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XXXIV Cycle

Reduced Order Modeling for Characterization of Patient-Specific Coronary Artery Bypass Grafts

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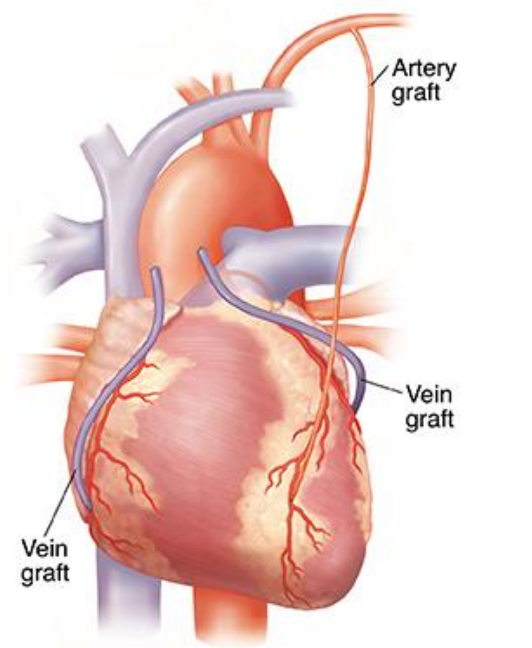
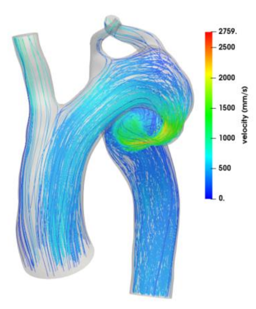
Research context and motivation

- **Cardiovascular disease** is one of the most diffused causes of mortality worldwide (31% of global deaths). A major role is played by **Coronary Artery Disease** (CAD): the vessels supplying oxygenated blood to the heart become occluded, and this can lead to heart failure.
- The most common surgical treatment for CAD is **coronary artery bypass grafting (CABG)**: new paths are created across occluded region.
- Grafts tend to fail some years after surgery (**up to 60%**), and the causes of such **failure** are still unknown.



Addressed research questions/problems

- Use **computational models** based on **Computational Fluid Dynamics (CFD) simulations**, which solve numerically **Navier-Stokes equations**.



information on **pressure** and **velocity** → intimal thickening **CABG failure**

- Advanced CFD models are coupled with information coming from sophisticated **imaging techniques** (e.g. CT, 4D-flow MRI) to obtain patient-specific cardiovascular models.

