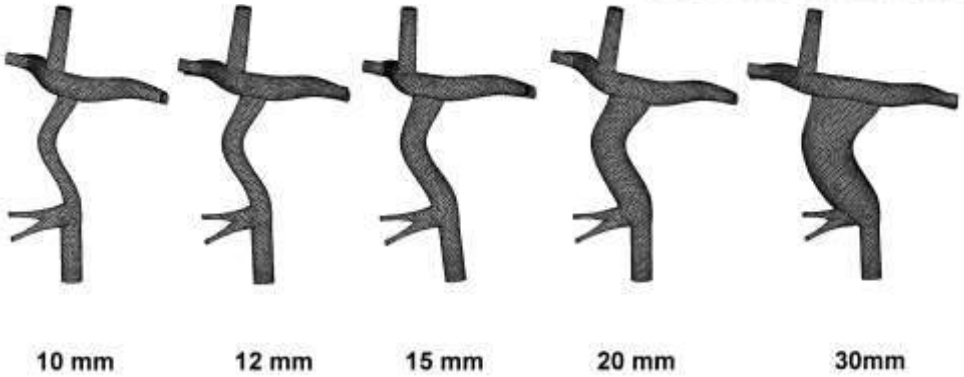
1st instance CFD changing clinical practice



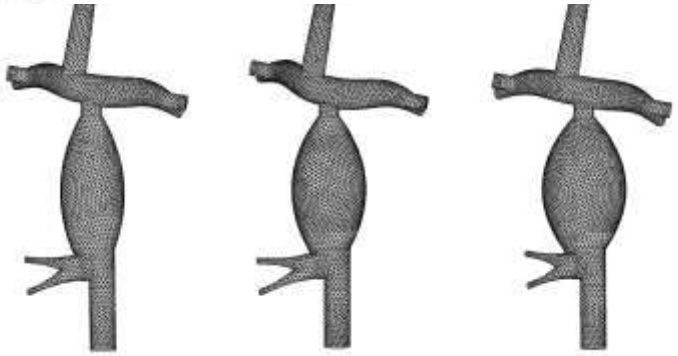


Computational Fluid Dynamic Study of Flow Optimization in Realistic Models of the Total Cavopulmonary Connections[1]

Tain-Yen Hsia, M.D.,*†[2] Francesco Migliavacca, Ph.D.,‡ Simone Pittaccio, M.Sc.,† Alessandro Radaelli, M.Sc.,§ Gabriele Dubini, Ph.D.,‡ Giancarlo Pennati, Ph.D.,‡ and Marc de Leval, M.D., F.R.C.S.†

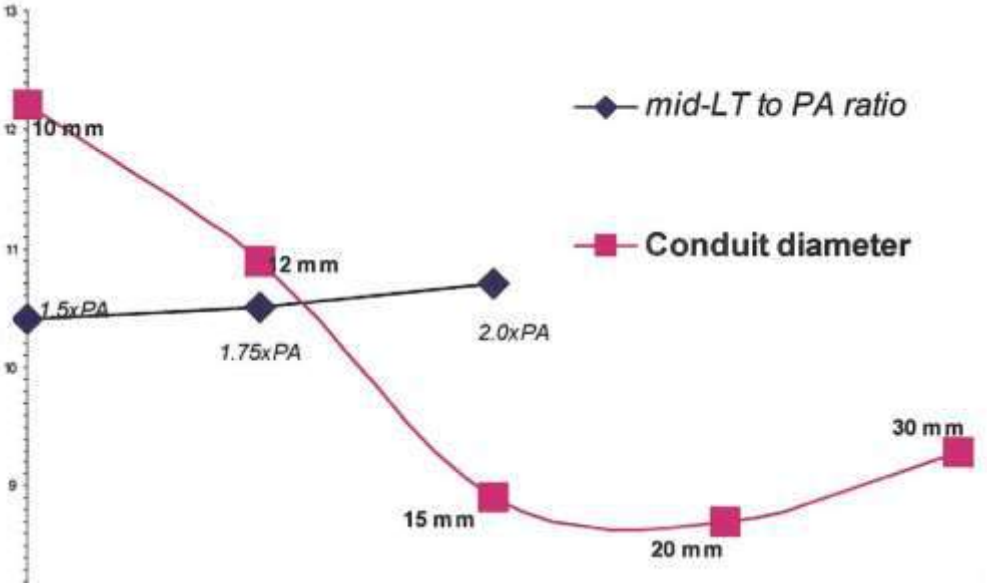


Extracardiac TCPC



Lateral tunnel dilation

Power Loss



Computational Fluid Dynamic Study of Flow Optimization in Realistic Models of the Total Cavopulmonary Connections[1]

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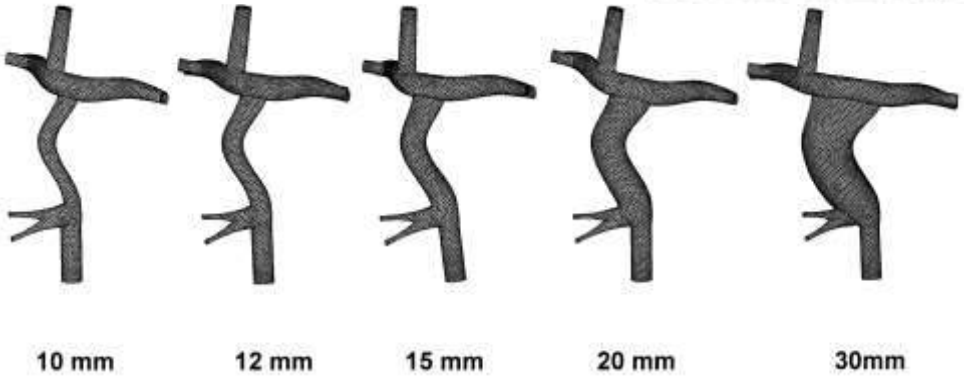

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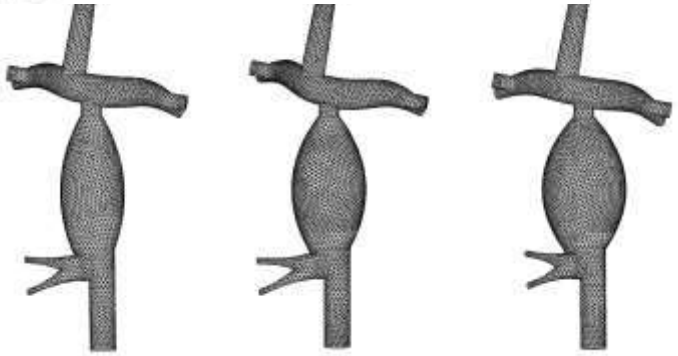
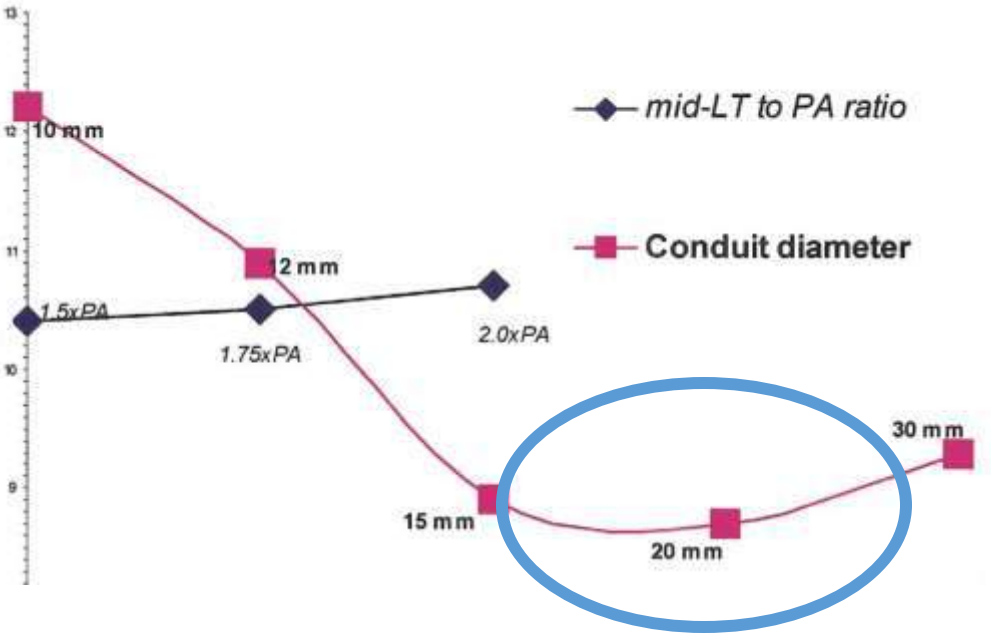
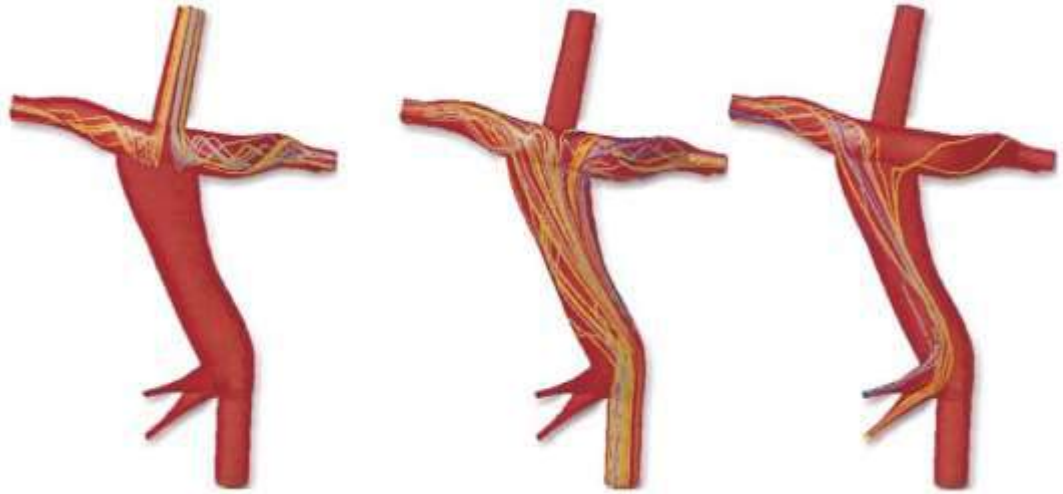


