POLITECNICO DI MILANO

LABORATORY OF BIOLOGICAL STRUCTURE MECHANICS

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Numerical Simulations for the Planning of Surgical Procedures

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Why pediatric cardiac surgery?

How many people in the United States and in Europe have a congenital heart defect?

Estimates suggest that about 1,000,000 Americans have a congenital heart defect (American Heart Association). Approximately 36,000 babies are live born with a heart defect each year in the European Union (EUROCAT Central Registry).

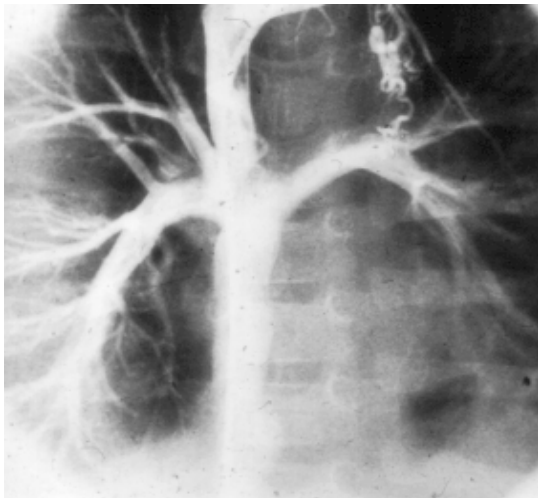
How serious is the problem?

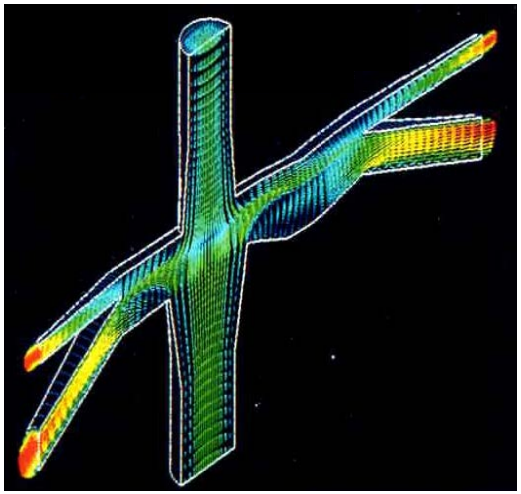
Congenital heart defects are the most common birth defect and are the number one cause of death from birth defects during the first year of life. Nearly twice as many children die from congenital heart disease in the United States each year as die from all forms of childhood cancers combined. Over 91,000 life years are lost each year in the US due to congenital heart disease. Charges for care exceed 2.2 billion dollars, for inpatient surgery alone (American Heart Association).

Are things improving?

Definitely. Overall mortality has significantly declined over the past few decades. For example, in the 1960s and 1970s the risk of dying following congenital heart surgery was about 30% and today it is around 5%.

How the story started: back to Great Ormond Street Hospital for Children, London, 1993, and to the Total CavoPulmonary Connection (TCPC)



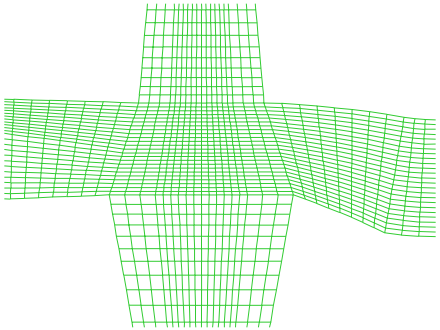


Prof. Marc R. de Leval
Laurea ad honorem in Biomedical Engineering, Politecnico di Milano, 2007

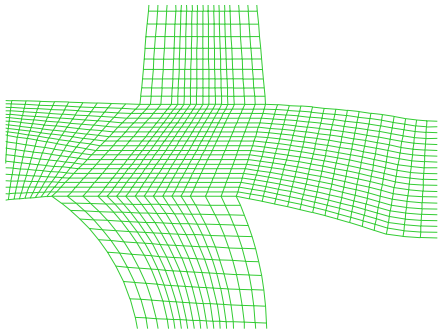
***Aim*:**
To investigate the effects of geometric/anatomic features (e.g. *offsetting* and shape of the anastomosis between the inferior vena cava and the pulmonary artery)

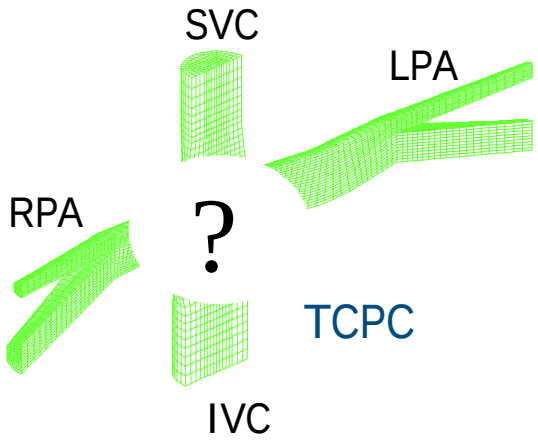
de Leval et al. Use of computational fluid dynamics in the design of surgical procedures: application to the study of competitive flows in cavo-pulmonary connections, J Thorac Cardiovasc Surg. ***1996***

TCPC: Total CavoPulmonary Connection

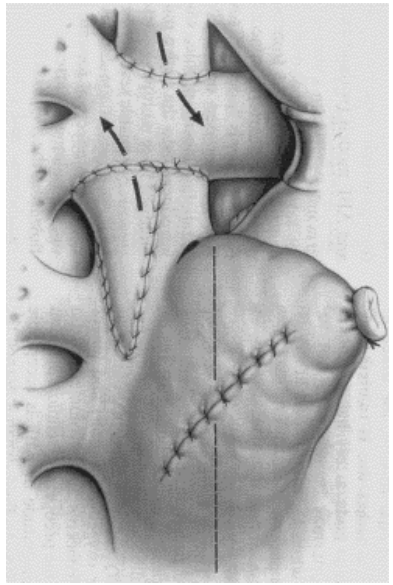


- 3-D geometry
- steady flow
- Newtonian fluid (*blood*)
- rigid walls





(de Leval et al., J Thorac Cardiovasc Surg, 96:682-695, 1988)



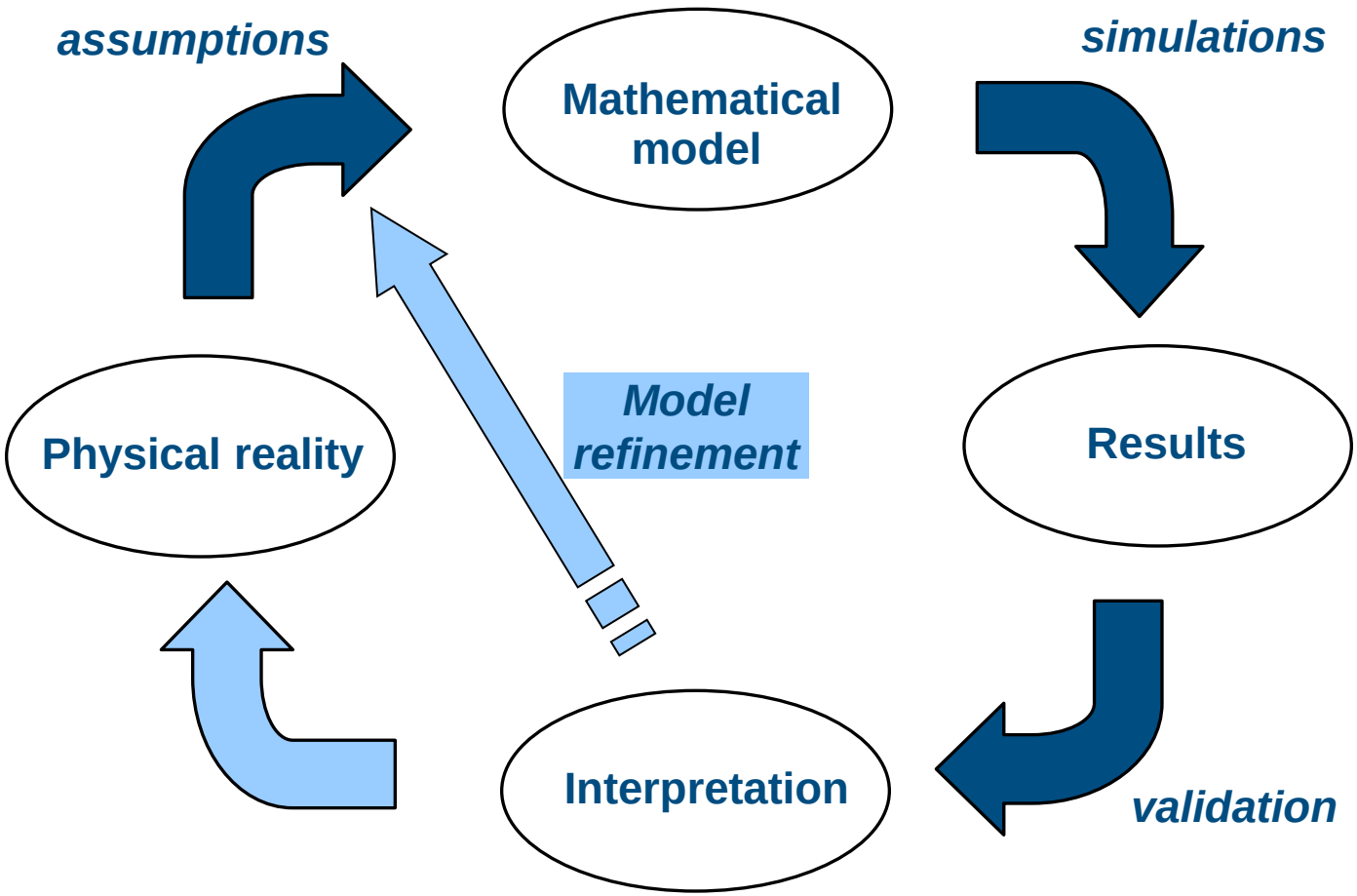
(de Leval et al., J Thorac Cardiovasc Surg, 113:502-13, 1996)

Numerical simulation for pediatric cardiac surgery:

