ATLAS-BASED FAST PATIENT-SPECIFIC SIMULATIONS OF THE PULMONARY ARTERY

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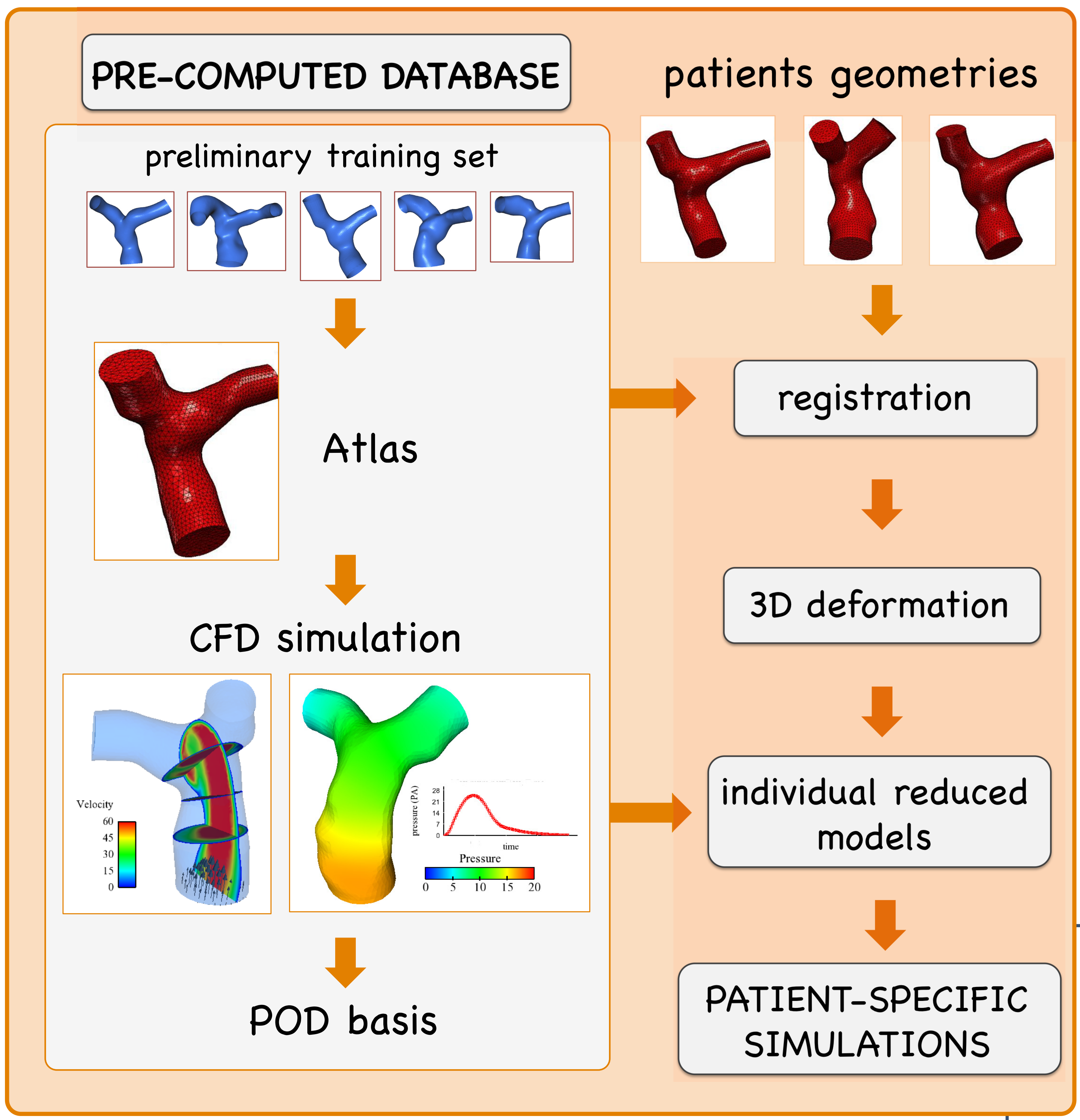
We present a novel method to enable fast patient-specific simulations, combining image analysis, computational fluid dynamics and model order reduction.