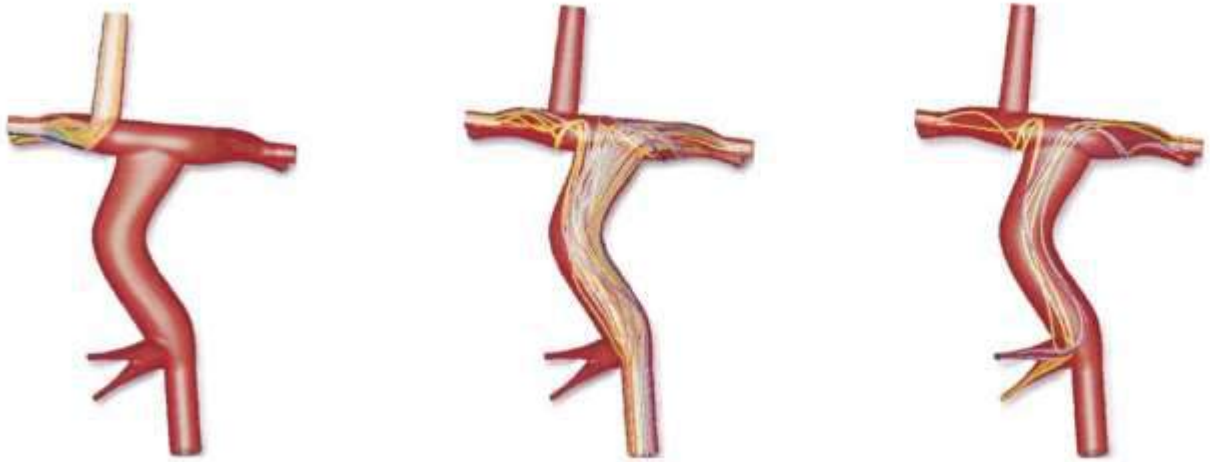
Lateral tunnel dilation

Power Loss





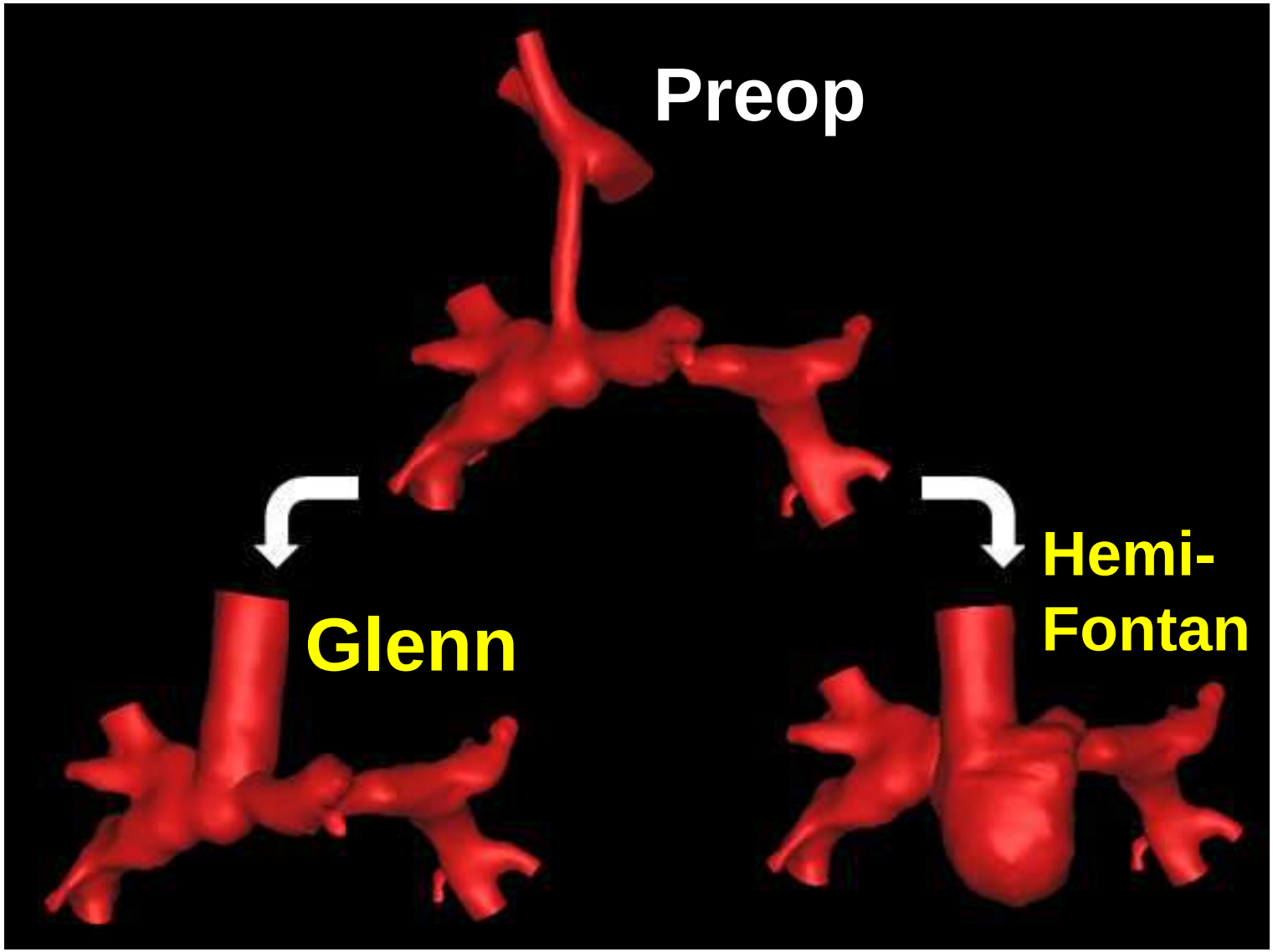
Extracardiac-Right
PA Anastomosis



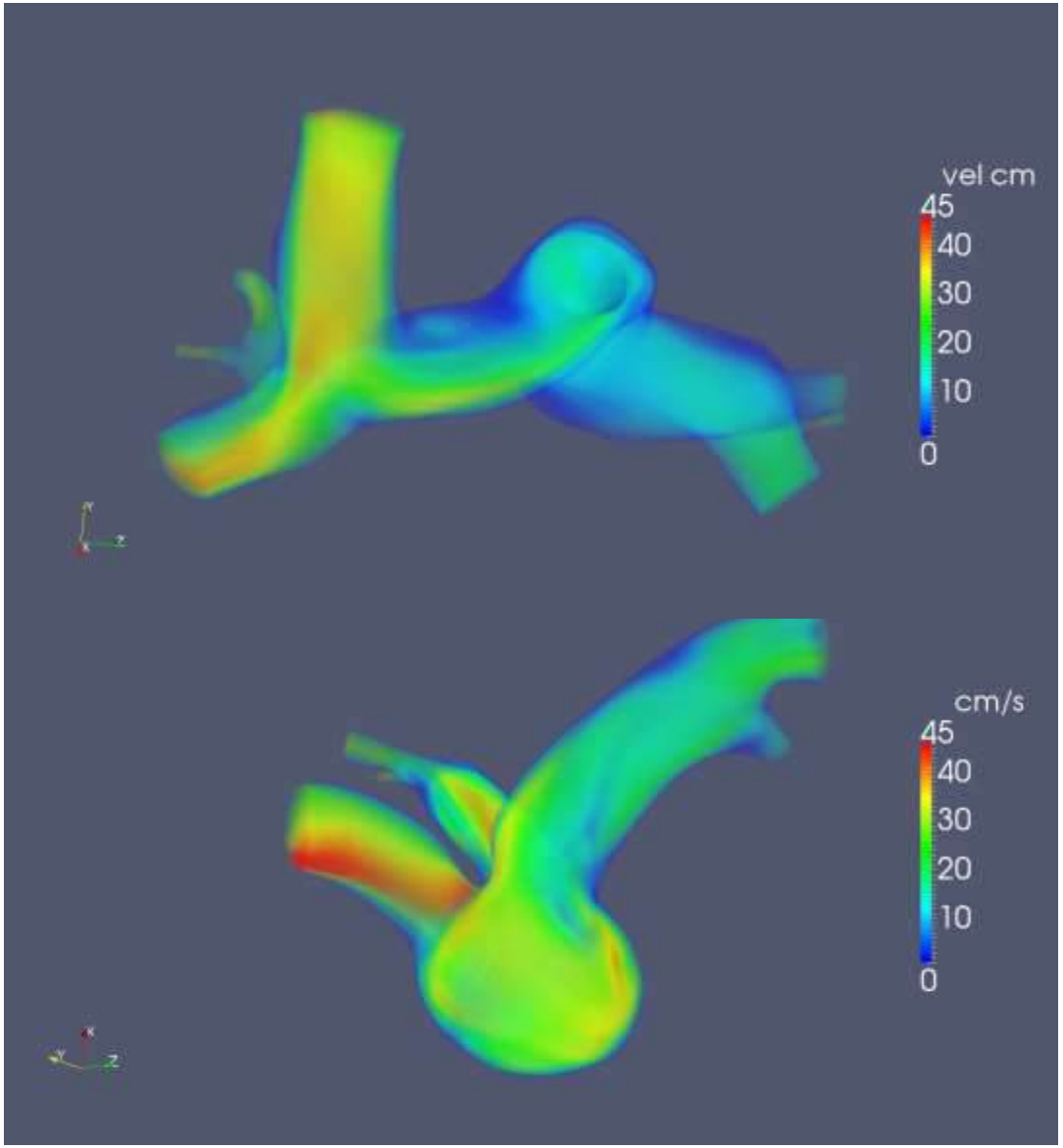
Extracardiac-Left
PA Anastomosis

20 mm

Virtual Stage 2



CFD: Flow, Pressure, Power Loss

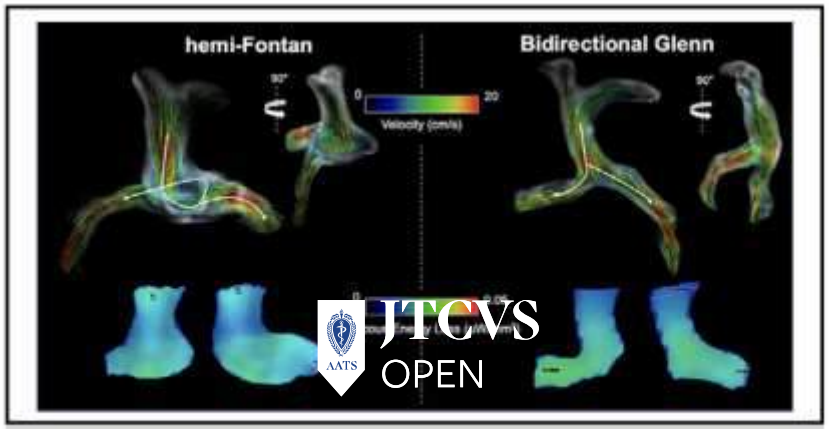


Hemi-Fontan and bidirectional Glenn operations result in flow-mediated viscous energy loss at the time of stage II palliation

JTCVS OPEN

12/2023

Michal Schäfer, MD, PhD,[a] Michael V. Di Maria, MD,[b] James Jaggers, MD,[a] Matthew L. Stone, MD, PhD,[a] David N. Campbell, MD,[a] D. Dunbar Ivy, MD,[b] and Max B. Mitchell, MD[a]