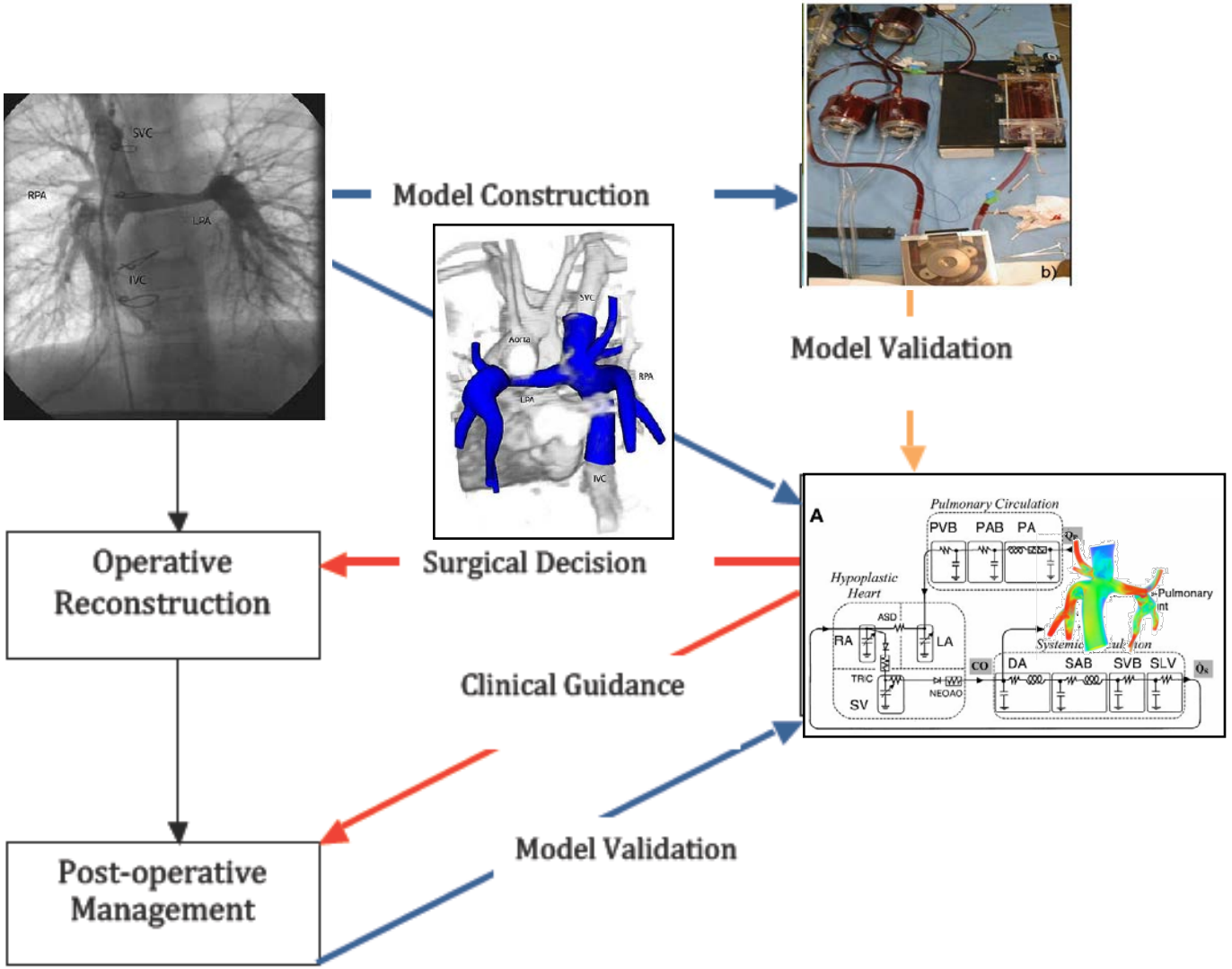
1. To investigate phenomena hardly measurable in the clinical setting
   - energy dissipation (recirculation areas, jets, etc.)
   - blood and oxygen flow distribution to organs
2. To optimize the surgery technique
3. To plan surgery

Multi-domain modelling approaches - 1

- observations
- data



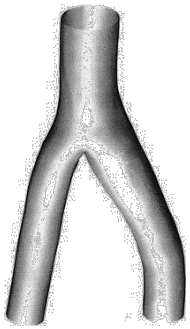
Multi-domain modelling approaches - 2

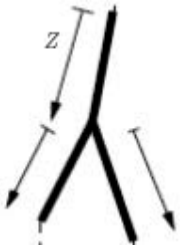


Multi-domain modelling approaches - 3

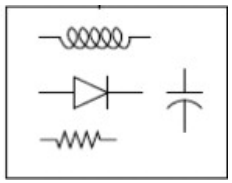
↘ Computational Fluid Dynamics (CFD)

3D 1D 0D





Z τ c



R L C

accuracy
CPU time

3D modelling
- local haemodynamics information
- rigid or deformable walls
- from idealized to patient-specific

1D modelling
- pulse wave propagation phenomena (curvature, branching, stenoses)
- rigid or elastic

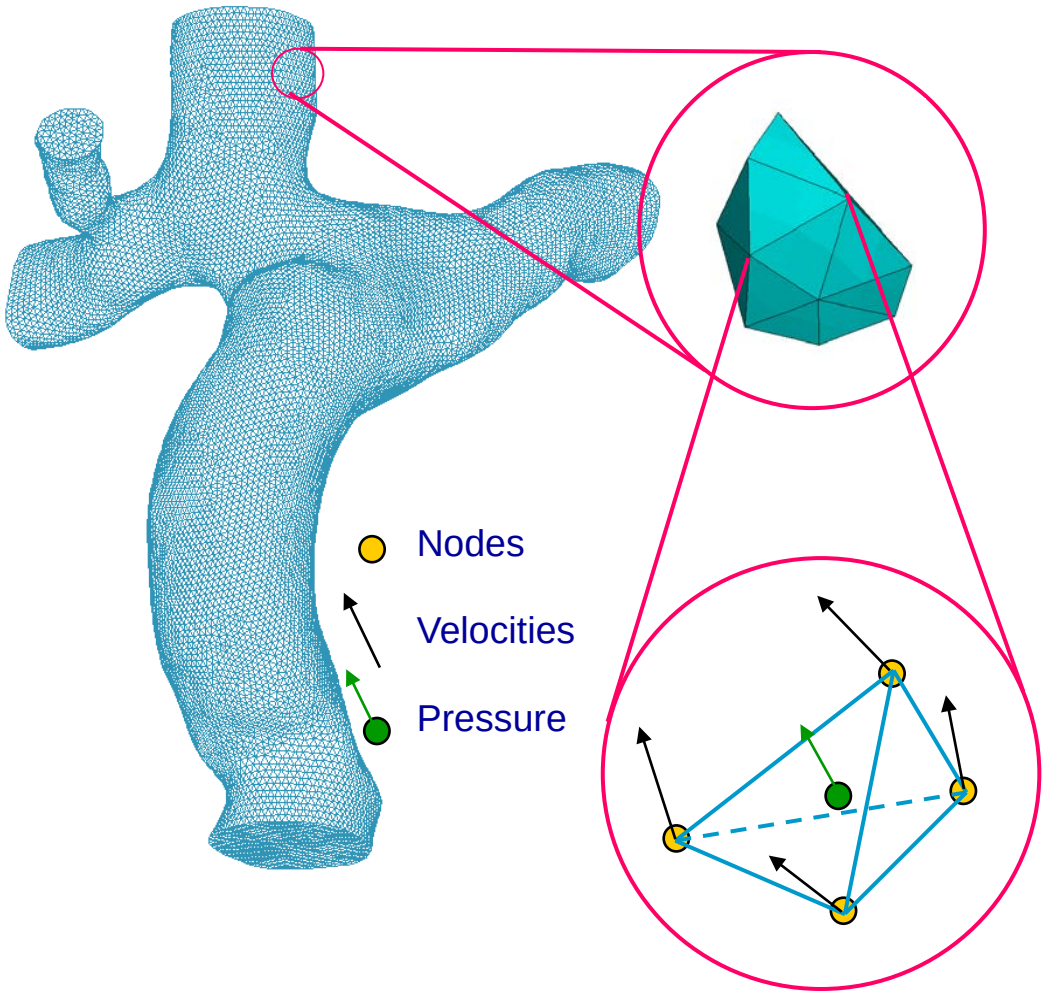
0D modelling (lumped parameter, LPM)
- more extensive circulatory networks
- fast-computing

Multi-domain modelling

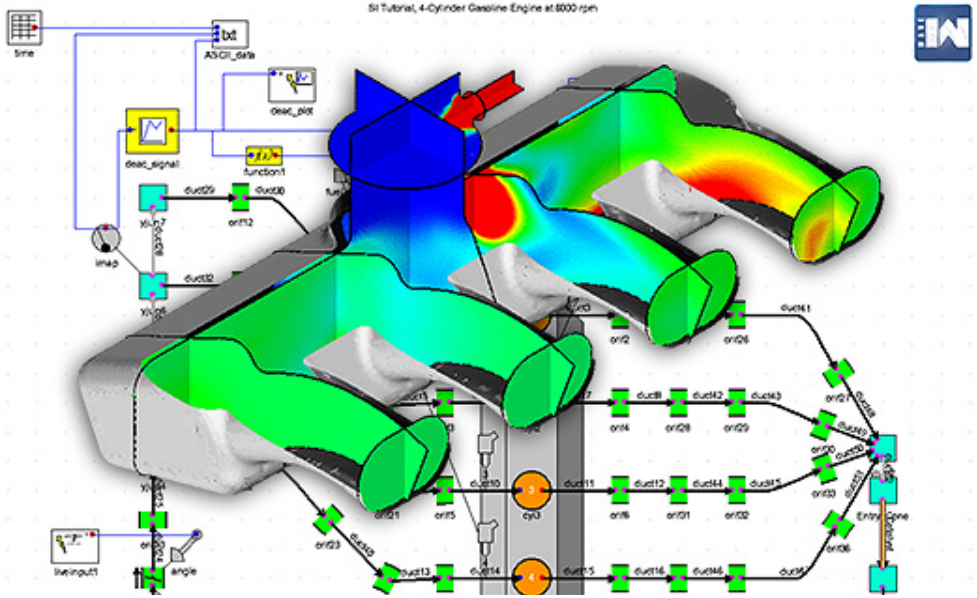
- coupling of 3D domain reproducing specific vascular portions (e.g. surgery site) with the downstream circulation described by LPM or 1D model
- **closed-loop** approach to account for the mutual interaction between the two domains.

Multi-domain modelling approaches - 4

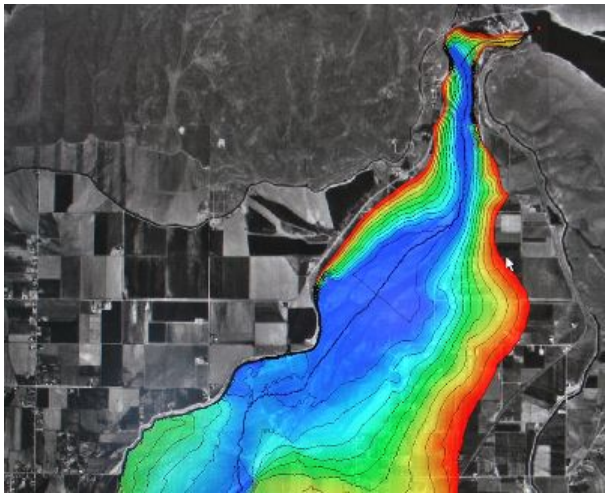
CFD allows an approximation of a real situation, dividing the physical problem domain (object) in smaller parts (elements or volumes) and solving each single part. If the division (mesh) is good, the results are an approximation, but very close to the reality.



Multi-domain models

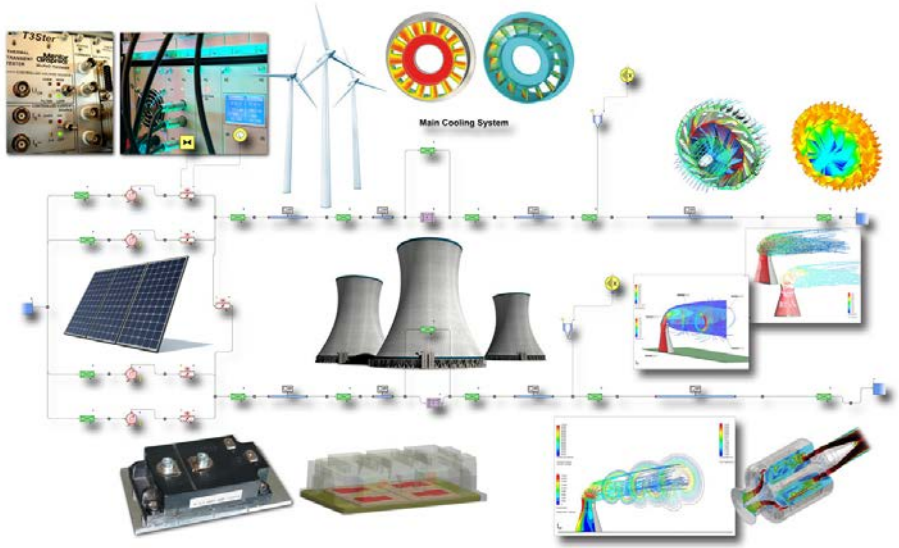


[from *http://www.ricardo.com/en-GB/What-we-do/Software/Products/VECTIS/Coupled-1D3D-Analysis/*]