- From a preliminary set of individual geometries, a representative template (*atlas*) of the pulmonary artery shape is created.
- Full CFD simulations of the blood flow are carried out only on the atlas geometry. Flow information is compressed into a basis for model order reduction (*proper orthogonal decomposition*), creating a precomputed flow database.
- Individual patient geometries are registered to the atlas, and the *precomputed* basis functions are mapped onto the individual meshes, generating a patient specific *reduced order flow model*.



RESULTS

The method has been validated on a set of three *Tetralogy of Fallot* patients. We compared *full* simulations, i.e. solving numerically the Navier-Stokes equations on patient geometries, and our *reduced* approach.

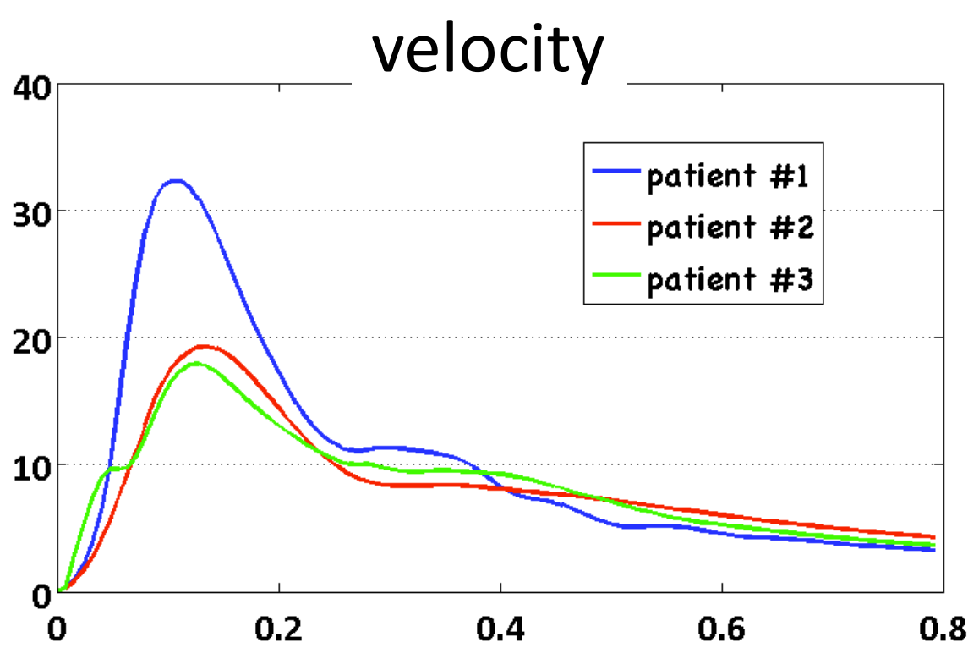
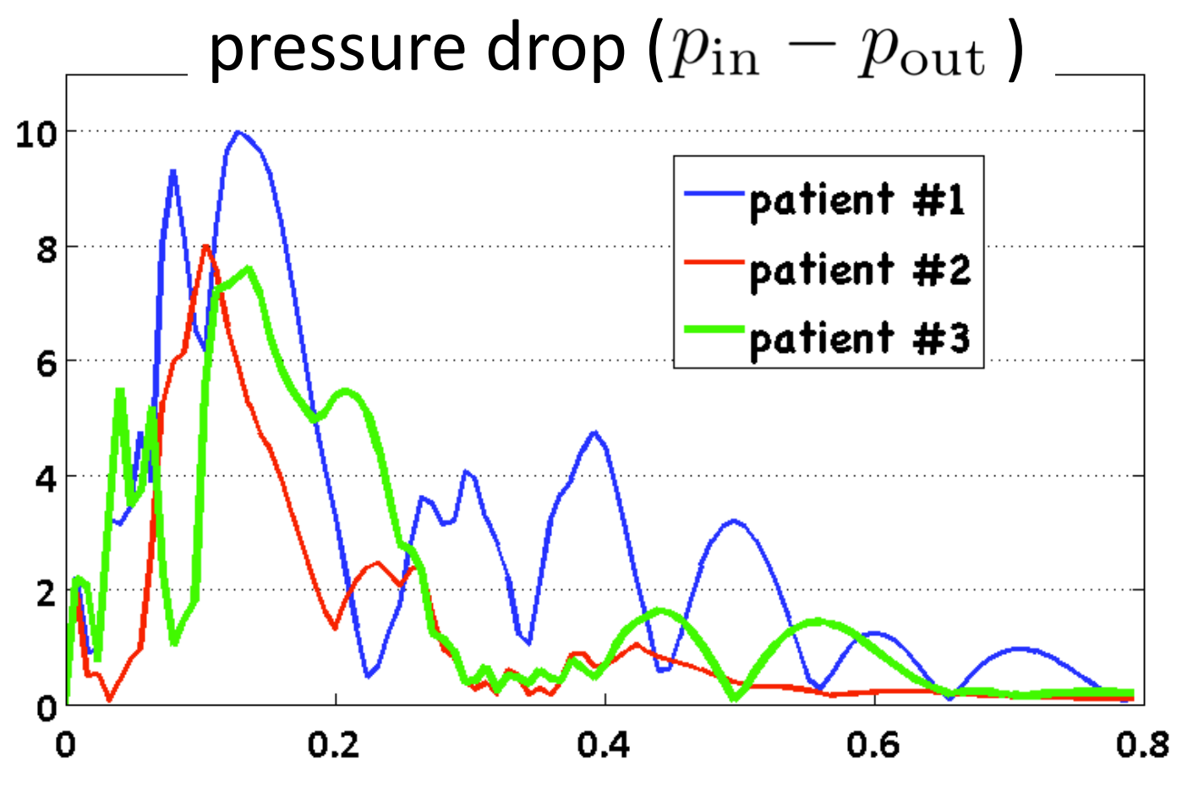
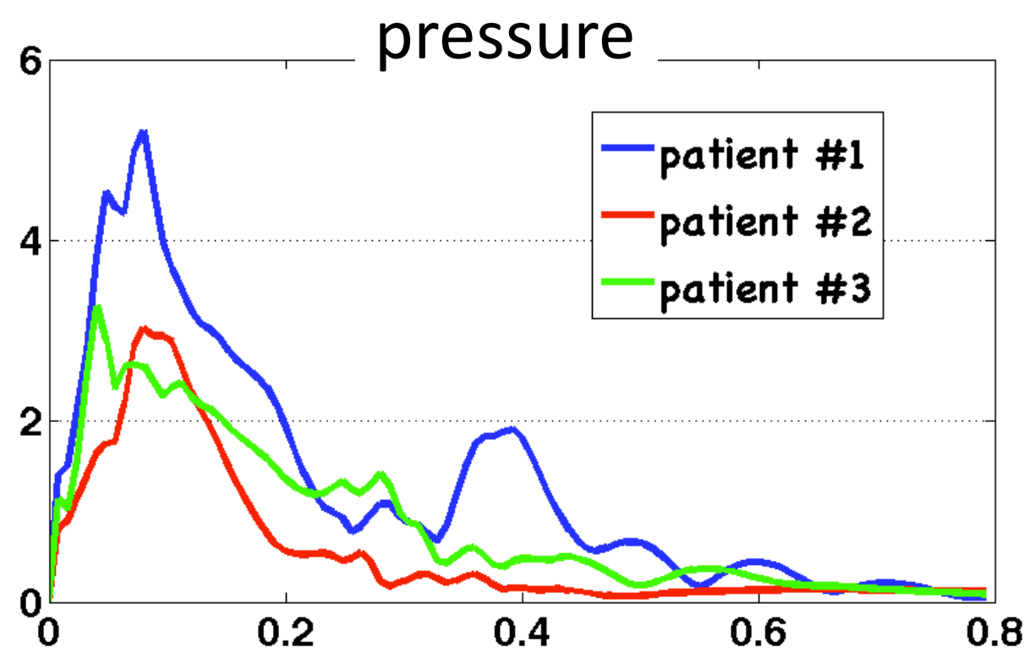


Fig. 3. Relative errors (%) between full and reduced simulations (20 POD basis functions) on three different patient geometries.





The reduced order model, with a smaller amount of unknowns, exhibits good approximation properties.

