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# Slide of the Seminar

# Hemodynamics of biological and mechanical valves

***Prof. Valeria Meschini***

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*(P.I. Prof. Luca Biferale)*

Università degli Studi di Roma Tor Vergata
C.F. n. 80213750583 – Partita IVA n. 02133971008 - Via della Ricerca Scientifica, 1 – 00133 ROMA

# Hemodynamics of biological and mechanical valves

**NewTURB MEETING- 18 July 2016**

*Università di Roma "Tor Vergata"*


**Valentina Meschini**

*Gran Sasso Science Institute*

**Prof. Roberto Verzicco**

*Università di Roma "Tor Vergata"*

*University of Twente*


in collaboration with

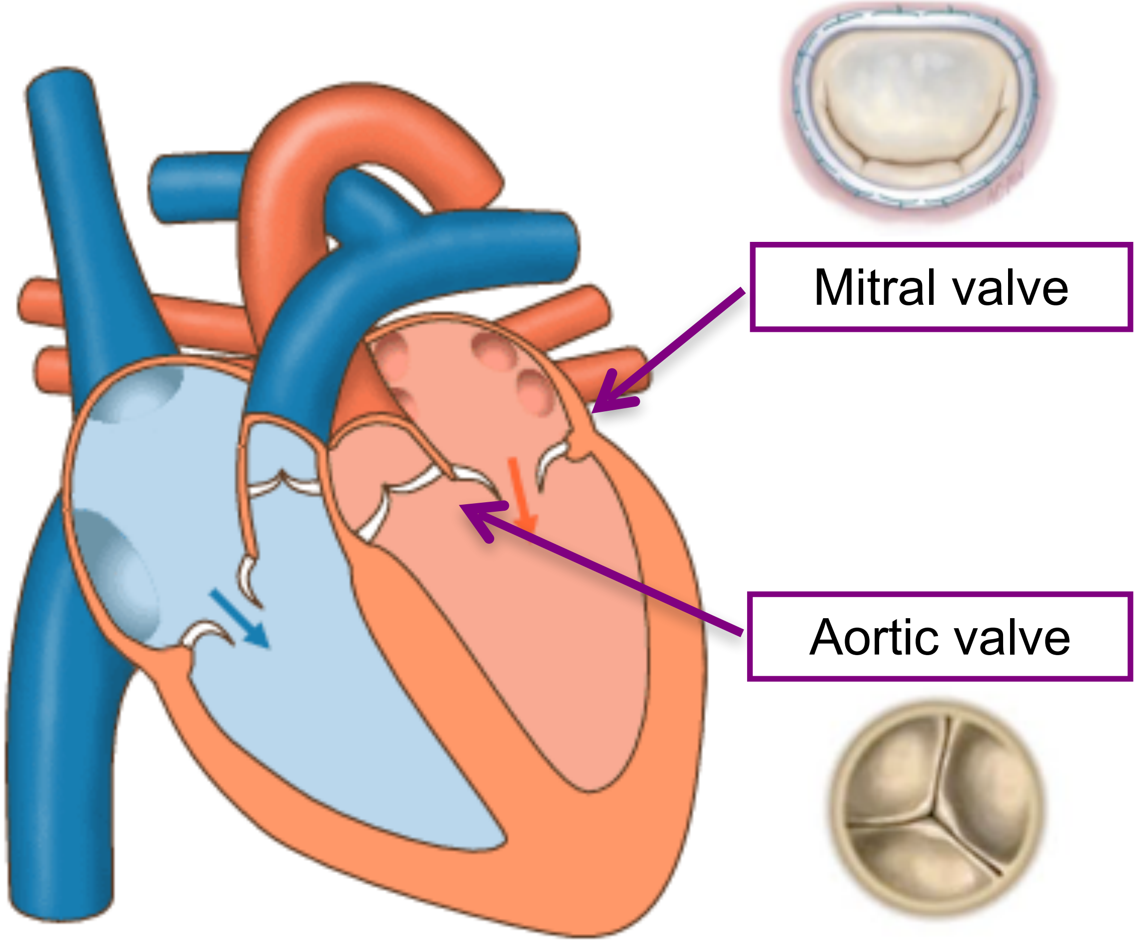
- **Prof. Marco De Tullio** - ***Politecnico di Bari***
- **Prof. Giorgio Querzoli** - ***Università di Cagliari***
- ***L. Weltert, R. De Paulis*** - ***Dipartimento di Cardiochirurgia,Ospedale Europeo, Roma***

# Background

The heart is made of two parts (Left and Right) each composed of two chambers (ventricle and atrium) and valves that ensure the correct flow direction