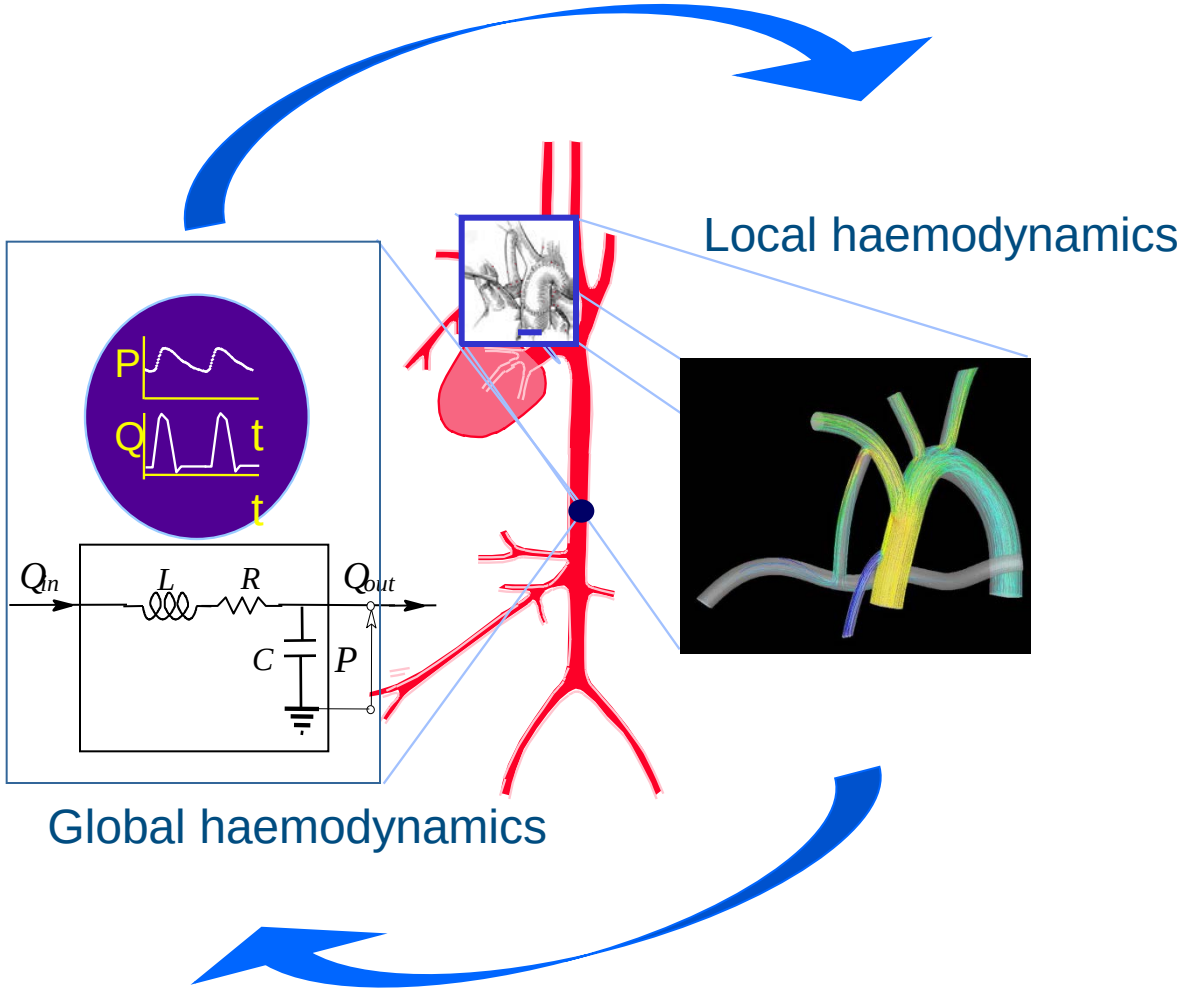
[from *http://xpsolutions.com/Software/XP2D/*]

Multi-domain model approach already in use in the automotive industry (e.g.intake and exhaust runners), environmental planning (e.g. impact of surface flooding on an existing sewer network), power generation industry (e.g. wind plant design), etc.

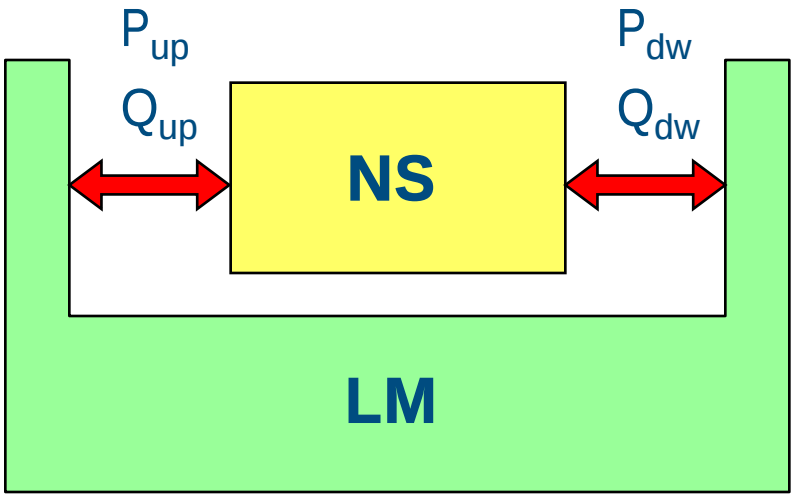


[from *http://www.mentor.com/products/mechanical/flowmaster/flowmaster-process-power-energy/*]

Multi-domain models



Partial differential equations (Navier-Stokes)

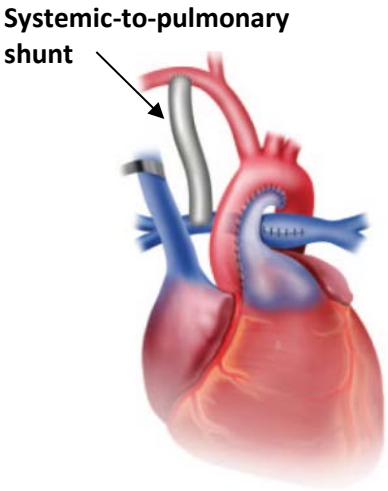


Ordinary differential equations (ODE)

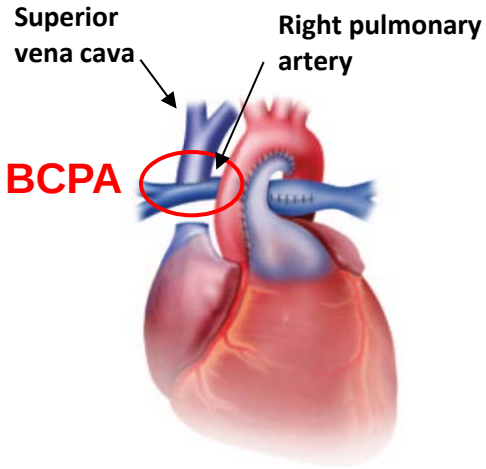
Quarteroni et al. "Coupling between lumped and distributed models for blood flow problems." Computing and Visual Science 4, 111-124, 2001.

Introduction: single-ventricle congenital heart diseases

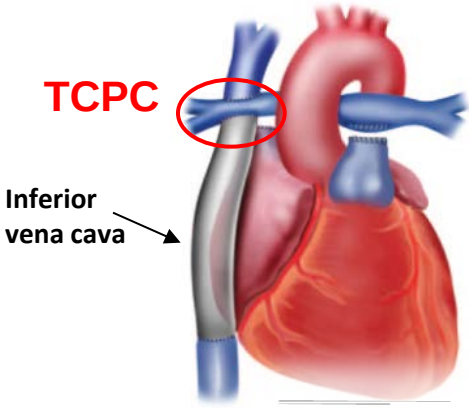
Stage 1



Stage 2



Stage 3



few days | 6 months | 3-5 years

Bidirectional Cavo-Pulmonary Anastomosis

Hemi-Fontan

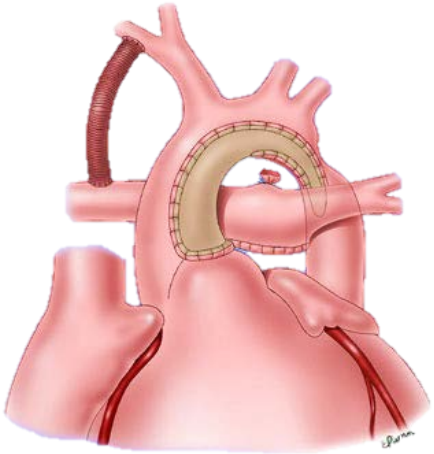
Total Cavo-Pulmonary Connection

Y-Graft – Lateral tunnel - ECC

Objective: virtual planning of different surgical options

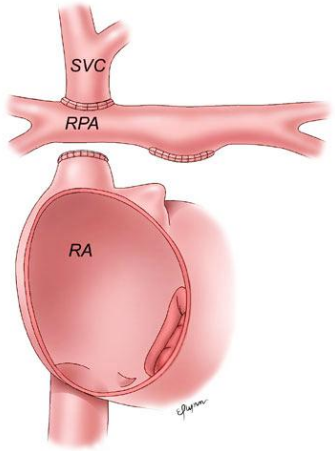
PRE-OPERATIVE

Stage 1

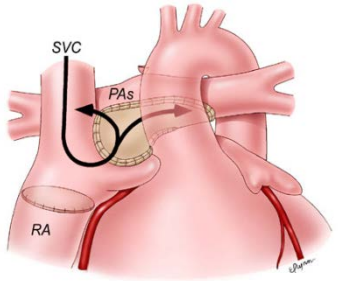


Stage 2 surgical options

POST-OPERATIVE



Glenn



Hemi-Fontan

www.childrenshospital.org

Steps of a **virtual surgical planning**:

- implementation of a **pre-operative computational model** to reproduce the hemodynamics of the patient
- comparison of **different surgical options** through CFD analysis.

WORKFLOW

- MR images
- Selected pressures and flows

Step 1

PRE-OPERATIVE CLINICAL DATA

- MRI images
- MRI, cath, echo-Doppler tracings

- 3D pre-op model
- Pre-op LPM

Step 2

PRE-OPERATIVE MODEL

- 3D reconstruction
- Pulmonary LPM
- Closed-loop LPM (systemic + pulmonary)

- Comparison
- Prediction

Step 3

POST-OPERATIVE MODEL

- 3D virtual surgery (different options)
- Closed-loop 3D-0D models

Step 4

SIMULATION AND VIRTUAL PLANNING

- Investigated fluid dynamic quantities
- Possible clinical scenarios

Fondation Leducq

WORKFLOW

- MR images
- Selected pressures and flows

Step 1

PRE-OPERATIVE CLINICAL DATA

MRI images

MRI, cath, echo-Doppler tracings

- 3D pre-op model
- Pre-op LPM

Step 2

PRE-OPERATIVE MODEL

3D reconstruction → Pulmonary LPM

Closed-loop LPM (systemic + pulmonary)

- Comparison
- Prediction

Step 3

POST-OPERATIVE MODEL

3D virtual surgery (different options)