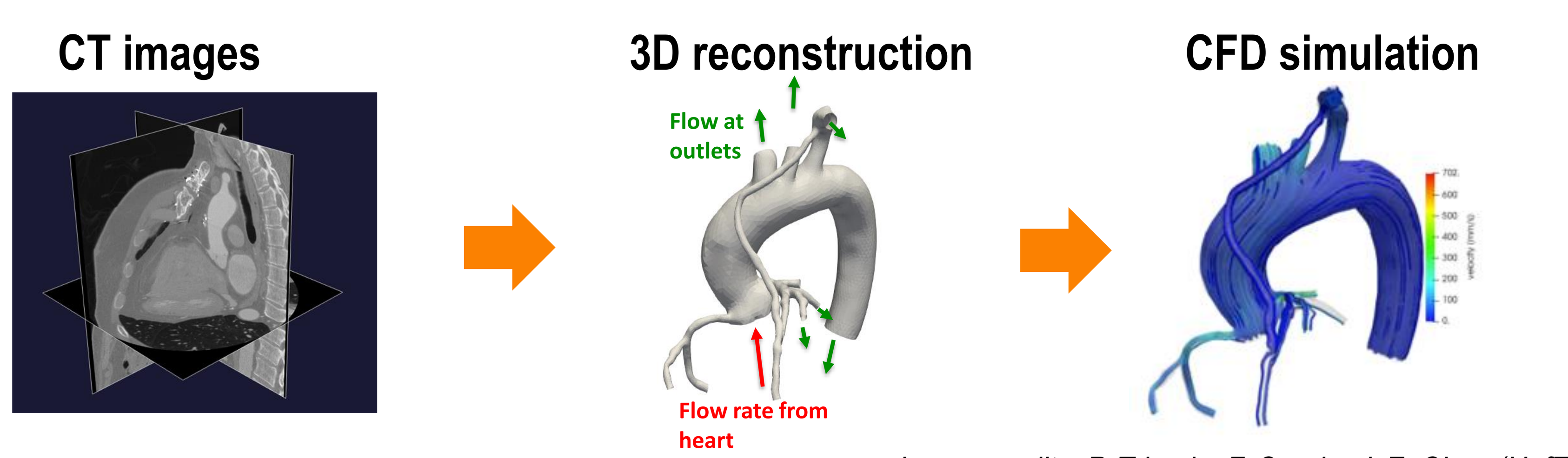


Image credits: P. Triverio, F. Condemi, Z. Chen (UofT)

The proposed approach brings many challenges:

- **Computational time:** patient-specific simulations are extremely complex and computationally expensive, so the use of novel **Model Order Reduction** techniques can help reducing computational time and resources.
- **Uncertainty:** the phenomena under modeling are complex and multiphysics, so they must be validated against patients measurements.
- **Boundary conditions:** accurate CFD simulations can be obtained only imposing correct boundary conditions, which are patient-specific.

Sunnybrook HEALTH SCIENCES CENTRE — UNIVERSITY OF TORONTO — SISSA

List of attended classes

- 01LCPRV – Experimental modeling: costruzione di modelli da dati sperimentali (08/04/2019, 6 CFU)
- 01TEPRT – Multiscale mathematical modeling in engineering, biology and medicine (25/02/2019, 5 CFU)
- 01TCORV – Surrogate and compact modeling: theory for the user (12/07/2019, 4 CFU)
- 01QRQRV – Compressed sensing: theory and applications (04/09/2019, 4 CFU)
- 01MMRRV – Advanced computational electromagnetics for antenna analysis and design (14/03/2019, 4 CFU)
- 02LWHRV – Communication (18/01/2019, 1 CFU)
- 01RNBRV – Communication II (03/05/2019, 2 CFU)
- 01RNCRV – Public Speaking (17/01/2019, 1 CFU)
- 01SYBRV – Research Integrity (05/09/2019, 1 CFU)
- 01SWPRV – Time Management (18/01/2019, 1 CFU)
- Reduced Order Models in Computational Fluid Dynamics, Summer School held at SISSA, Trieste, Italy (12/07/2019, 36 hours)
- Reduced Order Methods for Computational Mechanics, PhD course, SISSA, Trieste, Italy (06/05/2019, 21 hours)

Novel contributions

- **Patient-specific data assimilation:** merge observed information coming from intraoperative measurements and imaging into a CFD numerical model.
- **Optimal control** for automated selection of outflow boundary conditions in the form of Lumped Parameter Networks (LPN), to minimize misfit between clinical data and numerical results.
- Direct **validation** of developed framework on a cohort of **> 25** patients (largest study ever performed).

Adopted methodologies

- **Parameterized optimal control problem,** constrained by Navier-Stokes equations:

$$\textit{Given } \mu \in D, \textit{ find optimal pair } \big(v(\mu), p(\mu), u(\mu)\big) \in V \times P \times U \textit{ such that:}$$

$$\min J(v,p,u,\mu) = \frac{1}{2}\|v - v_d\|_V^2 + \frac{\alpha}{2}\|u(\mu)\|_U^2 \quad \textit{subject to}$$

$$\begin{cases} -\eta\Delta v(\mu) + (v(\mu)\cdot\nabla)v(\mu) + \nabla p(\mu) = 0 & \textit{in } \Omega \\ \nabla\cdot v(\mu) = 0 & \textit{in } \Omega \\ v(\mu) = v_{in}(\mu) & \textit{on } \Gamma_{in} \\ v(\mu) = 0 & \textit{on } \Gamma_w \\ \eta\nabla v(\mu)\cdot n - p(\mu)n = u(\mu) & \textit{on } \Gamma_o \end{cases}$$

- **Reduced Basis Methods:** projection based ROM methods for exploring solutions in a low dimensional manifold (**POD-Galerkin**).
- **Geometrical reconstruction** of blood vessels from clinical images (based on VMTK).
- Exploit analogies with **electronic domain:**
  - ❖ Represent vessel network as its equivalent LPN model;
  - ❖ Impose LPN as boundary conditions.