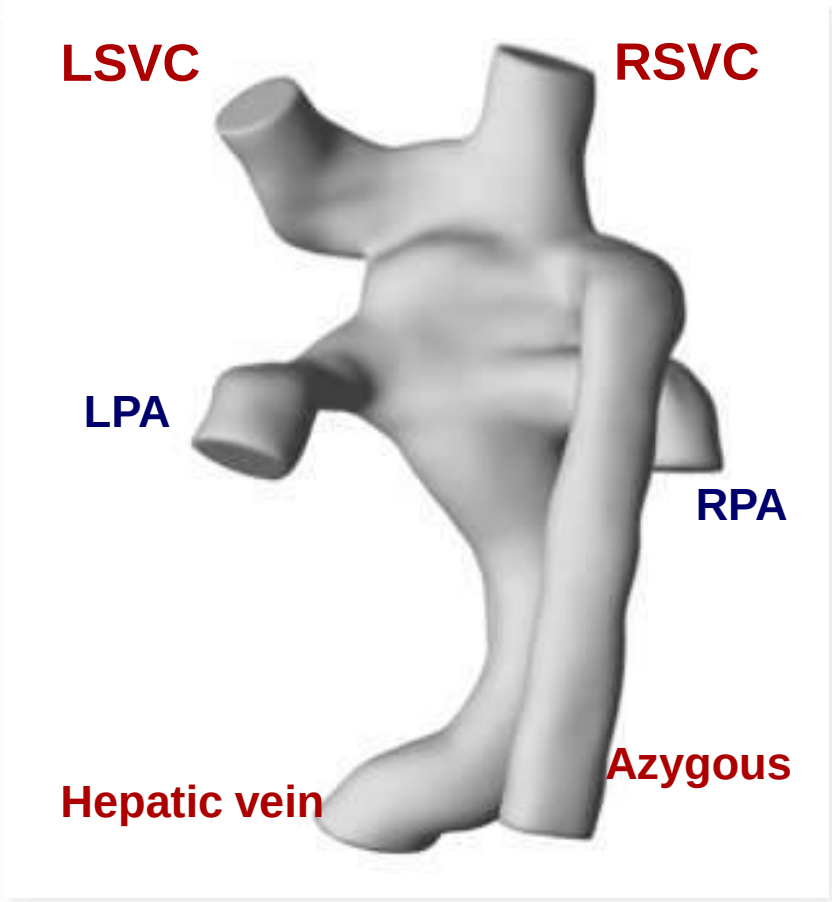


Comparison of HF and BDG flow hemodynamic patterns.

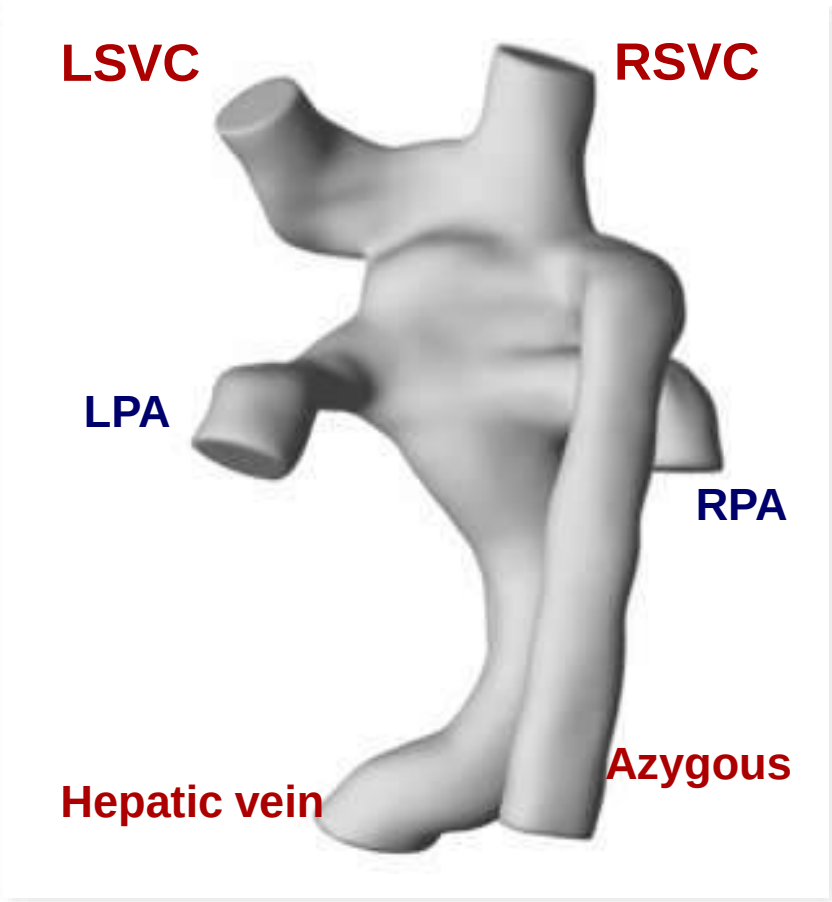
CENTRAL MESSAGE

The second stage of surgical palliation of HLHS using either HF or BDG results in similar flow-mediated viscous energy loss throughout the SCPC junction.

Virtual Surgical Planning: Left Pulmonary AVMs



Virtual Surgical Planning: Left Pulmonary AVMs



1 Ventricle

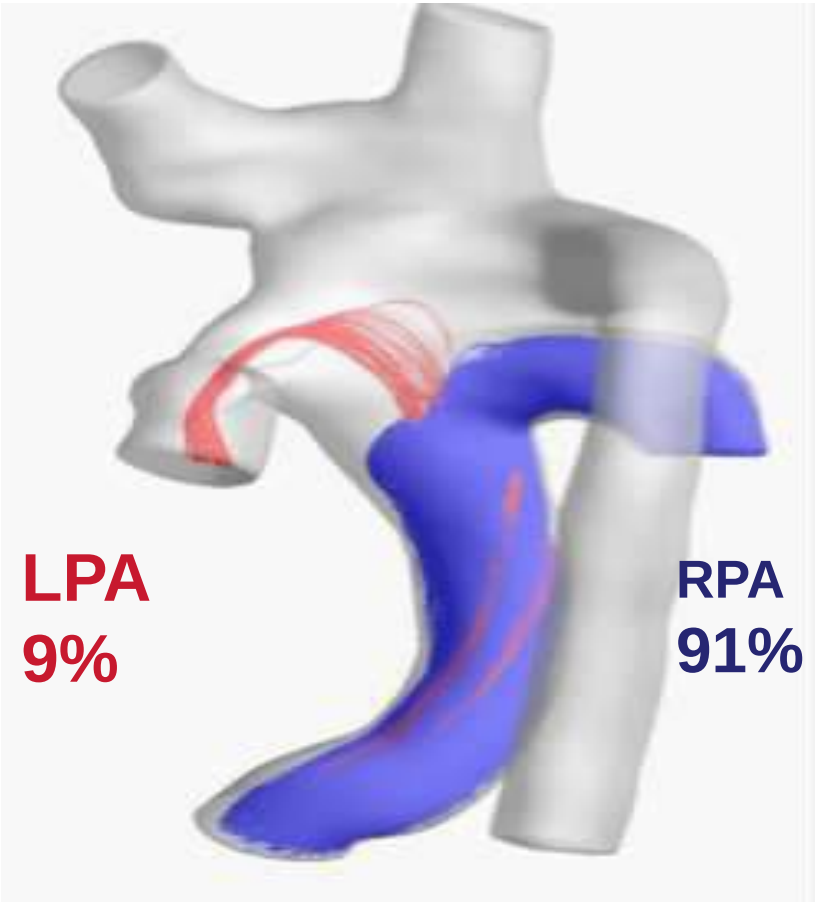
Interrupted IVC with Azygous continuation