Closed-loop 3D-0D models

Step 4

SIMULATION AND VIRTUAL PLANNING

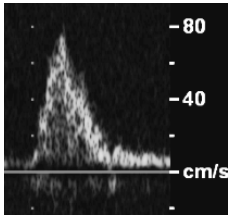
Investigated fluid dynamic quantities

Possible clinical scenarios

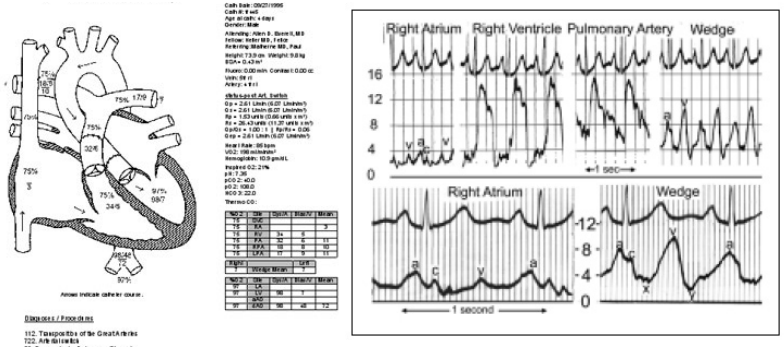
Fondation Leducq

STEP 1: Pre-operative clinical data

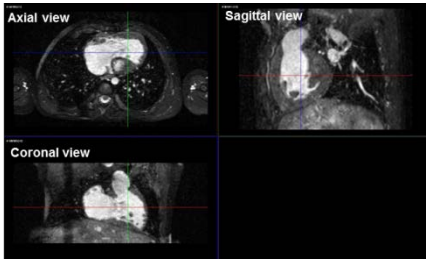
Doppler acquisition

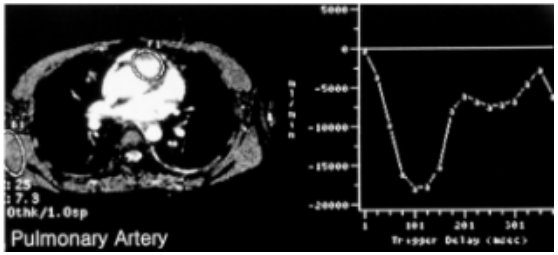


Catheterization

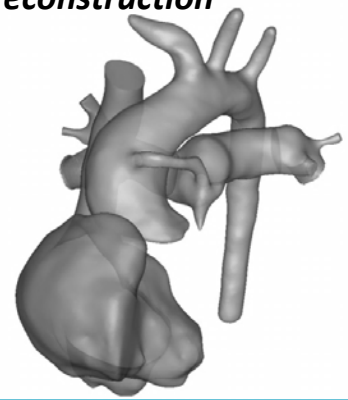


MR imaging and flows





Three-dimensional MR data reconstruction

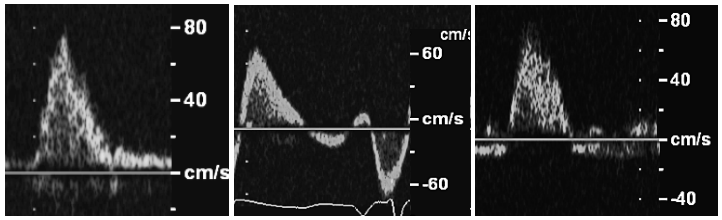


Fondation Leducq

STEP 1: Pre-operative clinical data

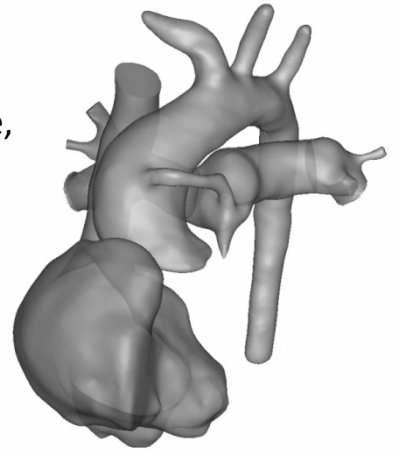
- ✓ 6 months-old infant (weight 6.9 kg, BSA 0.34 m^2)
- ✓ Hypoplastic right heart syndrome + pulmonary atresia
- ✓ 3.5 mm central shunt (from AoA to MPA) surgically placed on day of life #5

Doppler acquisition (5 weeks prior to surgery, under sedation)
Echocardiograpy system (iE33, Philips, Best, Netherlands)



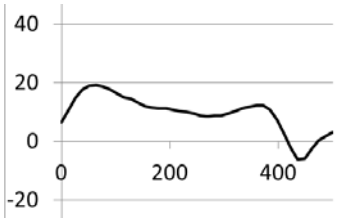
Catheterization (under sedation, 3 days before the surgery)
Biplane fluoroscopy suite (Toshiba America Med. Syst., Inc., CA, or Siemens Med. Solutions, USA, Inc. PA).

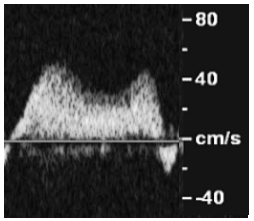
MR imaging (under general anesthesia immediately prior to surgery)
1.5 T scanner (Philips Intera Achieva, Best, Netherlands).
Imaging parameters: 4.4/2.3 (repetition time msec/echo time msec), 12° flip angle, 1.3–1.5-mm section thickness, 256 × 512 matrix, 400–500-mm field of view, one breath hold, one signal acquired, no electrocardiographic gating.

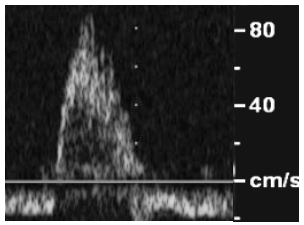


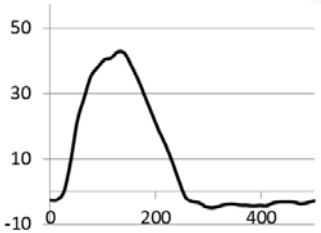
Three-dimensional MR data reconstruction
Mimics software (Materialise NV, Leuven, Belgium).
Image elaboration for each patient's MR data took 2–3 hours.

STEP 1: Pre-operative clinical MRI and Doppler flows



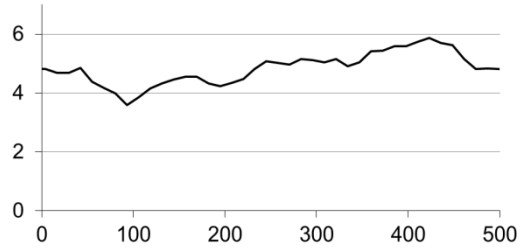




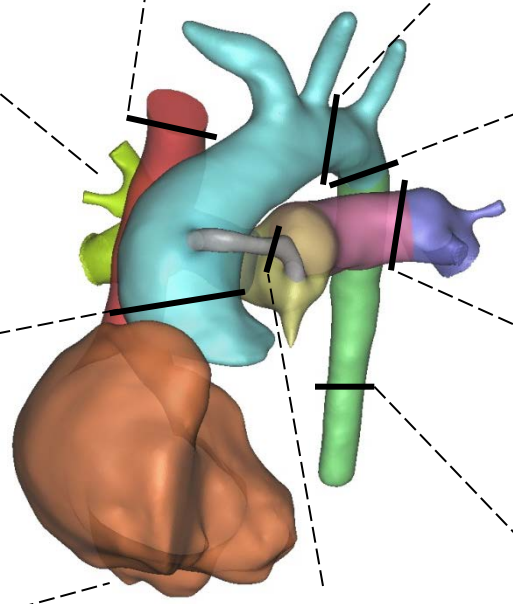


SVC

Transverse Ao



RPA



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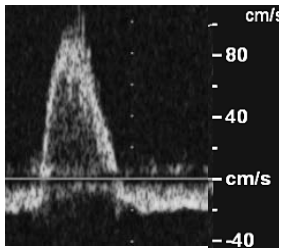
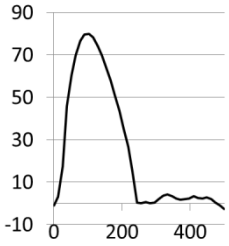
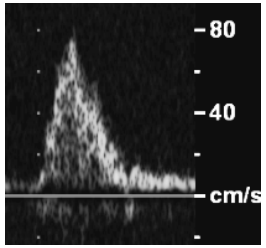
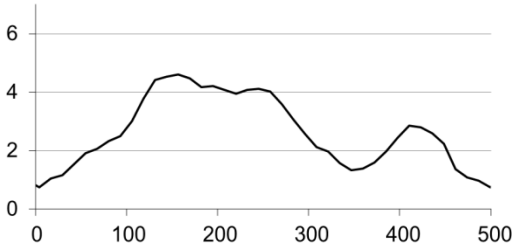


AoA





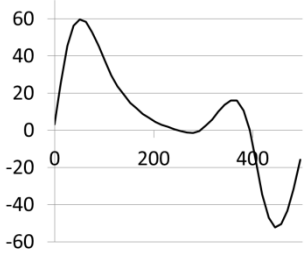
LPA

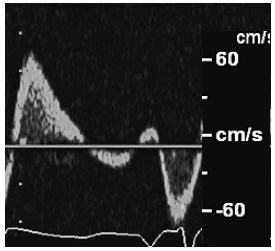


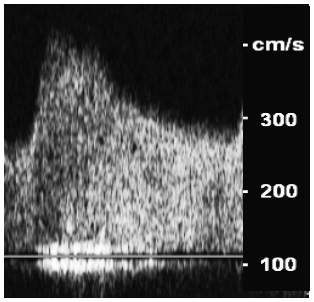
IVC

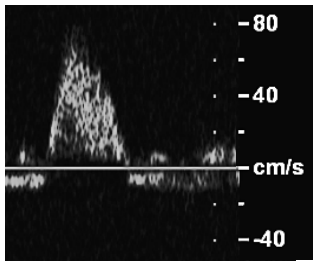
Shunt

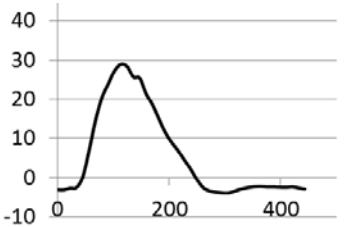
AoD





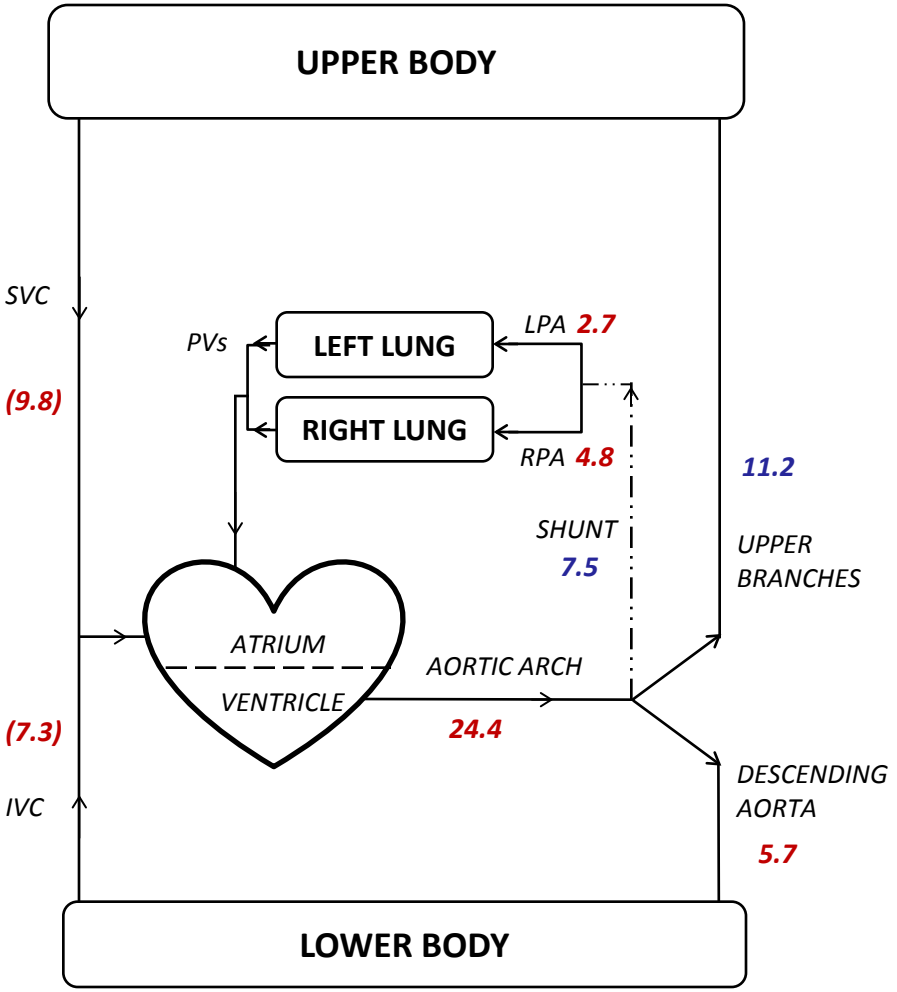






STEP 1: Pre-operative clinical data

[mmHg]	Pressures
P_{SV}	6 / 103 / 54
P_{SA}	5
P_{PA}	13
P_{SVC}	9
P_{DAo}	43
[ml]	**Volumes**
EDV	22.6
ESV	9.6