ACKNOWLEDGEMENTS

This work was partially supported by the INRIA Collaborative Research Action SIRAP

ATLAS COMPUTATION

The pulmonary artery of each patient was segmented from MR angiography. The generated meshes were then pre-processed for CFD simulations. From a preliminary mesh set, an unbiased template (atlas) of the artery shape was constructed using the forward method proposed in [1]. This approach is particularly suited for our purposes, as shapes are represented by *currents*, which can be used for meshes without point correspondence.

COMPUTATIONAL FLUID DYNAMICS

Using a finite element method, blood flow on the atlas geometry is simulated solving numerically the Navier-Stokes equations for blood pressure (p) and velocity ($\mathbf{u}$) :

$$\rho_f \partial_t \mathbf{u} + \rho_f \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p - \mu \Delta \mathbf{u} = 0$$
$$\operatorname{div} \mathbf{u} = 0$$

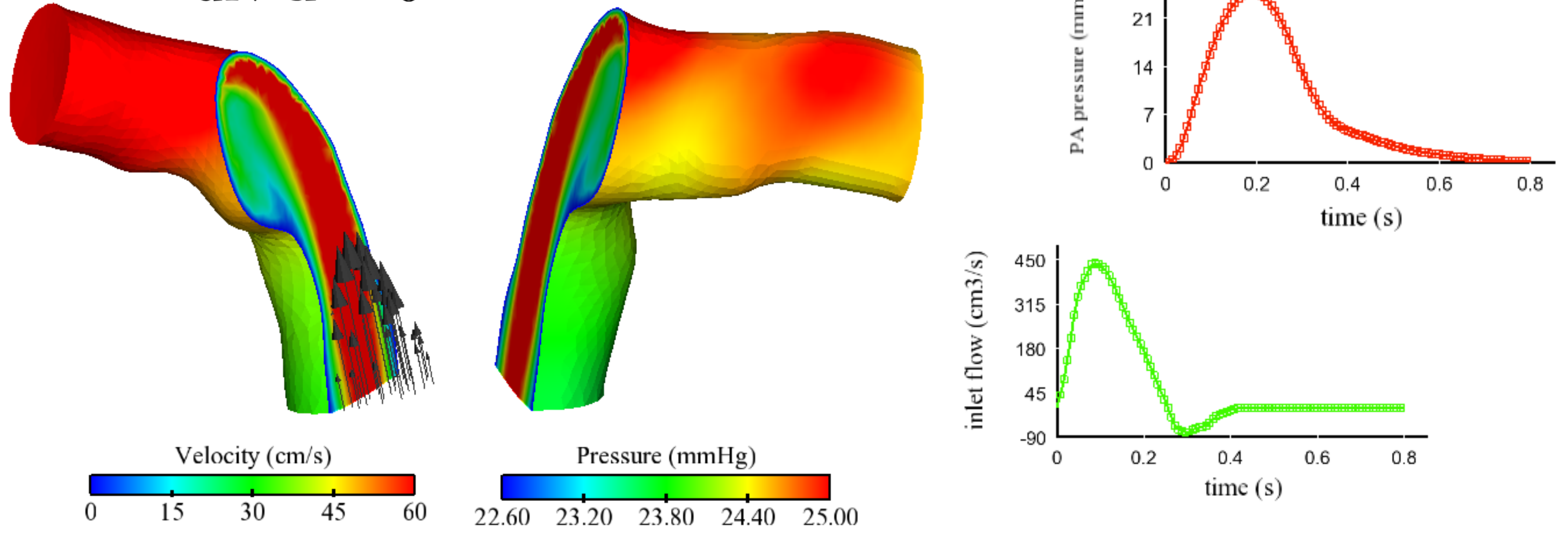


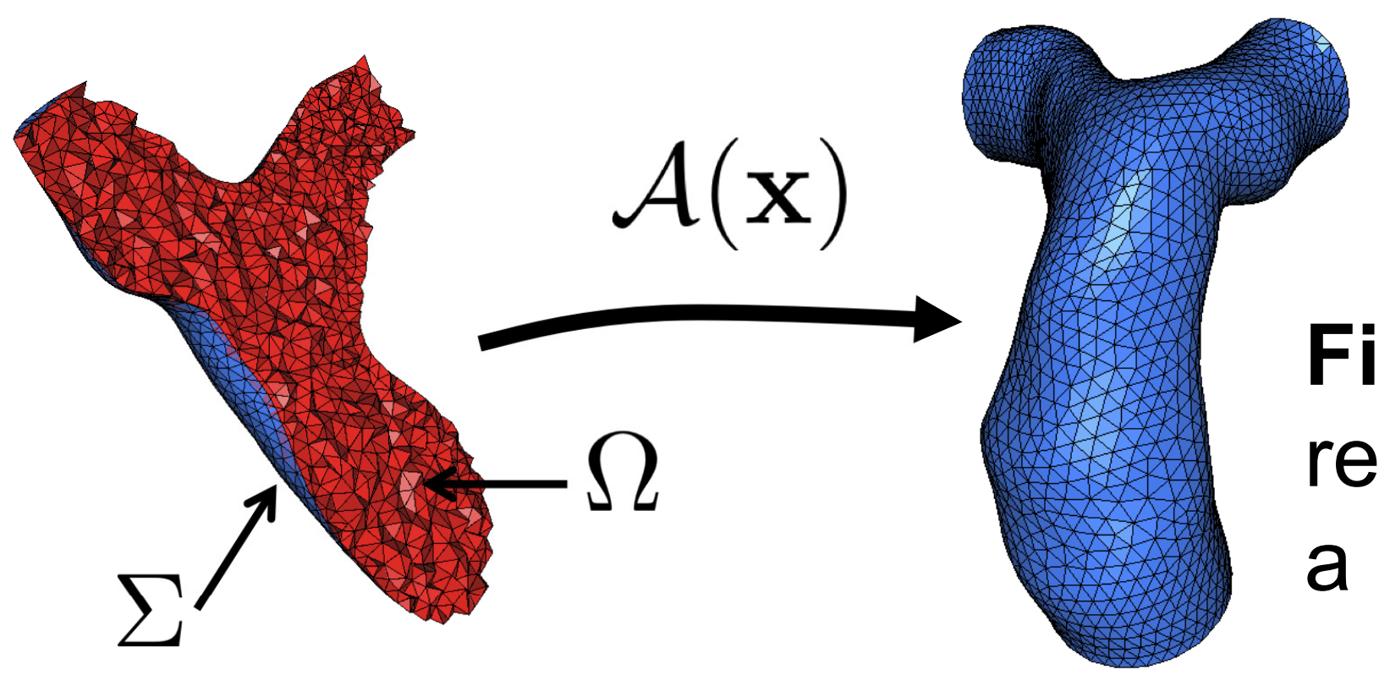
Fig. 1. Snapshot of a CFD simulation. Inlet flow of 4.2L/min. Outlet pressure (pulmonary artery) between 0 - 25mmHg, imposed through a Windkessel model.

Proper orthogonal decomposition

From a set of snapshots of the atlas solution at different instants of time, we compute a basis of a proper orthogonal decomposition (POD) [2] for velocity and pressure, which consists of a reduced number of functions able to describe the fluid solution with high accuracy.