s/p Kawashima

TCPC = Hepatic vein to extracardiac conduit

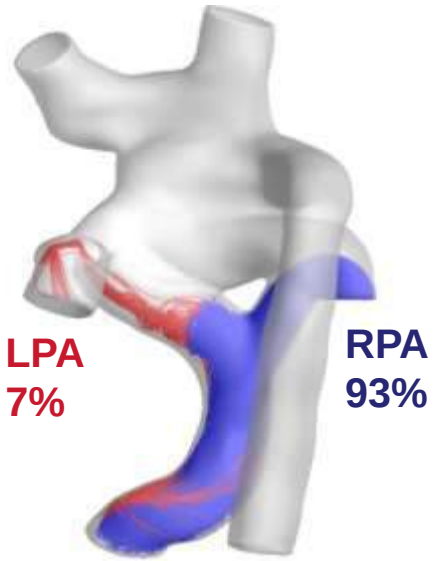
Severe left pulmonary AVMs

Left Pulmonary AVMs

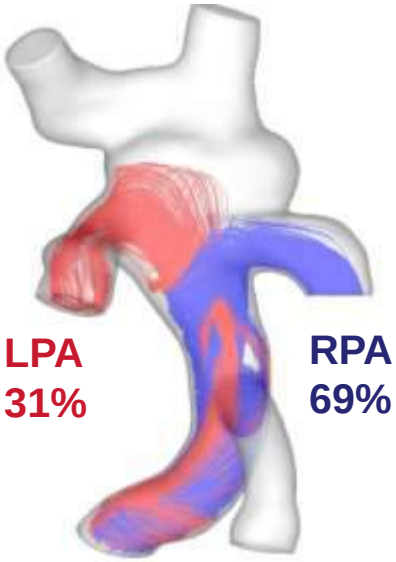


Predict hepatic flow distribution

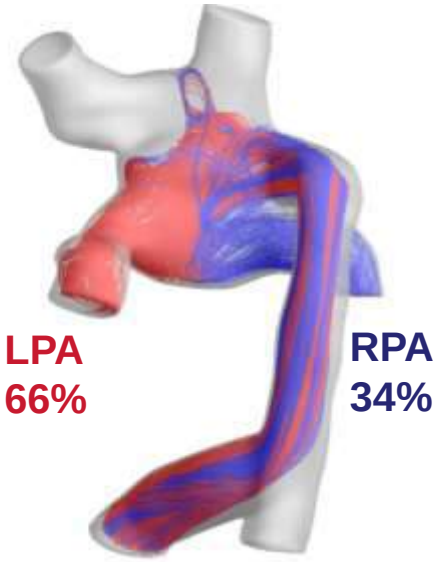
Y-Graft



Azygous to conduit



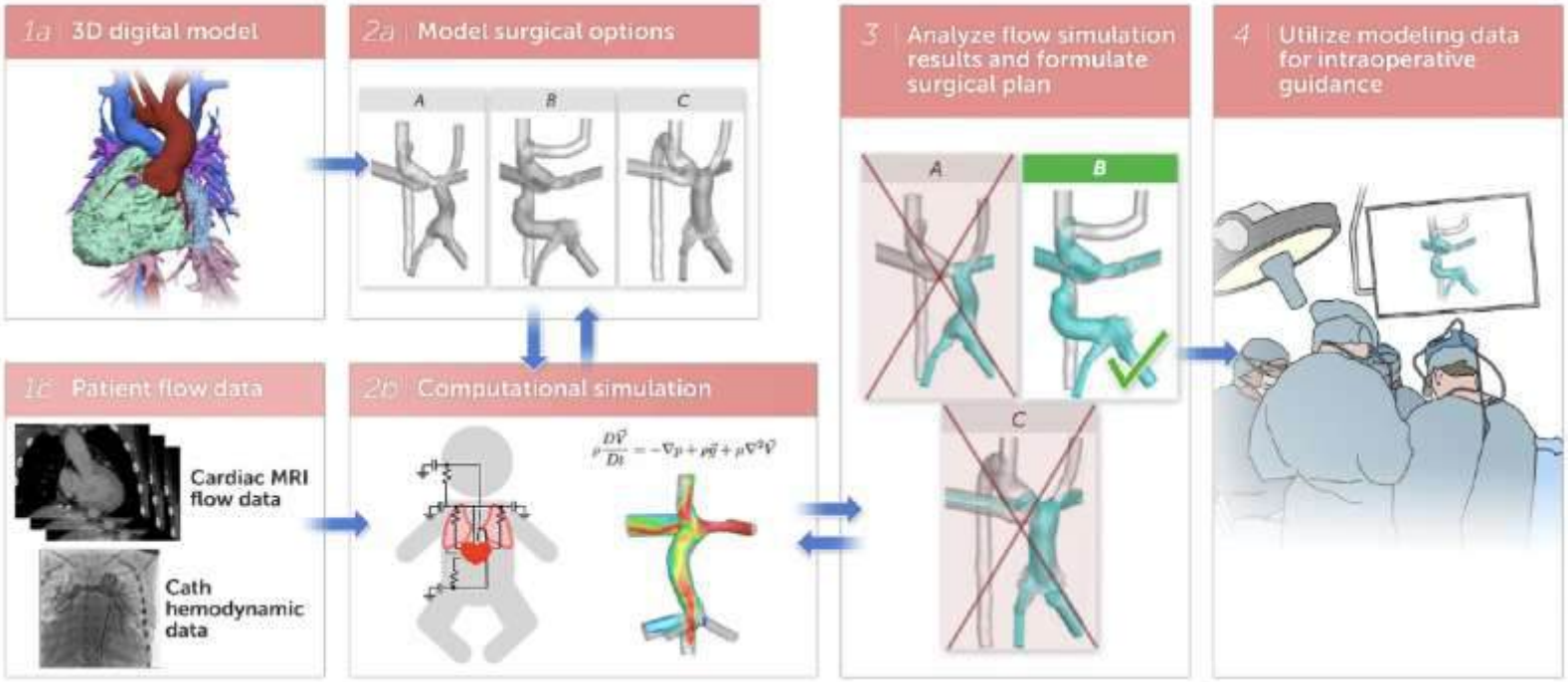
Hepatic vein to Azygous



Multiphysiologic State Computational Fluid Dynamics Modeling for Planning Fontan With Interrupted Inferior Vena Cava

JACC Advances
An Open Access Journal
VOL. 3, NO. 7, 2024

David M. Hoganson, MD,[a] Vijay Govindarajan, PhD,[a] Noah E. Schulz, MS,[a] Emily R. Eickhoff, MS,[a] Roger E. Breitbart, MD,[b] Gerald R. Marx, MD,[b] Pedro J. del Nido, MD,[a] Peter E. Hammer, PhD[a]



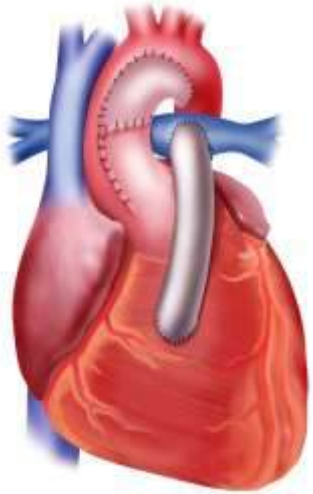
3 Ways Computational Modeling Helps Us

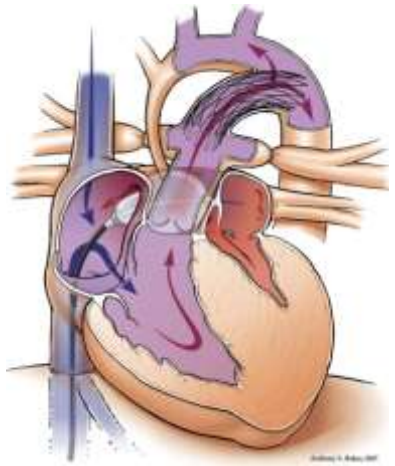
Improve/Modify Surgical Operation

Insights/Clinical Decision Support

Innovation/Novel Concepts

Stage 1 Palliation





The NEW ENGLAND JOURNAL of MEDICINE

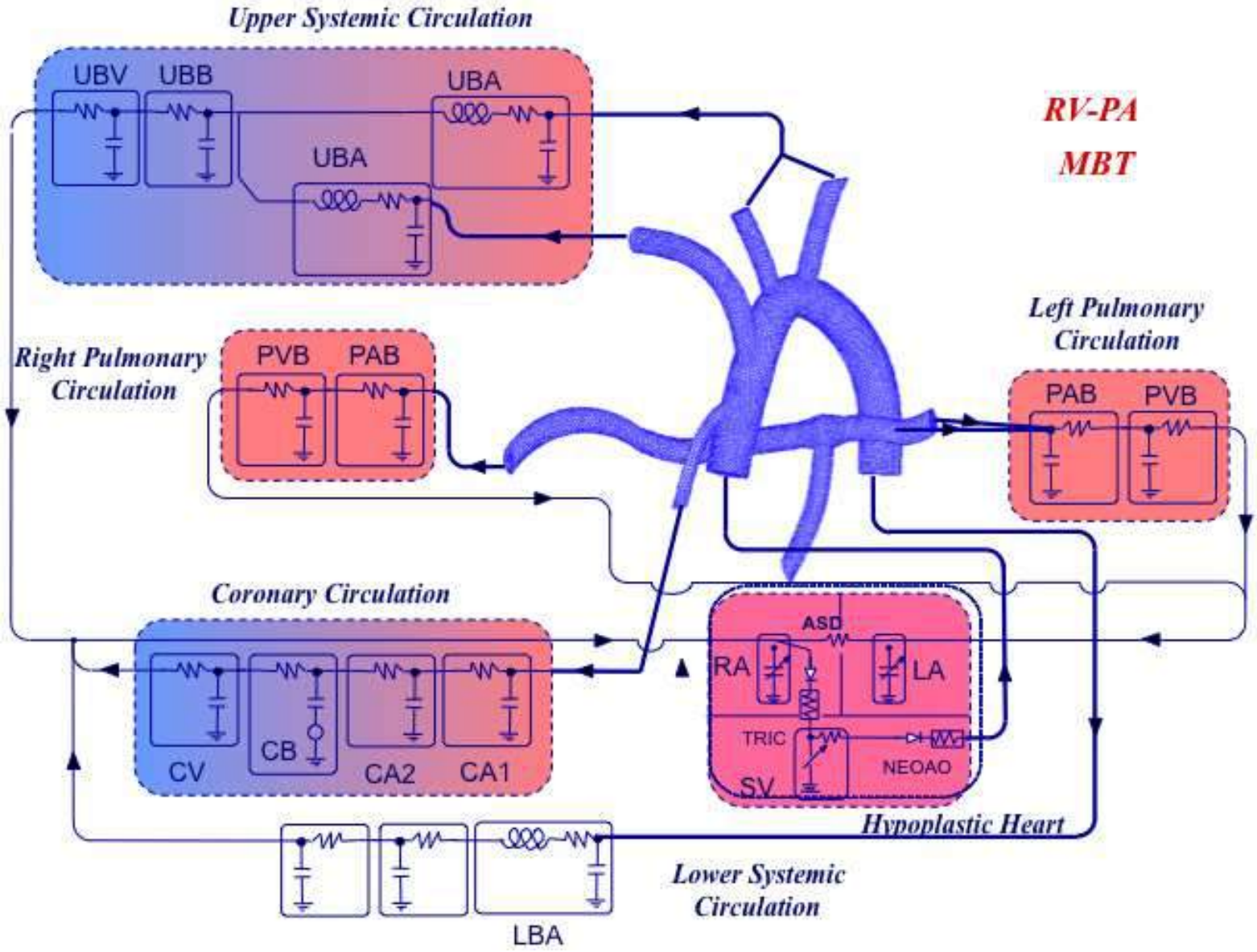
ORIGINAL ARTICLE

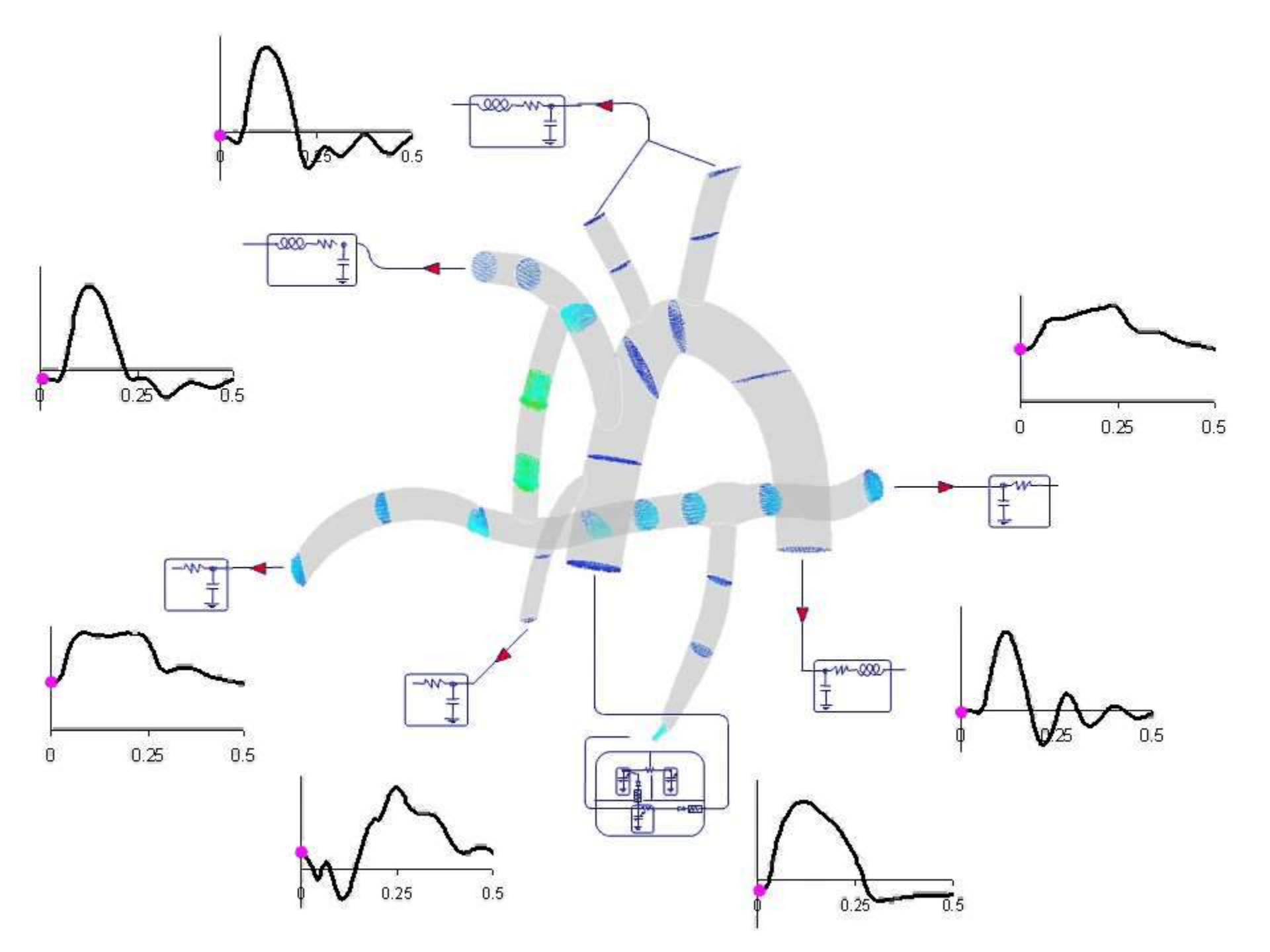
Comparison of Shunt Types in the Norwood Procedure for Single-Ventricle Lesions