(MEASURED FLOWS – NOT USED)

MEASURED FLOWS [ml/s]

CALCULATED FLOWS

WORKFLOW

- MR images
- Selected pressures and flows

Step 1

PRE-OPERATIVE CLINICAL DATA

MRI images

MRI, cath, echo-Doppler tracings

- 3D pre-op model
- Pre-op LPM

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3D reconstruction → Pulmonary LPM

Closed-loop LPM
(systemic + pulmonary)

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Step 4

SIMULATION AND VIRTUAL PLANNING

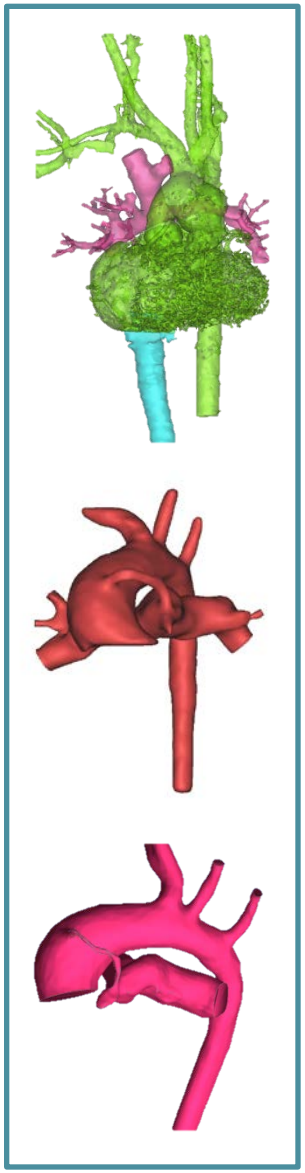
Investigated fluid dynamic quantities

Possible clinical scenarios

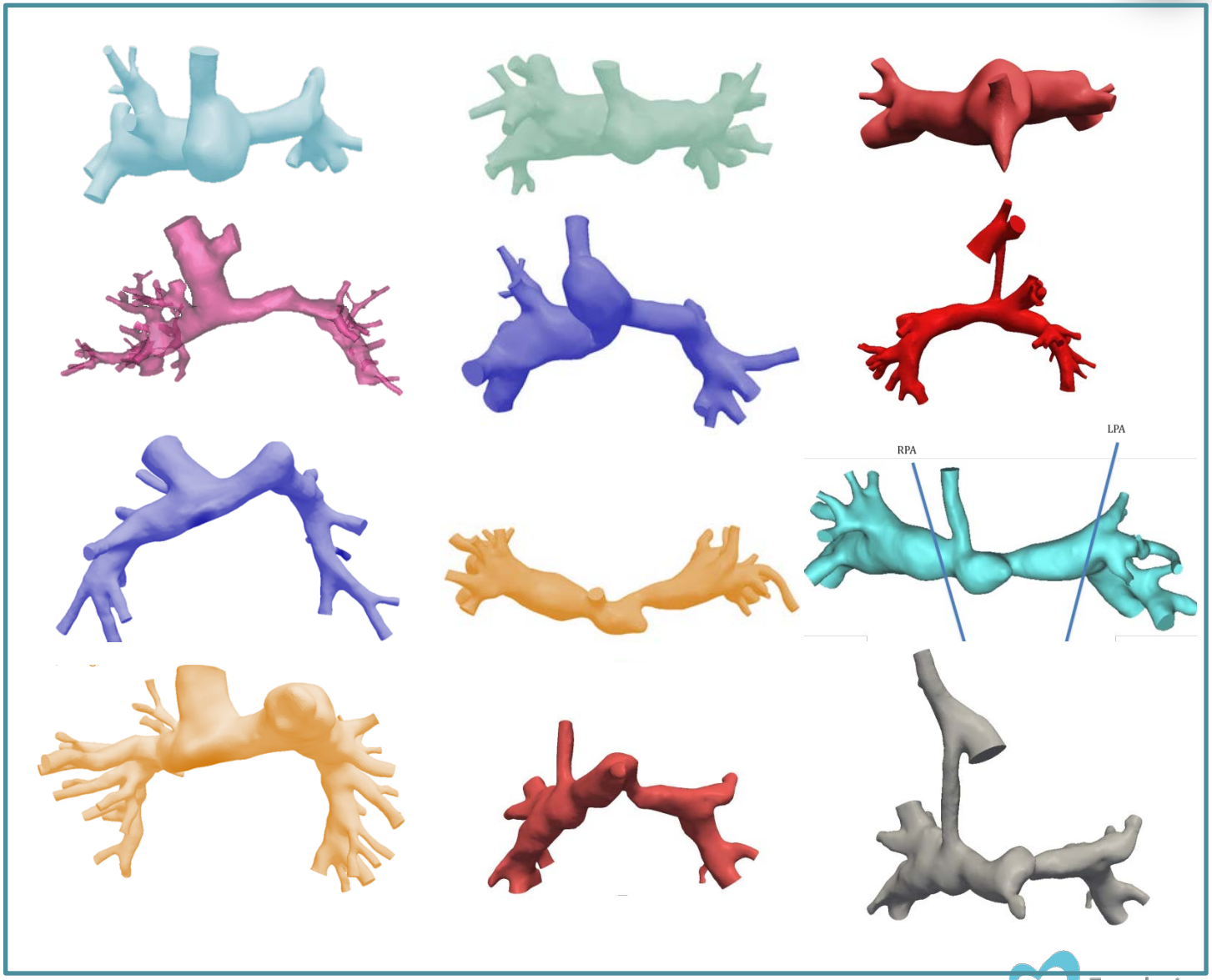
Fondation Leducq

STEP 2: Pre-operative 3D reconstruction

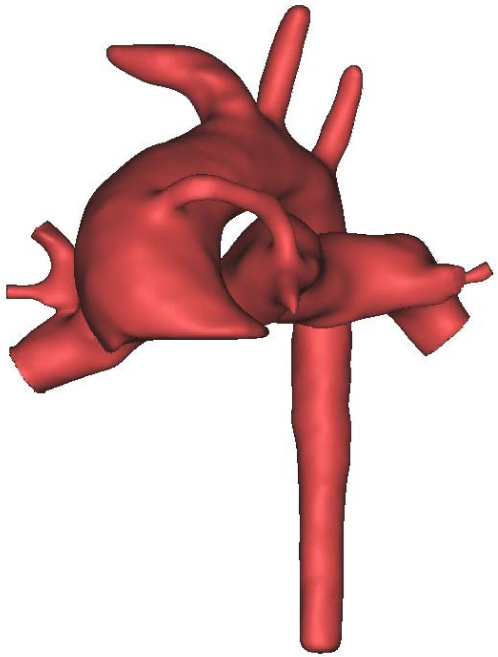
Whole geometry reconstruction



Selection of the sub-model of the pulmonary arterial vasculature



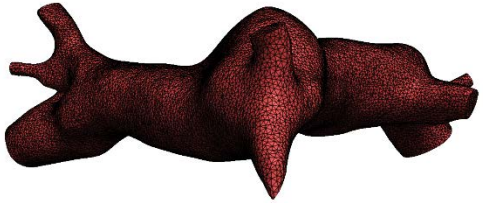
STEP 2: Pre-operative 3D reconstruction



Whole geometry reconstruction

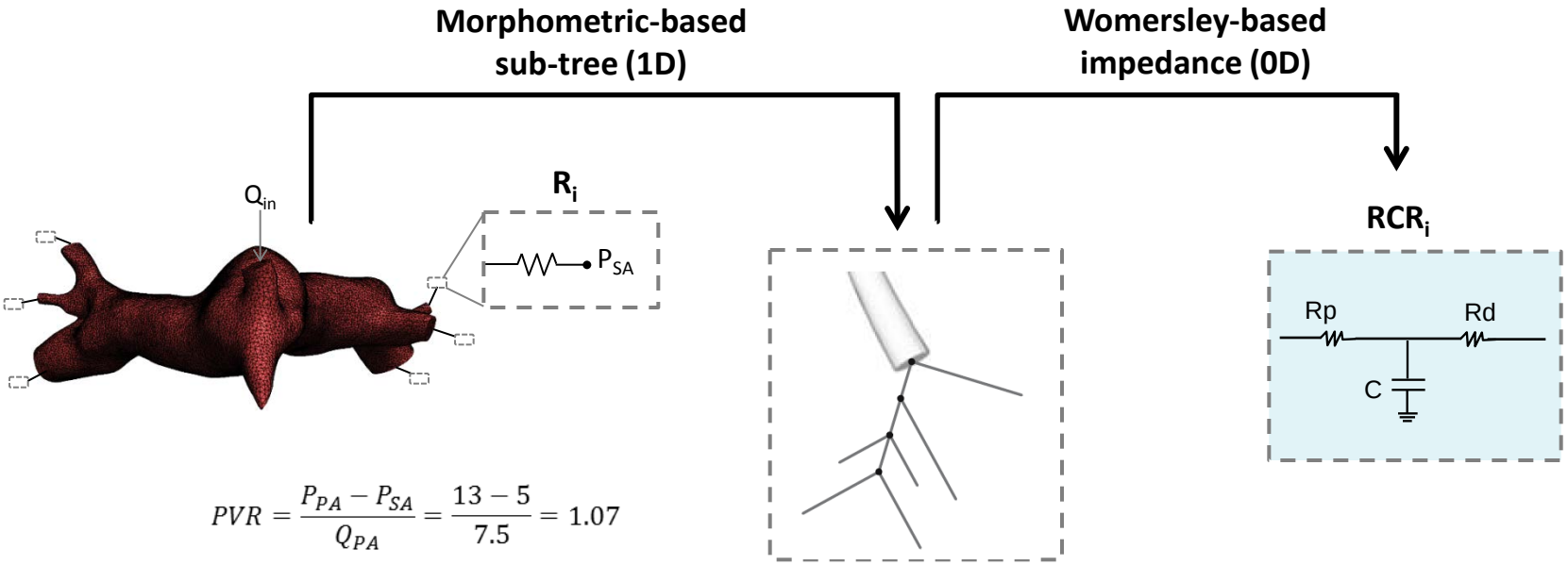
Selection of the sub-model of the pulmonary arterial vasculature

MESHSIM
(Simmetrix, Inc., NY)



Volume meshing

STEP 2: Pre-operative pulmonary LPM - morphometric approach

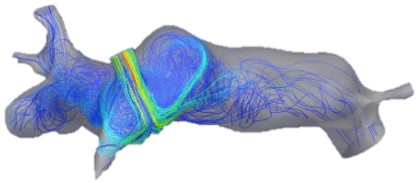


$$PVR = \frac{P_{PA} - P_{SA}}{Q_{PA}} = \frac{13 - 5}{7.5} = 1.07$$

R_i of each i-th outlet based on:
- inflow Q_{in}
- flow split between right and left lungs
- ΔP between 3D inlet and single atrium SA
- size of each outlet branch $Q_i \propto S_i{}^{\alpha}$