FAST PATIENT-SPECIFIC SIMULATIONS

1. Registration and 3D-deformation. The atlas surface is *registered* to each patient, establishing a one-to-one correspondence between surface points. Surface maps are then harmonically extended to the atlas volume mesh, describing *three-dimensional patient meshes as deformation of the atlas*.



$$\Delta \mathcal{A} = 0, \text{ in } \Omega$$
$$\mathcal{A}_{|\Sigma} = \mathbf{d}_\Sigma$$

Fig. 2. The surface map ($\mathbf{d}_\Sigma$), obtained after registration, serves as boundary condition to compute a 3D deformation $\mathcal{A}$ by harmonic extension.

2. POD mapping. Using the 3D deformation, POD basis functions can be mapped onto the individual meshes [3]. Velocity basis functions on the patient geometry ($\mathbf{w}$) have been computed using a *Piola transform*, a vector fields map preserving locally the incompressibility condition:

$$\mathbf{w}_{\mathrm{patient}}(\mathbf{y}) = \frac{1}{|\det F(\mathbf{x})|} F(\mathbf{x}) \mathbf{w}_{\mathrm{atlas}}(\mathbf{x}), \ \mathbf{y} = \mathcal{A}(\mathbf{x}), \ F = \nabla \mathcal{A}$$

This generates *patient-specific reduced models* for fast individual simulations.

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