Richard G. Ohye, M.D., Lynn A. Sleeper, Sc.D., Lynn Mahony, M.D., Jane W. Newburger, M.D., M.P.H., Gail D. Pearson, M.D., Sc.D., Minmin Lu, M.S., Caren S. Goldberg, M.D., Sarah Tabbutt, M.D., Ph.D., Peter C. Frommelt, M.D., Nancy S. Ghanayem, M.D., Peter C. Laussen, M.B., B.S., John F. Rhodes, M.D., Alan B. Lewis, M.D., Seema Mital, M.D., Chitra Ravishankar, M.D., Ismee A. Williams, M.D., Carolyn Dunbar-Masterson, B.S.N., R.N., Andrew M. Atz, M.D., Steven Colan, M.D., L. LuAnn Minich, M.D., Christian Pizarro, M.D., Kirk R. Kanter, M.D., James Jaggers, M.D., Jeffrey P. Jacobs, M.D., Catherine Dent Krawczeski, M.D., Nancy Pike, R.N., Ph.D., Brian W. McCrindle, M.D., M.P.H., Lisa Virzi, R.N., M.S., M.B.A., and J. William Gaynor, M.D., for the Pediatric Heart Network Investigators

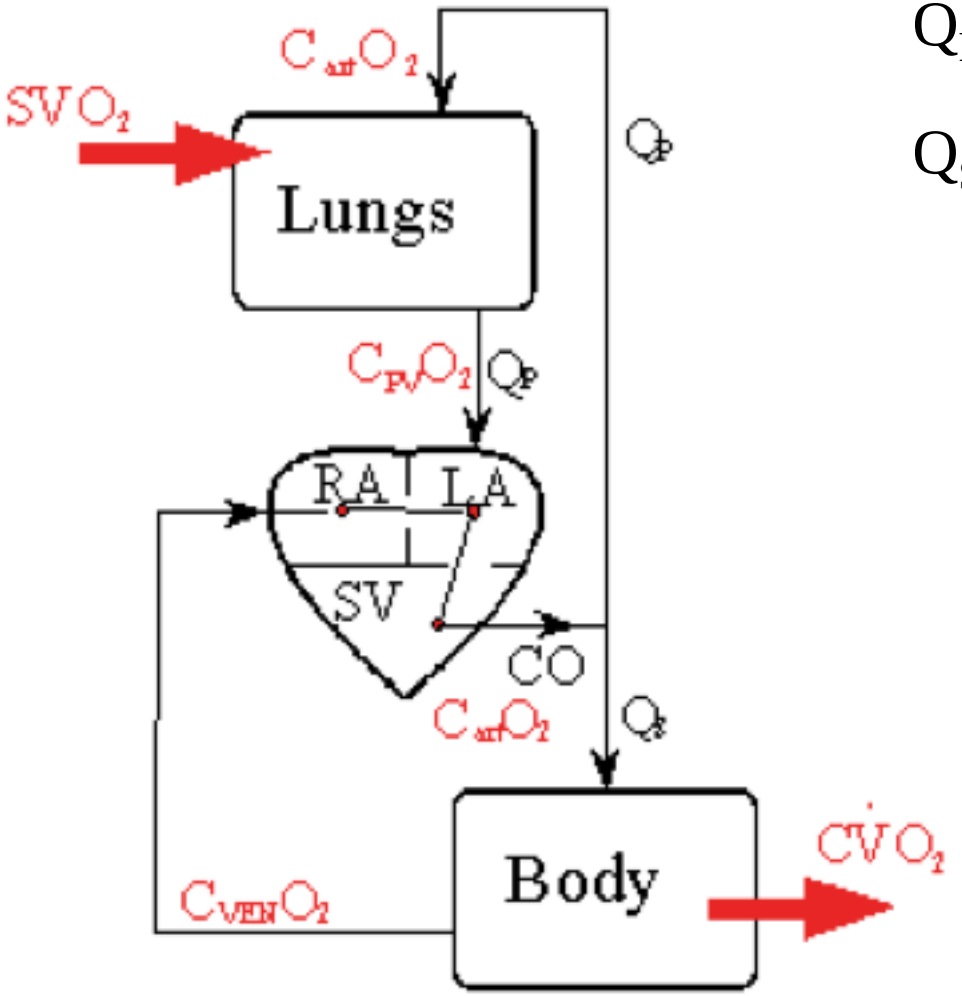
Physiology Equivalent?

Closed Loop: Multiscale Modeling




0
0.25
0.5

Oxygen Delivery



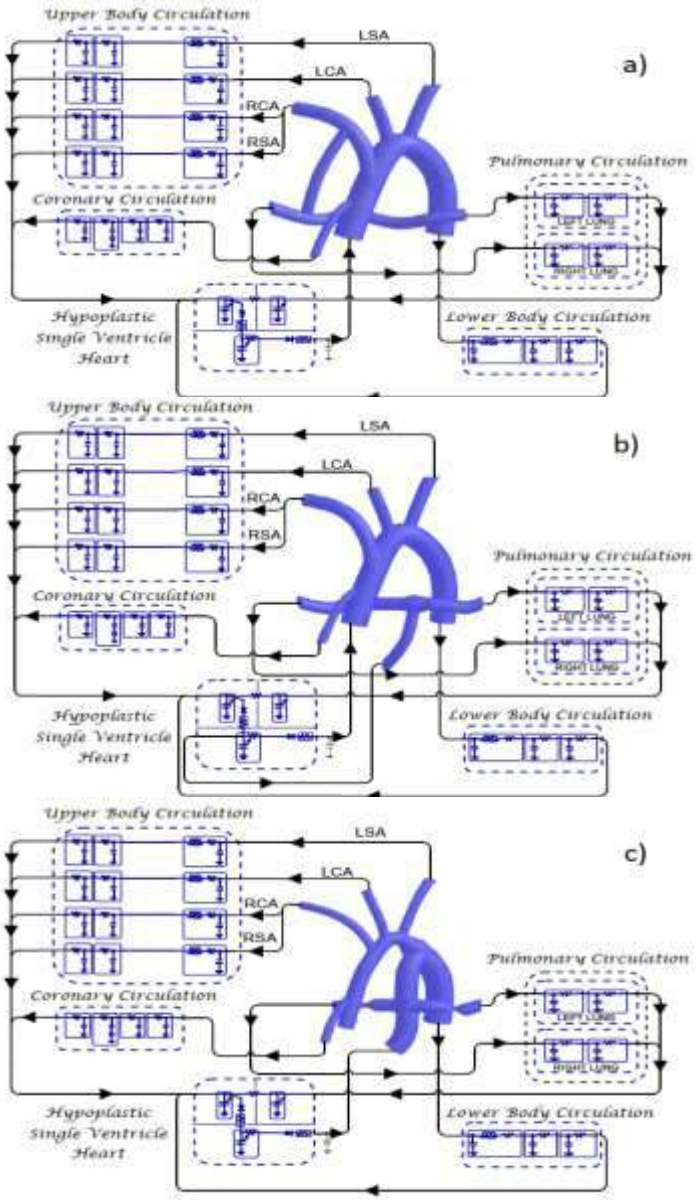
$$Q_P \cdot C_{ART}O_2 + SVO_2 = Q_P \cdot C_{PV}O_2$$

$$Q_S \cdot C_{ART}O_2 - CVO_2 = Q_S \cdot C_{VEN}O_2$$

$$SVO_2 = CVO_2$$

$$O_2\,\text{delivery} = \frac{Q_S \cdot C_{ART}O_2}{BSA}$$

$$Sat_{ART} = \frac{C_{ART}O_2}{O_X Cap} \cdot 100$$



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journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Multiscale models of the hybrid palliation for hypoplastic left heart syndrome

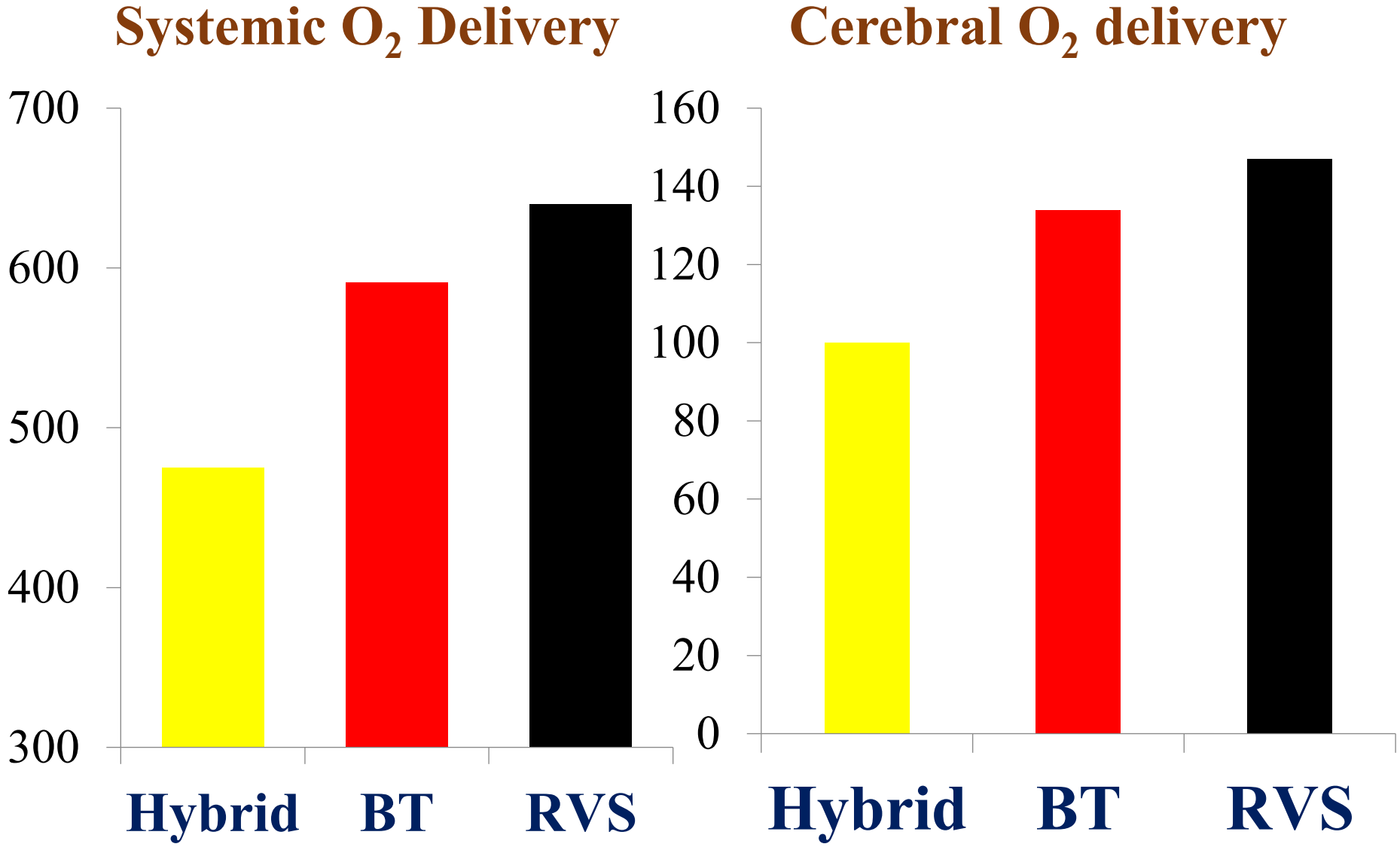
Chiara Corsini [a], Daria Cosentino [b], Giancarlo Pennati [a], Gabriele Dubini [a], Tain-Yen Hsia [b], Francesco Migliavacca [a,*]