The valves of the left side (Mitral and Aortic) are most commonly affected by diseases due to the large pressure they withstand (100-150 mmHg)

Sometimes valves need replacement



# Some diseases

## Valvular pathologies

Stenosis

Increased pressure drop across the valve

Leakage

Undesired regurgitation (back-flow)

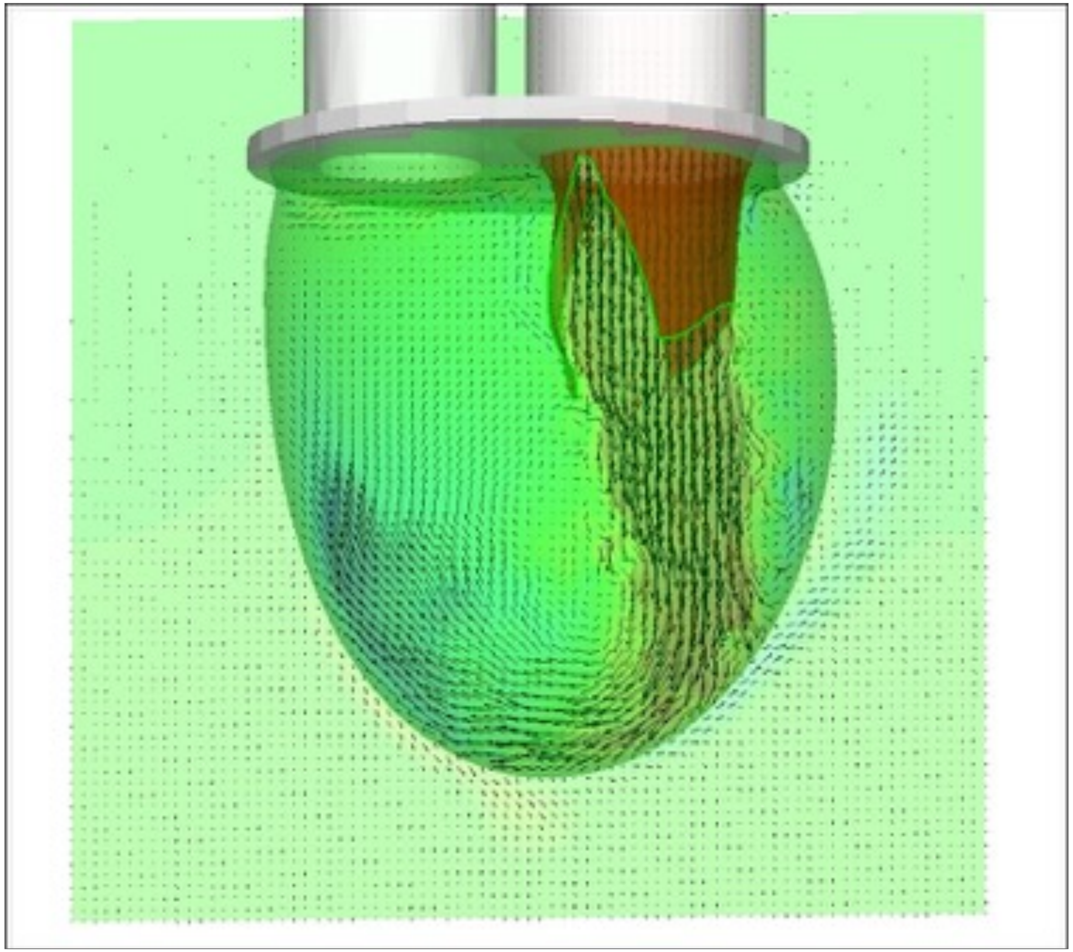
# Some diseases
## Valve replacement

| Biologic | Mechanic |
|---|---|
|  |  |
| ☺ Good hemodynamics | ☹ Bad hemodynamics (need for anticoagulants) |
| ☹ Limited durability (10-15 years) | ☺ Lifelong durability |
| | ☹ Noise |

# Computational model of the left ventricle

Left ventricle with mechanical or natural **mitral valve**

**Fluid-Structure-Interaction** model



# Numerical tool

## The ingredients:

- Direct Numerical Simulation fluid solver
- Structural solver
- Immersed Boundary Technique
- Fluid-Structure-Interaction