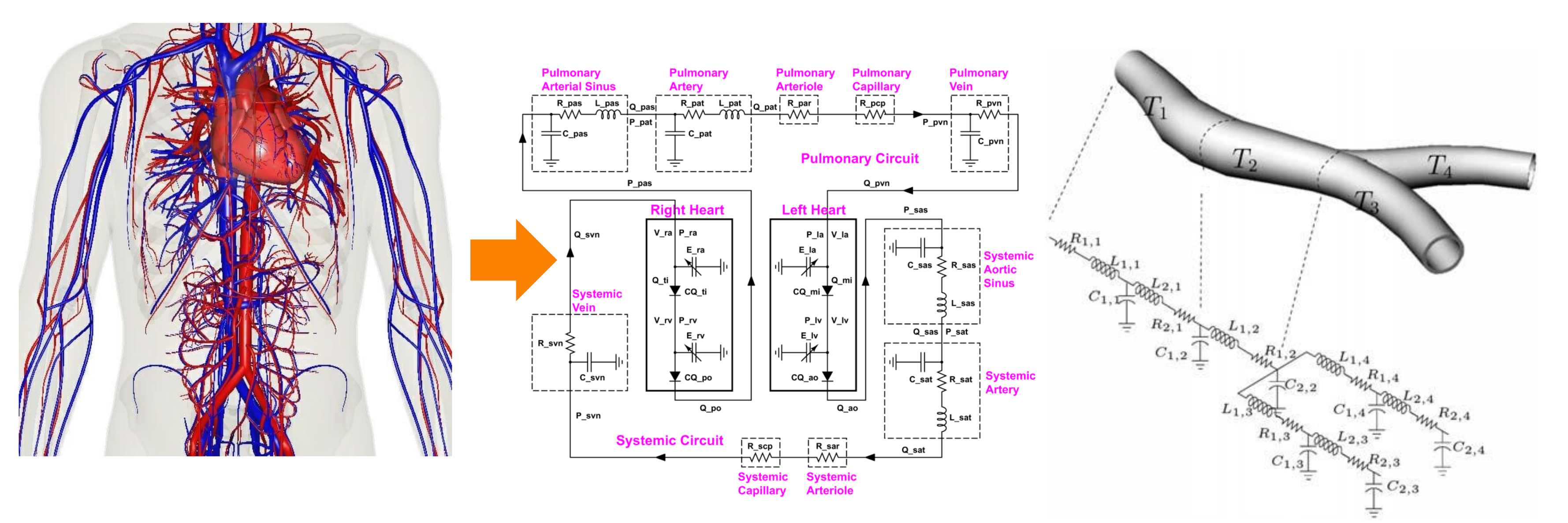


Image credits: L. Formaggia et al, "Cardiovascular Mathematics", Springer, 2009

Future work

- Integration of the optimal control framework with patient-specific geometries.
- Analyze correlation of results obtained from CFD models with measurements taken on patients one year after surgery.
- Uncertainty estimation for new LPN boundary conditions.

External research activity

- 09/09/2019 – ongoing: external research activity at SISSA (International School for Advanced Studies), Trieste, Italy, MathLab group, under the supervision of prof. Gianluigi Rozza.

Submitted and published works

- Fevola E., Zanco A., Grivet-Talocia S., Bradde T. and De Stefano M., "*An Adaptive Sampling Process for Automated Multivariate Macromodeling Based on Hamiltonian-Based Passivity Metrics*", IEEE Transactions on Components, Packaging and Manufacturing Technology, 2019, Early Access.
- Fevola E., Zanco A., Grivet-Talocia S., Bradde T. and De Stefano M., "*An Adaptive Algorithm for Fully Automated Extraction of Passive Parameterized Macromodels*", IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, Cambridge, MA, USA, May 29-31 2019.
- Fevola E., Zanco A., Grivet-Talocia S., Bradde T. and De Stefano M., "*A 3D Passivity-Based Adaptive Algorithm for Automated Parameterized Macromodeling of Electromagnetic Structures*", International Conference on Electromagnetics in Advanced Applications, Granada, ES, September 9-13 2019.

POLITECNICO DI TORINO

PhD program in
Electrical, Electronics and Communications Engineering