Circulation

Surgery for Congenital Heart Disease

Use of Mathematical Modeling to Compare and Predict Hemodynamic Effects Between Hybrid and Surgical Norwood Palliations for Hypoplastic Left Heart Syndrome

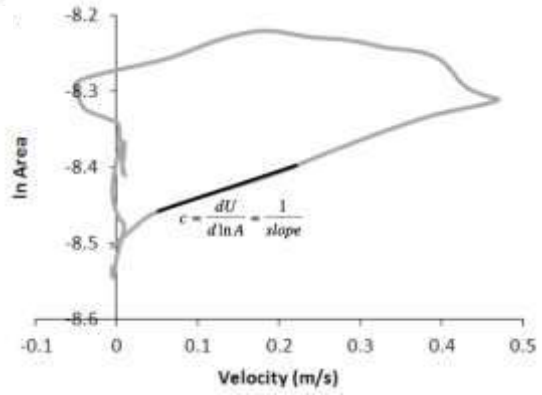
Tain-Yen Hsia, MD; Daria Cosentino, MS; Chiara Corsini, MS; Giancarlo Pennati, PhD; Gabriele Dubini, PhD; Francesco Migliavacca, PhD; for the Modeling of Congenital Hearts Alliance (MOCHA) Investigators

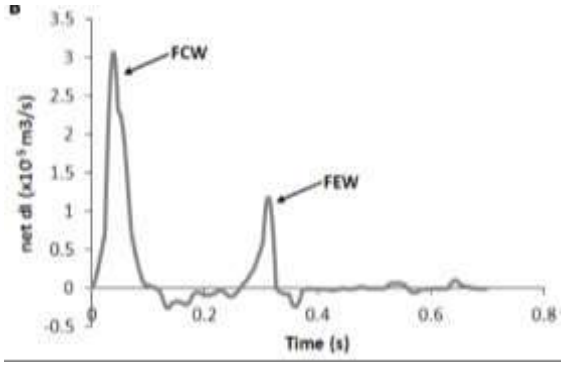

Systemic O_2 Delivery
700
600
500
400
300
Hybrid
BT
RVS
Cerebral O_2 delivery
160
140
120
100
80
60
40
20
0
Hybrid
BT
RVS

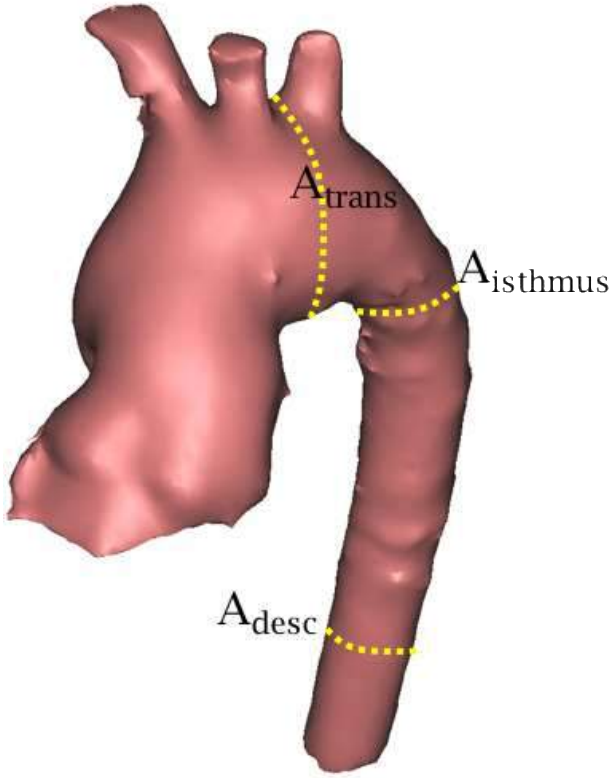
Aortic Arch

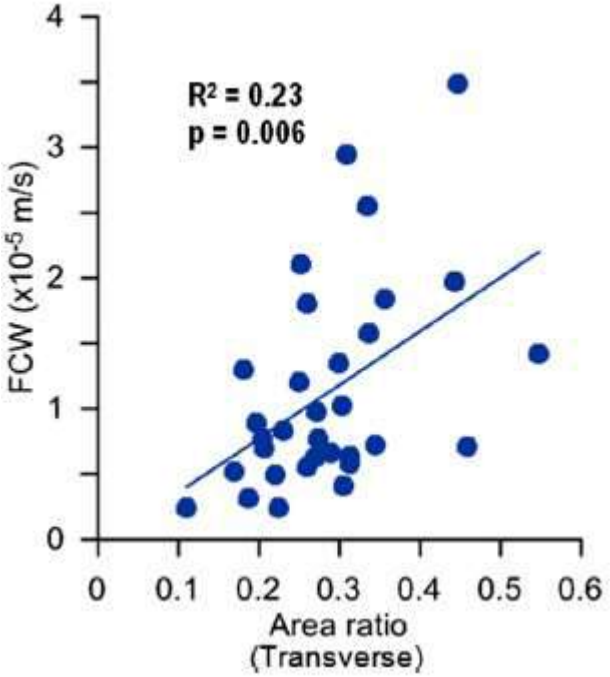
Wave Intensity Analysis

Norwood Aortic Arch = Poor Ventricular-Arterial Coupling





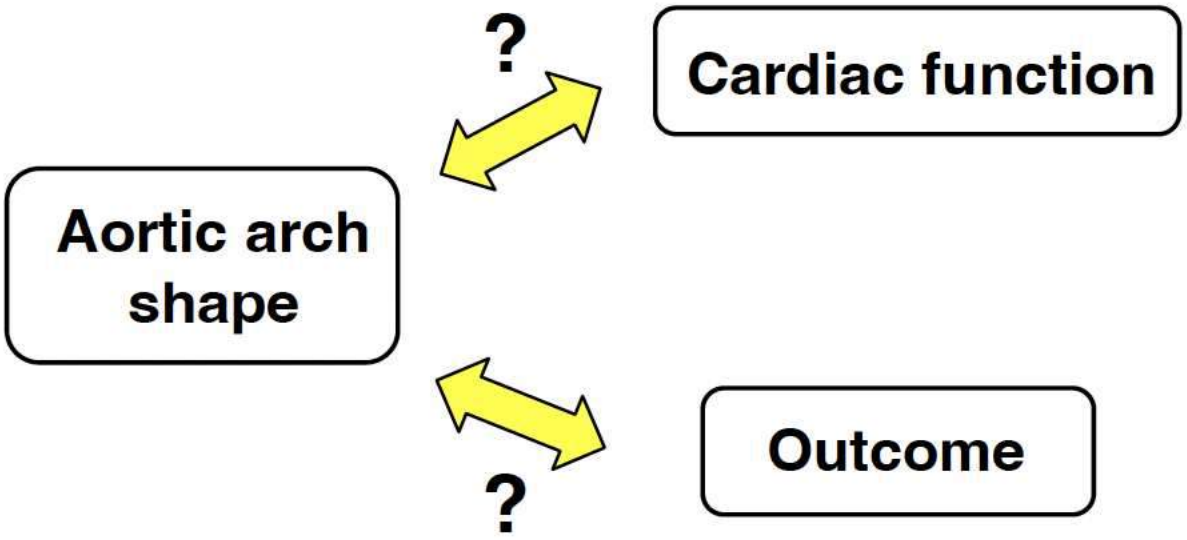




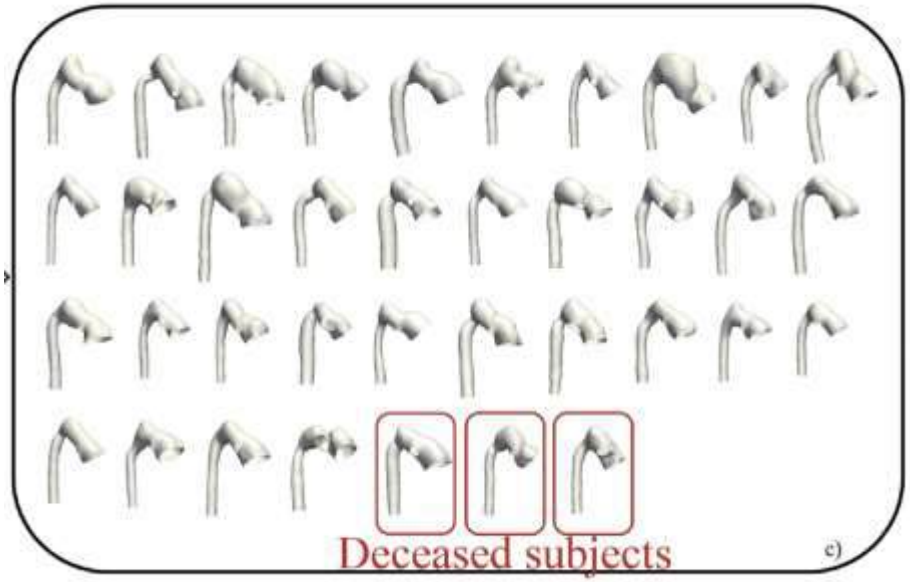
Looks Do Matter! Aortic Arch Shape After Hypoplastic Left Heart Syndrome Palliation Correlates With Cavopulmonary Outcomes

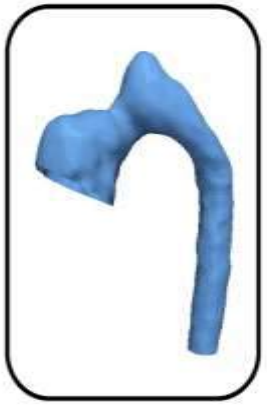
Jan L. Bruse, MS, Elena Cervi, MD, Kristin McLeod, PhD, Giovanni Biglino, PhD, Maxime Sermesant, PhD, Xavier Pennec, PhD, Andrew M. Taylor, MD, Silvia Schievano, PhD, and Tain-Yen Hsia, MD, for the Modeling of Congenital Hearts Alliance (MOCHA) Collaborative Group*

(Ann Thorac Surg 2017;103:645–54)