**The simulation of such complex flows would be impossible without IB methods**

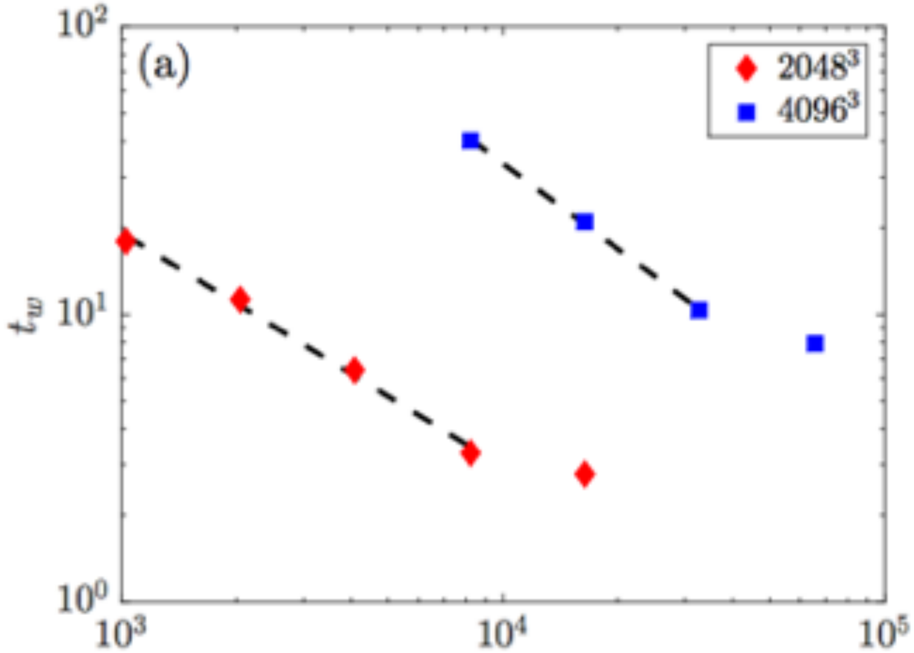
Typical physiological conditions:

Cycle period: 866 ms (70 bpm)
Mean flowrate: 5 l/min
Peak flowrate: 28 l/min
$Re_{peak} = 6200$
Grid ≈20M nodes
dt = 2-200 μs

# Fluid Solver: AFiD

## Highly parallel code for turbulence

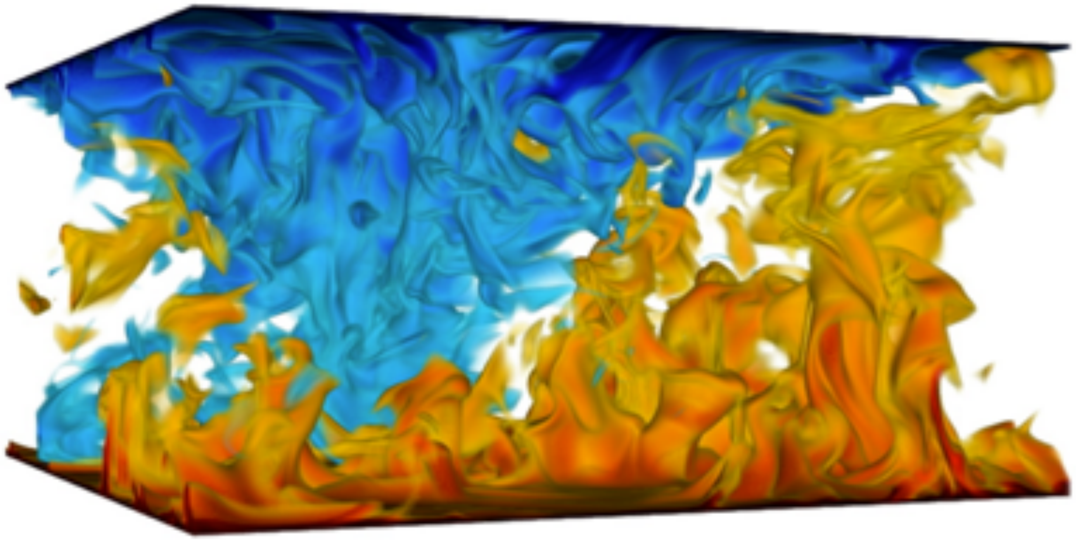
Open-source code available at
www.afid.eu




**Reference and tutorial:**
Van der Poel et al. (2015), Computers & Fluids **116**, “A pencil distributed finite difference code for strongly turbulent wall-bounded flows”