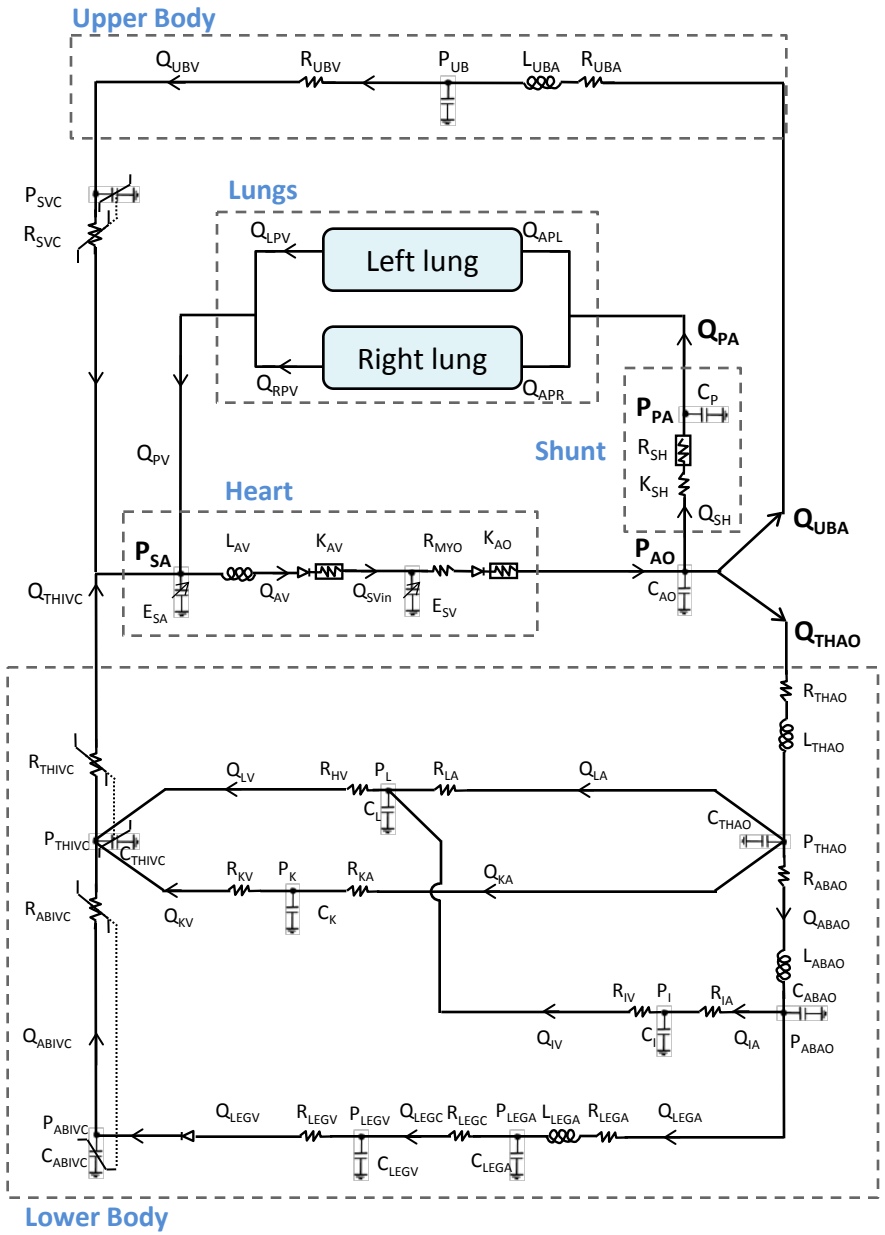
- The sub-tree with the impedance spectrum closest to R_i is selected.
- R_p, C, R_d are given by least-squares fit of the impedance spectrum

Iterative simulations until convergence



Troianowski et al., 2011 J. Biomech. Eng.
Spilker et al., 2007 Ann. Biomed. Eng.

STEP 2: Pre-operative closed-loop LPM



Setting of the parameters

- HR = 120 bpm
- BSA = 0.34 m^2
- Vascular resistances *[mmHg*s/ml]*

$$UBSVR = \frac{P_{Ao} - P_{SA}}{Q_{UBA}} = \frac{43 - 5}{11.2} = 3.39$$

$$LBSVR = \frac{P_{Ao} - P_{SA}}{Q_{THAO}} = \frac{43 - 5}{5.7} = 6.67$$

- Pulmonary RCRs provided by morphometric approach

- Shunt

  Operating point: dP= 43-13 = 30 mmHg, Q_{SH} = 7.5ml/s

  Relation: $dP = R_{SH}Q_{SH} + K_{SH}Q_{SH}^2$

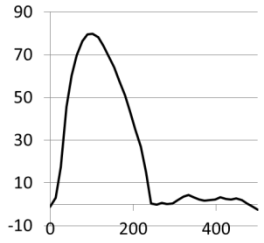
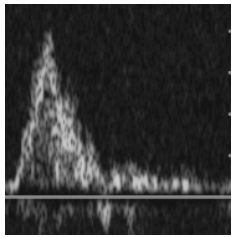
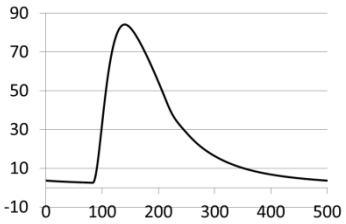
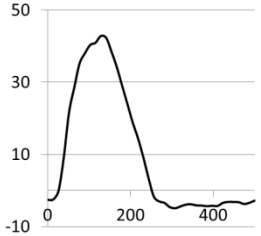
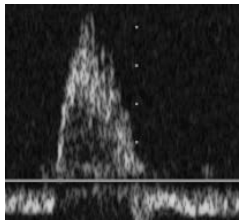
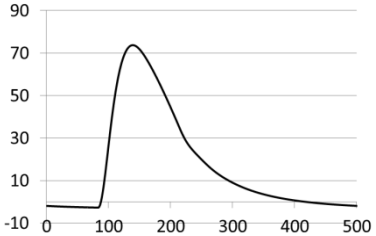
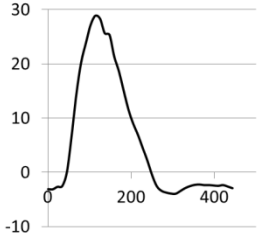
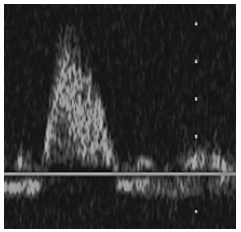
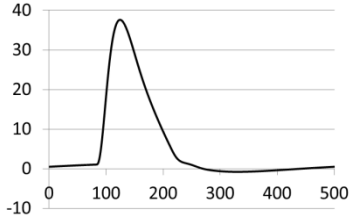
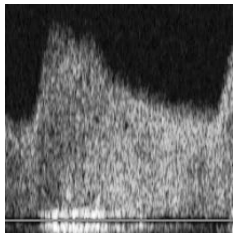
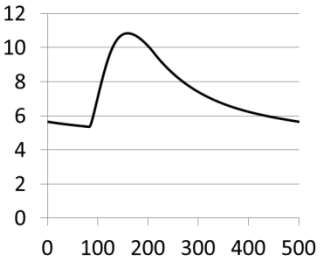
Migliavacca et al., 2001, Am J Physiol Heart Circ Physiol

- Respiratory effects were not included

- Single values of resistance and compliance vary depending on the BSA

Snyder, Rideout, 1969, IEEE Trans Bio-Med Eng

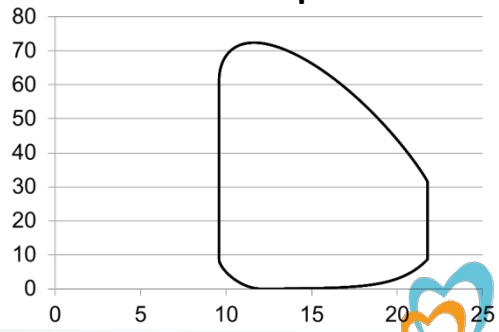
STEP 2: Pre-operative closed-loop LPM - Results

	MRI	DOPPLER	LPM
A.Ao			
TransAo			
D.Ao			
Shunt			

[ml/s]	Clinical mean values	LPM
Q_{UB}	11.2	11.3
Q_{LB}	5.7	5.7
Q_{LPA}	2.7	2.8
Q_{RPA}	4.8	4.8
CO	24.4	24.4

[mmHg]	Reference clinical data	LPM
P_{SV}	6 / 103 / 54	0 / 72 / 25
P_{SA}	5	6.8
P_{PA}	13	14.7
P_{SVC}	9	7.9
P_{DAo}	43	43.8
[ml]	**Clinical mean values**	**LPM**
EDV	22.6	21.8
ESV	9.6	9.6

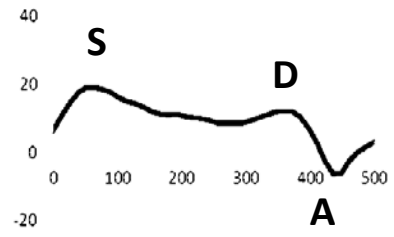
PV Loop

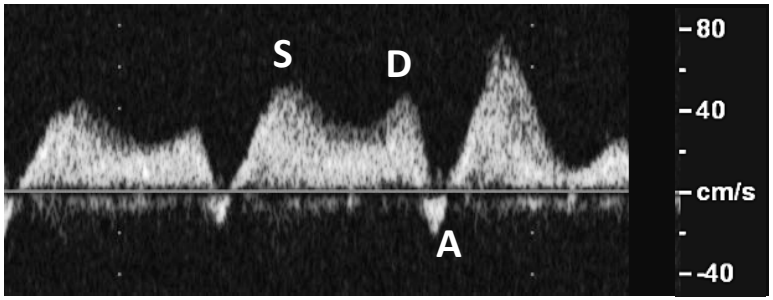


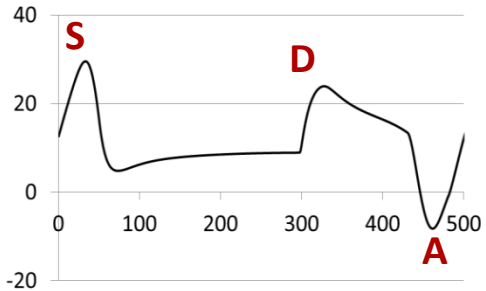
STEP 2: Pre-operative closed-loop LPM - Results