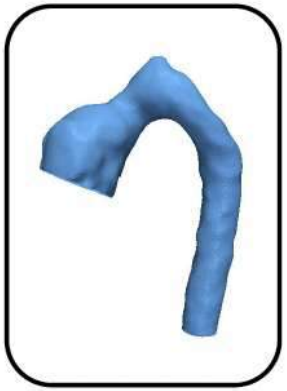


Computational Statistical Shape Analysis





Shapes associated with high end-diastolic volume



… with **high postop Glenn pressures**

THE JOURNAL OF THORACIC AND CARDIOVASCULAR SURGERY

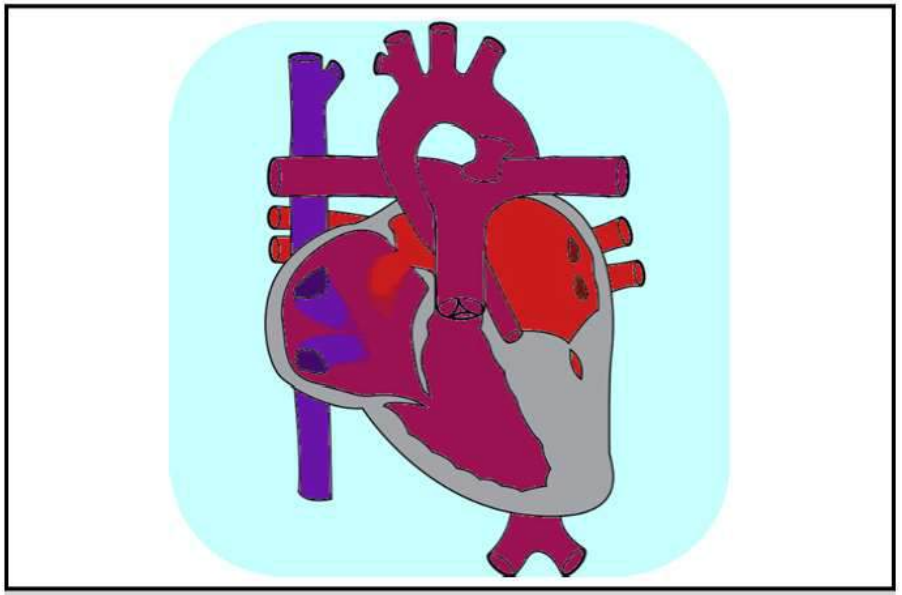
An interactive simulation tool for patient-specific clinical decision support in single-ventricle physiology

Pediatric Cardiac Surgery Annual
Seminars
IN THORACIC AND CARDIOVASCULAR SURGERY
AATS

Computational Modeling to Support Surgical Decision Making in Single Ventricle Physiology

Tain-Yen Hsia, MD,[a] Timothy Conover, PhD,[a] and Richard Figliola, PhD[a] for the Modeling of Congenital Hearts Alliance (MOCHA) Investigators[1]

Available on the App Store



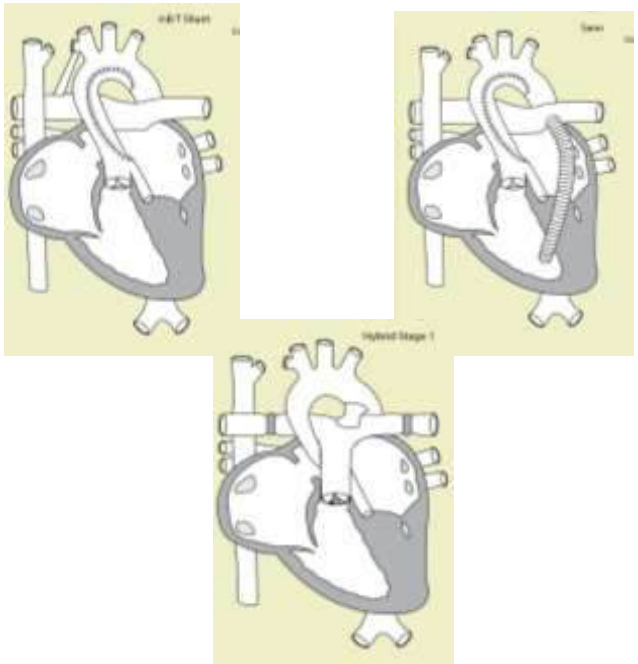
Icon for the iOS app.

CFD For All!

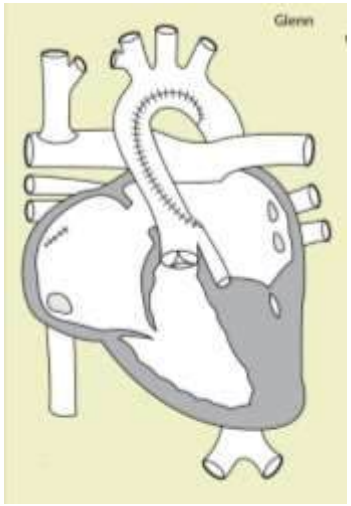
Predictive Simulation for all 3 Stages

- **Patient Specific (Personalized Medicine)**
- **User Friendly**
- **Input = bedside data / clinical information**

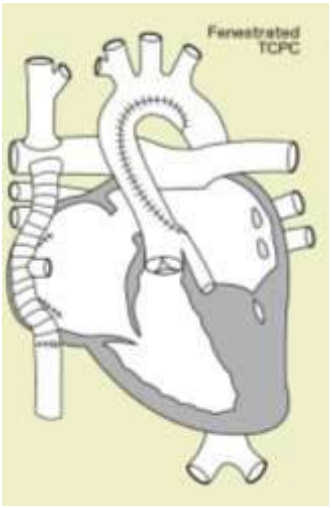
Stage 1

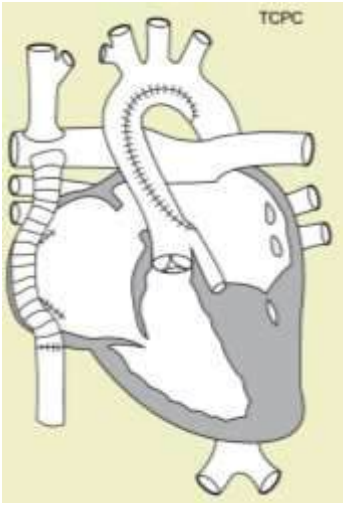


Stage 2



Stage 3

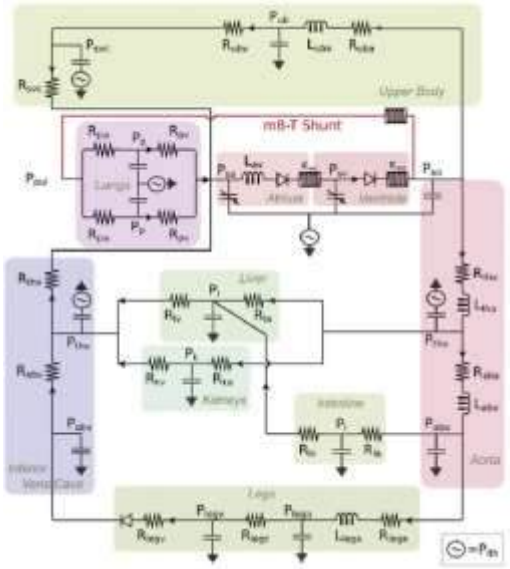




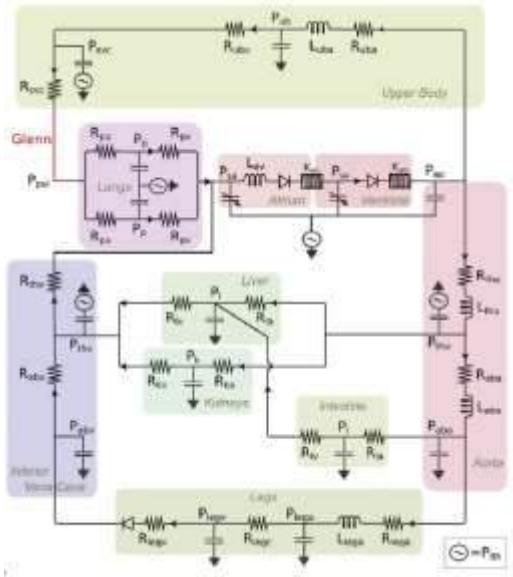
Predictive Simulation for all 3 Stages

- **Lumped parameter network of entire circulation (0-D)**
- **No 3D modeling = Fast!**
- **iOS and Web-based**

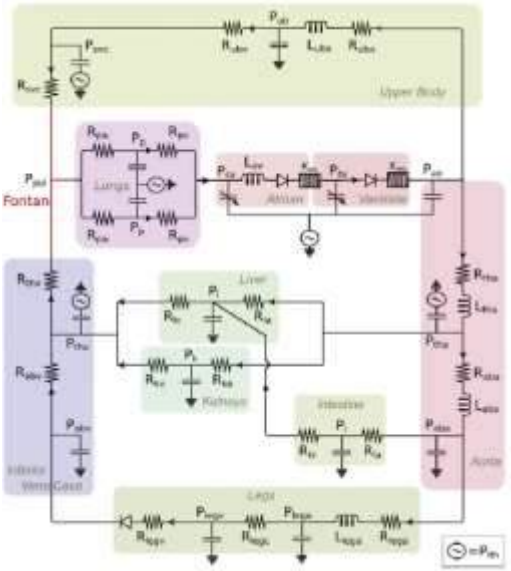
Stage 1

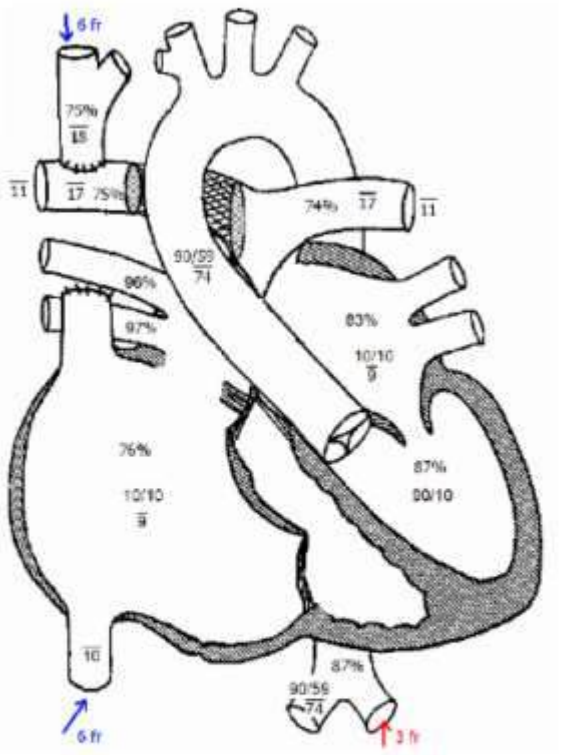


Stage 2



Stage 3





Arrows indicate catheter course.