MRI **DOPPLER** **LPM**

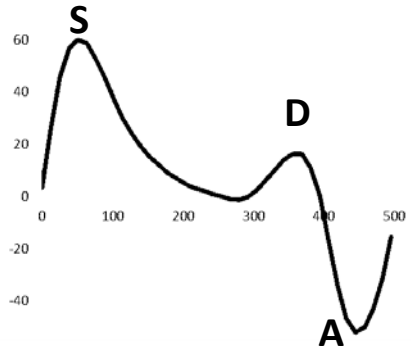
SVC

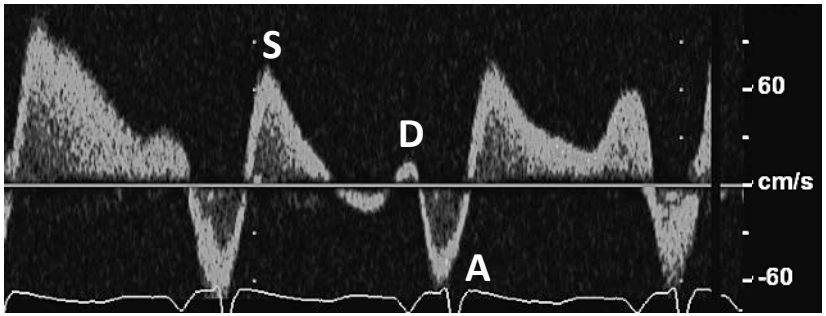


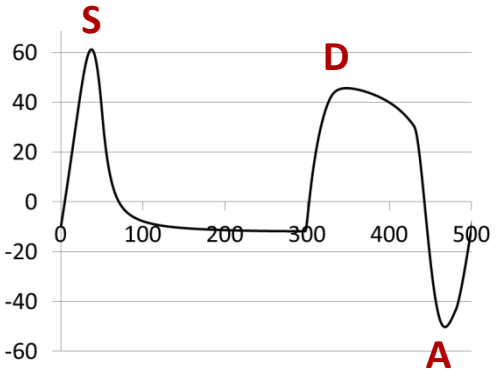




IVC

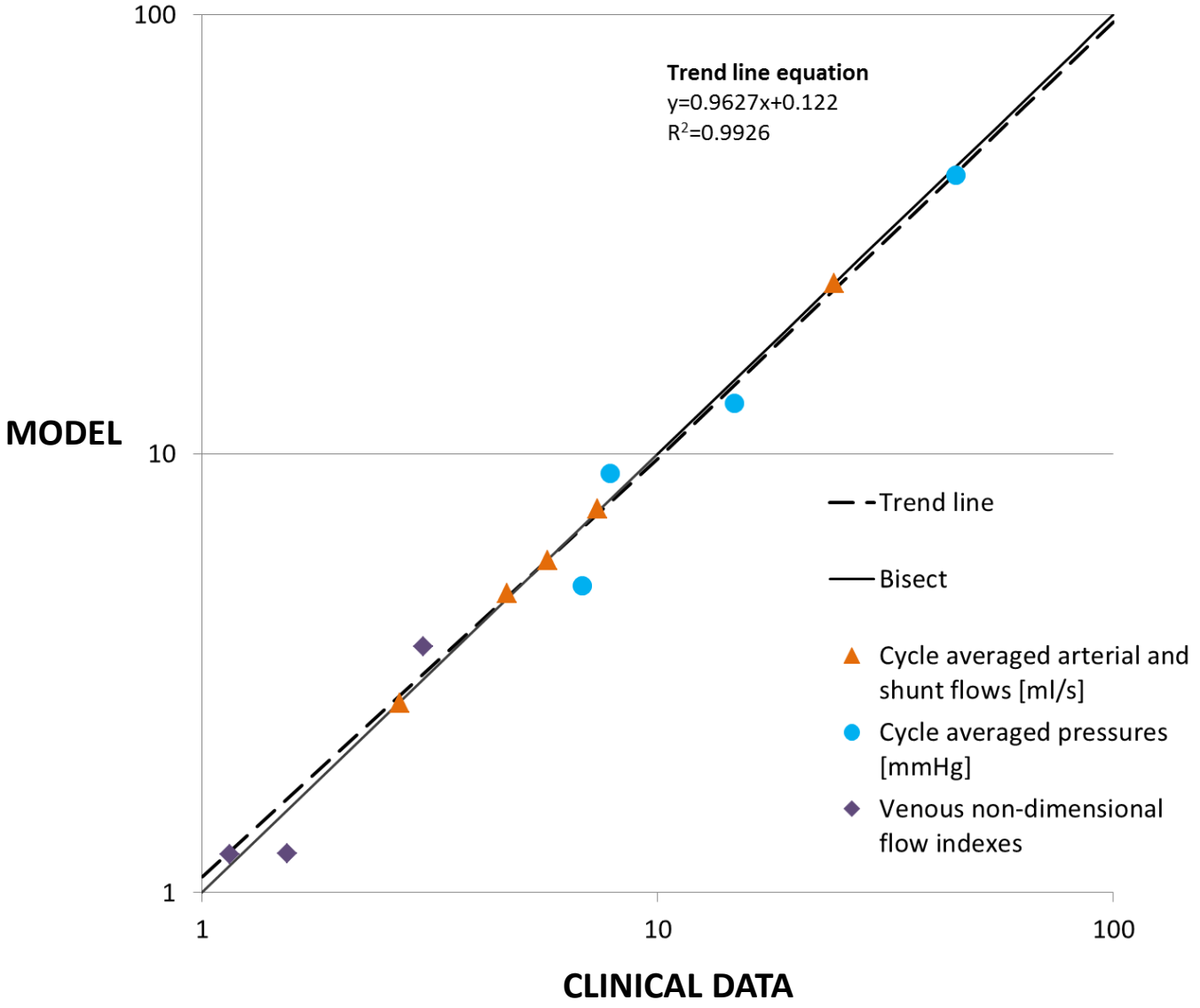






	MRI	LPM
S/D SVC	1,54	1,49
S/A SVC	-3,06	-3,05
S/D IVC	3,75	2,33
S/A IVC	-1,15	-0,95

STEP 2: Pre-operative closed-loop LPM - Results



WORKFLOW

- MR images
- Selected pressures and flows

Step 1

PRE-OPERATIVE CLINICAL DATA

MRI images

MRI, cath, echo-Doppler tracings

- 3D pre-op model
- Pre-op LPM

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PRE-OPERATIVE MODEL

3D reconstruction → Pulmonary LPM

Closed-loop LPM (systemic + pulmonary)

- Comparison
- Prediction

Step 3

POST-OPERATIVE MODEL

3D virtual surgery (different options)

Closed-loop 3D-0D models

Step 4

SIMULATION AND VIRTUAL PLANNING

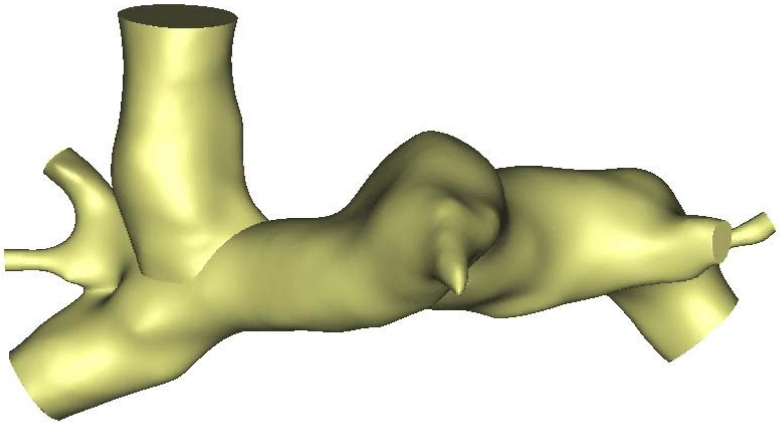
Investigated fluid dynamic quantities

Possible clinical scenarios

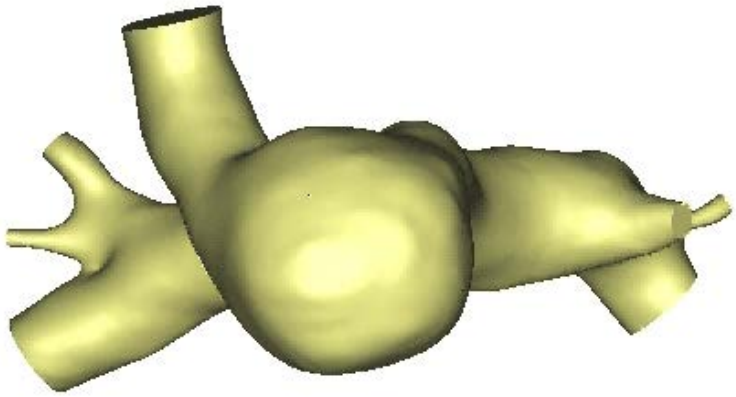
Fondation Leducq

STEP 3: Post-operative model – 3D virtual surgery

Different options:

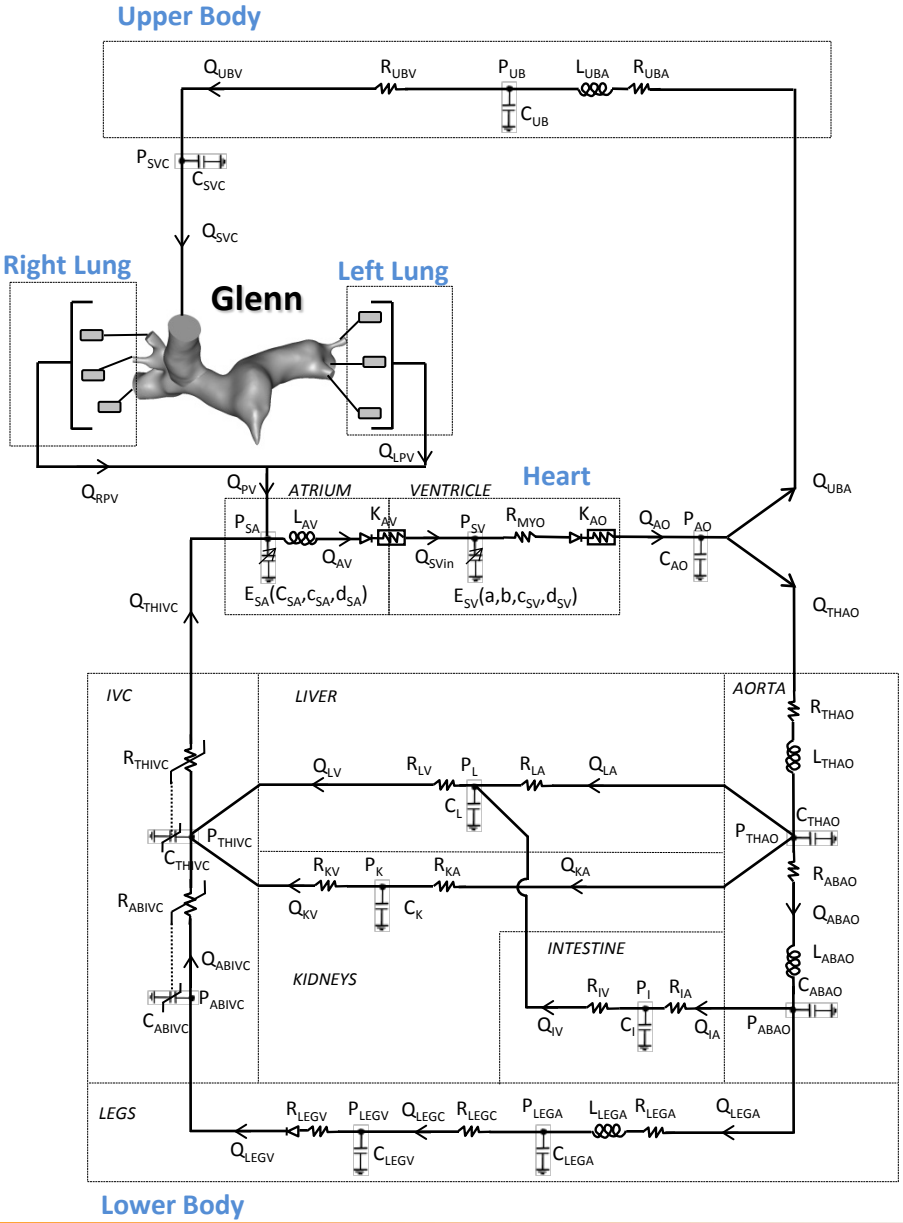


Glenn

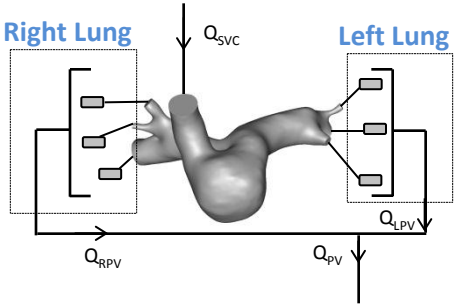


hemi-Fontan

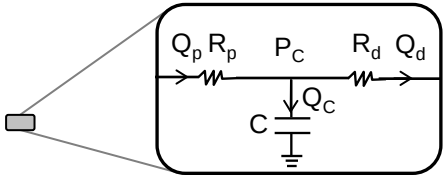
STEP 3: Post-operative model – closed-loop 3D-0D models



Hemi-Fontan



Pulmonary RCR blocks



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- Selected pressures and flows

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MRI, cath, echo-Doppler tracings

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- Pre-op LPM

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- Prediction

Step 3

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3D virtual surgery (different options)

Closed-loop 3D-0D models

Step 4

SIMULATION AND VIRTUAL PLANNING

Investigated fluid dynamic quantities

Possible clinical scenarios

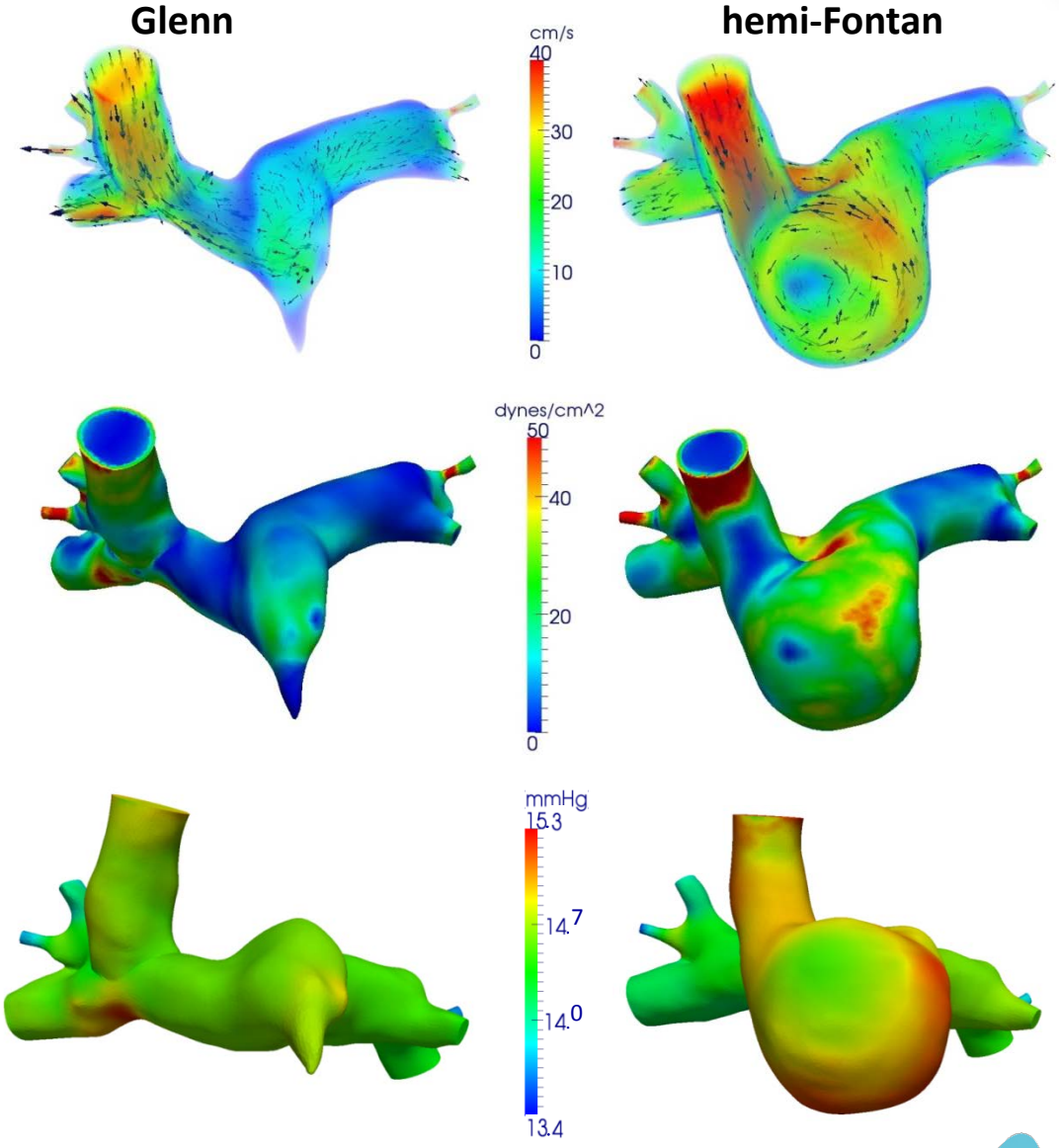
Fondation Leducq

STEP 3: Post-operative model – Simulation results

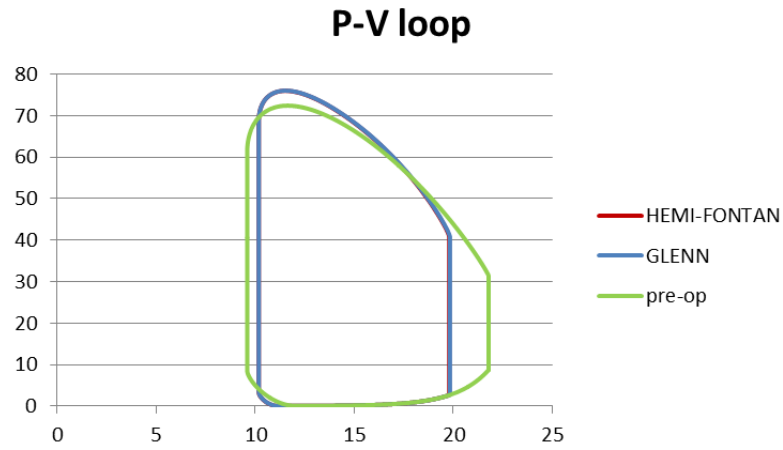
Velocities at peak flow

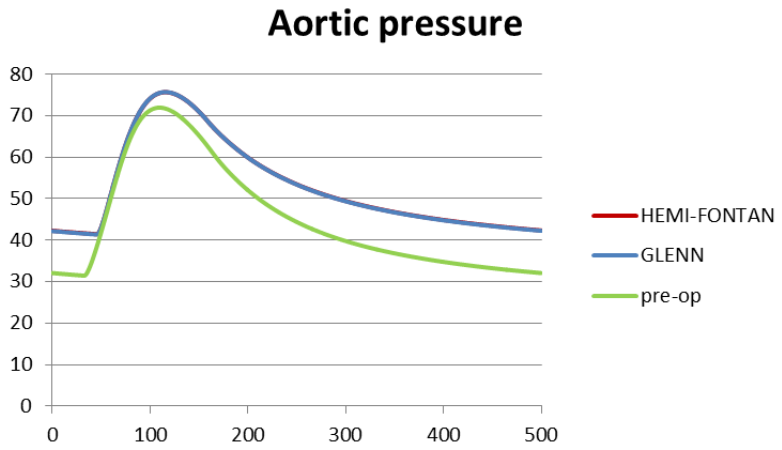
Time-averaged wall shear stress (WSS)

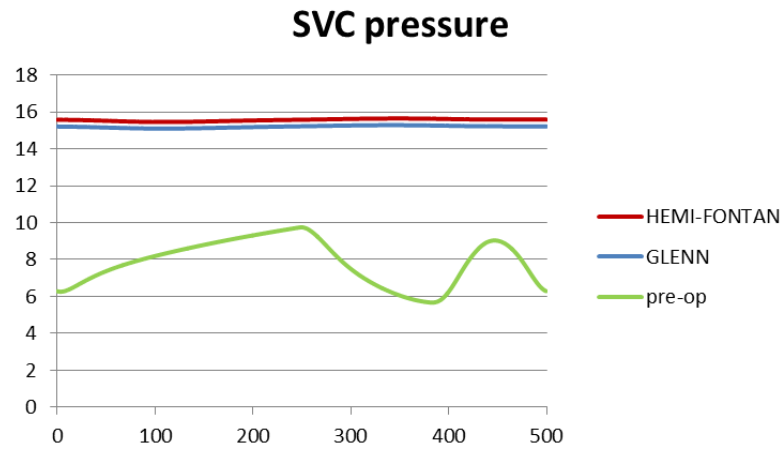
Time-averaged pressures

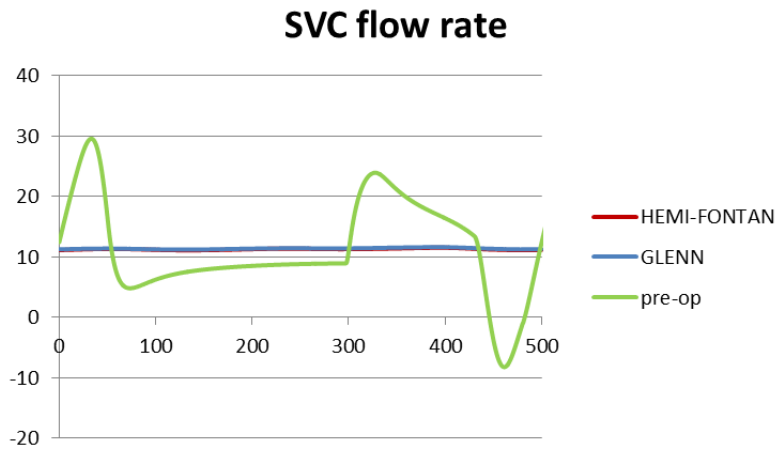


STEP 3: Post-operative model – Simulation results









STEP 3: Post-operative model – Simulation results

Investigated fluid dynamic quantities	Glenn	Hemi-Fontan
Q_{SVC} (ml/s)	11.4	11.3
Q_{IVC} (ml/s)	7.87	7.89
Q_{LPA} (ml/s)	4.17	4.21
Q_{RPA} (ml/s)	7.21	7.07
P_{SVC} (mmHg)	15.1	15.4
P_{Ao} (mmHg)	53.1	53.1
P_{SA} (mmHg)	2.48	2.43
Power Loss-- Surgical Junction (mW)	0.61	1.26
Efficiency-- Surgical Junction	0.97	0.95
Ventricular power (mW)	166	166

Fondation Leducq

Conclusions

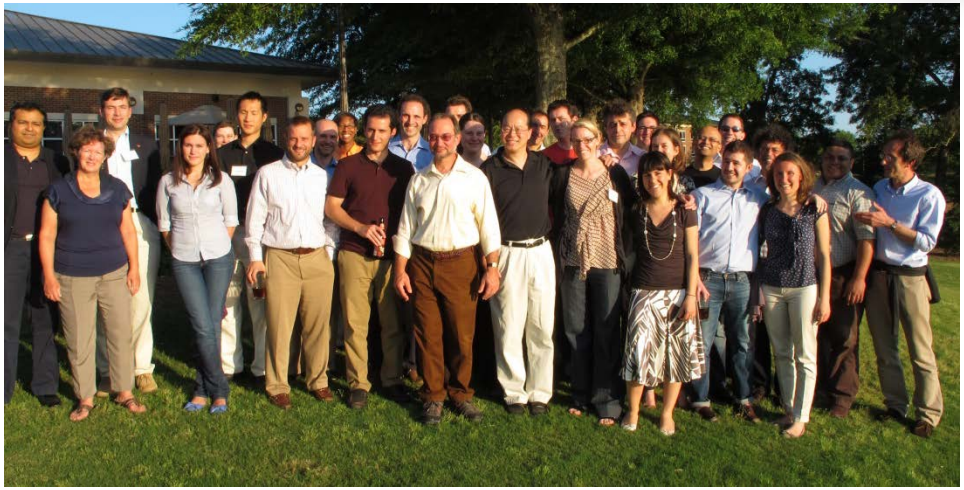
The workflow

- constant interactions among clinicians and engineers to:
  - collect the patient's clinical data
  - select the data to be used in the modeling process
  - build a preoperative patient-specific model that reproduced the patient
  - simulate different postoperative surgical options
  - compare the local and global hemodynamic results

Not shown

- Different postoperative scenarios (e.g. agitation, exercise) have been simulated

Acknowledgements



Great Ormond Street Hospital for Children, London, UK

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UCSD, CA, USA

INRIA Paris-Rocquencourt, Le Chesnay, France

UCL Institute of Cardiovascular Science, London, UK

University of Michigan, Ann Arbor, MI, USA

Medical University of South Carolina, Charleston, SC, USA

Stanford University, Stanford, CA, USA

"Multi-scale Modeling of Single Ventricle Hearts for Clinical Decision Support" Transatlantic Project

http://modelingventricle.clemson.edu

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