Diagnoses / Procedures

AE00001. No adverse eventsProcedure - Diagnostic Cath
125. Pulmonary artery: Peripheral (Balloon dilation)
370. Ebstein's anomaly

Comments

Ava is a 4yo girl with severe Ebstein's anomaly of the tricuspid valve

[redacted]

Birth Date: 01/15/2014
Cath Date: 01/10/2019
Cath #: E100011107
Age at cath: 4 years
Gender: Female

Attending: Jeremy D. Asnes, MD; Britton C. Keeshan, MD; Fahey MD, John T
Fellow: Sunny Chang
Referring:
Other:

Height: 97.8 cm Weight: 14.6 kg
BSA = 0.62 m2

Fluoro: Contrast:
Vein: Right femoral 6fr
Artery: Left femoral 3fr

baseline

Qp = 1.93 L/min (3.11 L/min/m2)
Qs = 3.54 L/min (5.70 L/min/m2)
Rp = 3.11 units (1.93 units x m2)
Rs = 18.36 units (11.40 units x m2)
Qp/Qs = 0.55 : 1 | Rp/Rs = 0.17
Qep = 1.93 L/min (3.11 L/min/m2)

Heart Rate: 123 bpm
VO2: 161 ml/min/m2
Hemoglobin: 17.3 gm/dL

Inspired O2: 21%
pH: 7.31
pCO2: 41.4
pO2: 61.0
HCO3: 21.0

Thermo CO

%O2	Site	Sys/A	Dias/V	Mean
75	SVC			18
76	RA	10	10	9
	RV			
	PA			
75	RPA			17
74	LPA			17

Right		Left
11	Wedge Mean	11

%O2	Site	Sys/A	Dias/V	Mean
83	LA	10	10	9
87	LV	90.0	10	
	aAO	90	59	74
87.0	dAO	90	59	74

IVC
Mean: 10
RUPV: O2%: 96

RLPV: O2%: 97

4 y.o. Ebstein's Functional tricuspid atresia

s/p Glenn, LPA stent

78-82% Sat

SVC pressure =17

TPG = 8

LVEDP = 11

? High Risk TCPC

Virtual TCPC

No Fenestration

Qp:Qs	**1**
O2 Sat	**97 %**
Atrial Pressure	**10**
Fontan Pressure	**19**
TPG	**9**
O2 Delivery	**1059**

Virtual TCPC

	No Fenestration	Sildenafil + 4 mm Fenestration
Qp:Qs	1	0.75
O2 Sat	97 %	92 %
Atrial Pressure	10	10
Fontan Pressure	19	17
TPG	9	7
O2 Delivery	1059	1030

Real fenestrated TCPC + sildenafil

	No Fenestration	Sildenafil + 4 mm Fenestration	Post-Op
Qp:Qs	1	0.75	
O2 Sat	97 %	92 %	89-92 %
Atrial Pressure	10	10	9-10
Fontan Pressure	19	17	16-17
TPG	9	7	7-8
O2 Delivery	1059	1030	

3 Ways Computational Modeling Helps Us

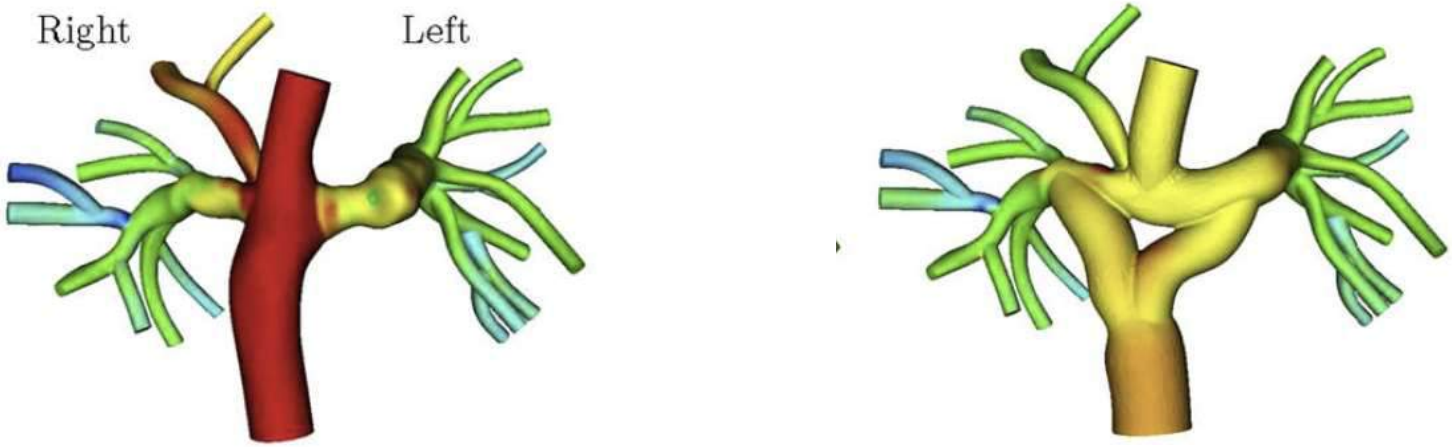
Improve/Modify Surgical Operation

Insights/Clinical Decision Support

Innovation/Novel Concepts

Evaluation of a novel Y-shaped extracardiac Fontan baffle using computational fluid dynamics

The Journal of Thoracic and Cardiovascular Surgery · February 2009



Evaluation of a novel Y-shaped extracardiac Fontan baffle using computational fluid dynamics

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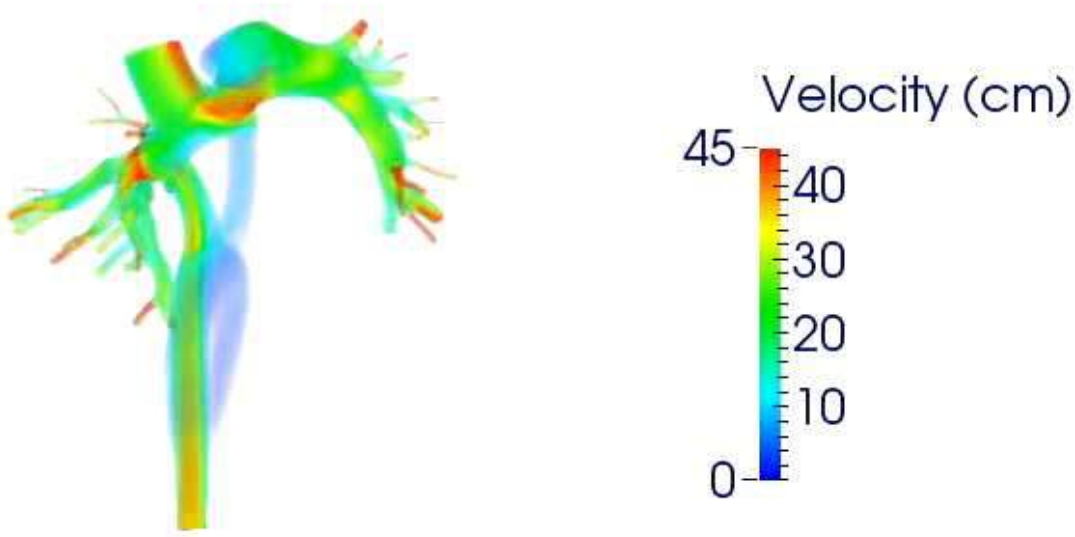


Improve Flow Efficiency (low energy loss)

Balanced Hepatic Venous Flow (prevent AVM)

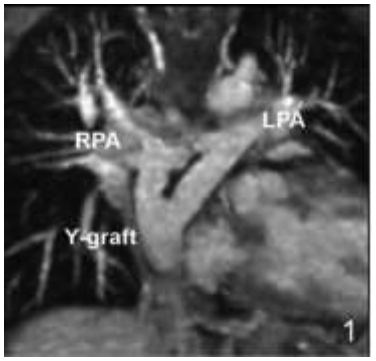
Technical feasibility and intermediate outcomes of using a handcrafted, area-preserving, bifurcated Y-graft modification of the Fontan procedure

The Journal of Thoracic and Cardiovascular Surgery • Volume 149, Number 1

M. Reddy (Stanford): 6 patients

1 ECMO, 1 right limb thrombosis

Abandoned



A pulsatile hemodynamic evaluation of the commercially available bifurcated Y-graft Fontan modification and comparison with the lateral tunnel and extracardiac conduits

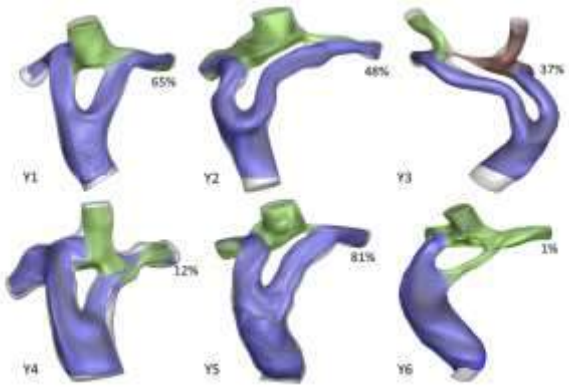
The Journal of Thoracic and Cardiovascular Surgery • Volume 151, Number 6

K. Kantor (Atlanta): 45 patients

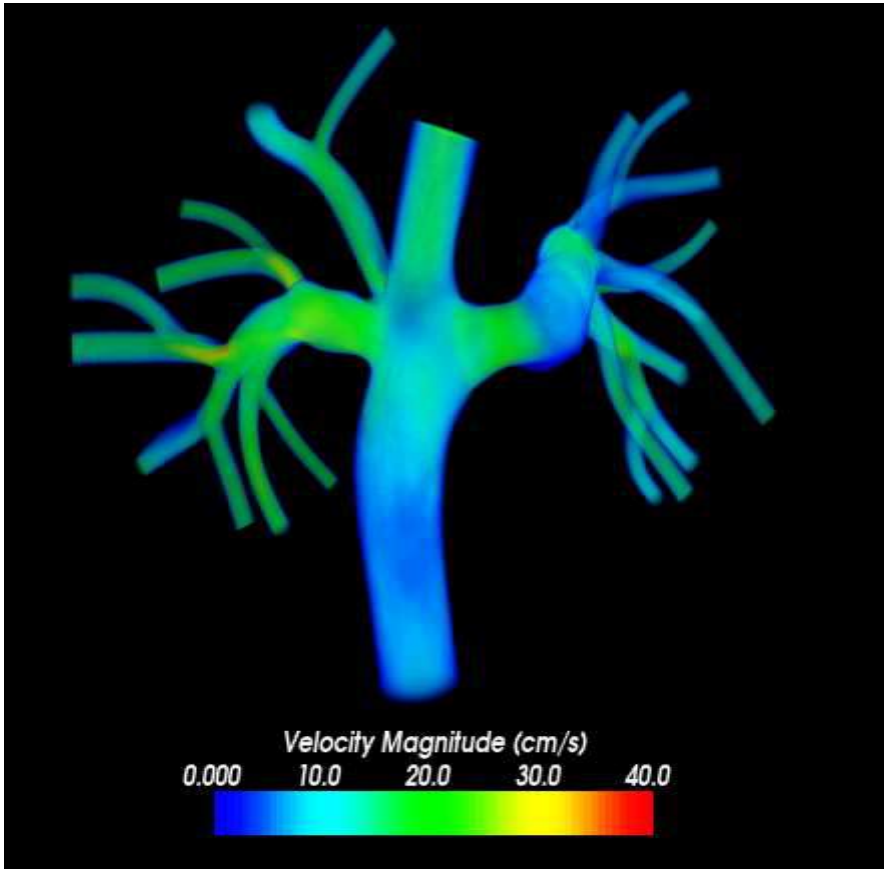
38% re-admission for pleural effusion, 2 death
More complicated operation (vs. traditional)

Worse energy loss
Poorer hepatic flow distribution

Abandoned



Computer Modeling IS:



Mathematical solution to complex problem

Effects of surgery, anatomy, and physiology

Supplement clinical decision-making

Allows for novel innovations

Computer Modeling Is NOT:

Predictor of clinical outcome

Account for all biological processes

Dictate clinical decisions

Replace JCC/MDT

Thank You!