**Upcoming modules:**

- Cylindrical coordinates (Taylor Couette)
- Lagrangian particles
- Double diffusive convection
- GPU architectures



afid-users@lists.surfsara.nl

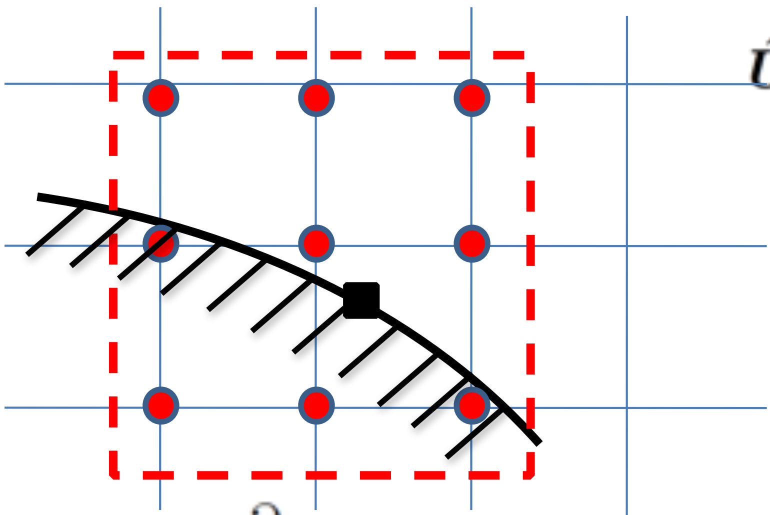
Physics of Fluids

SURF SARA

# Immersed boundary methods

Rigid/fixed bodies are handled by the Direct Forcing procedure (Fadlun et al., JCP, 2000)

For moving/deforming bodies the complex geometry is handled by a versatile Moving Least Squares (MLS) approach (Vanella and Balaras, JCP, 2009)



$$\hat{U}(\boldsymbol{x}) = \sum_{k=1}^{ne} \phi_k^l(\boldsymbol{x})\,\hat{\boldsymbol{u}}_k$$

$$\boldsymbol{F} = \frac{U_b - \hat{U}}{\Delta t}$$

$$\boldsymbol{f}^k = \sum_{l=1}^{nl} c_l\,\phi_k^l\,\boldsymbol{F}_l$$

$$\frac{\partial \mathbf{u}_f}{\partial t} + \nabla \cdot (\mathbf{u}_f \mathbf{u}_f) = -\frac{\nabla p}{\rho_f} + \nu \nabla^2 \mathbf{u}_f + \boldsymbol{f}$$

Smooth hydrodynamic forces.

Zero-thickness bodies can be modelled (e.g., leaflets of biological valve, left ventricle)

# Structure Solver

## Finite Element Method

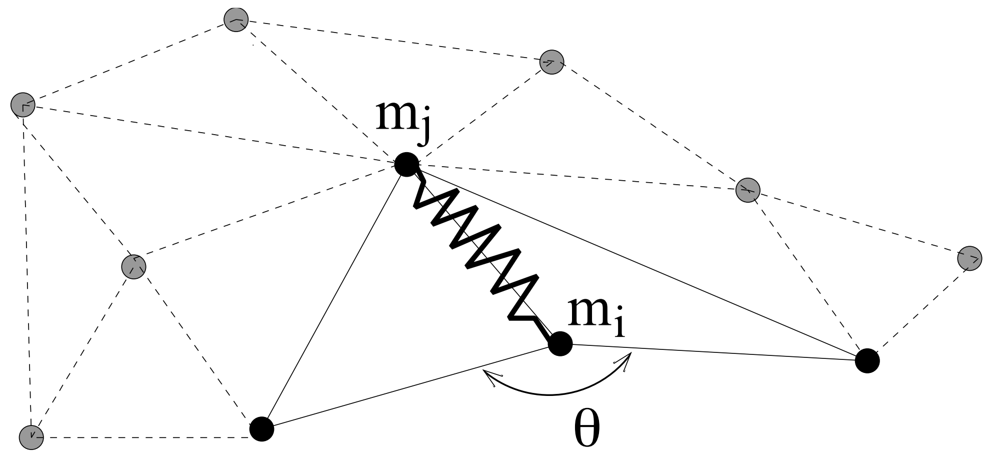
$$\nabla \cdot \sigma_s = \rho_s \frac{\partial^2 d_s}{\partial t^2} \qquad \sigma_s = C E_s$$

$$E_s = \frac{1}{2}\left[\nabla \cdot d_s + (\nabla \cdot d_s)^T + (\nabla \cdot d_s)^T \nabla \cdot d_s\right]$$

Standard finite-element approach (CALCULIX or ANSYS)

## Spring-mass method

$$\mathbf{F}_i = m_i \mathbf{a}_i$$
$$\mathbf{F}_i = \nabla \Phi_i$$



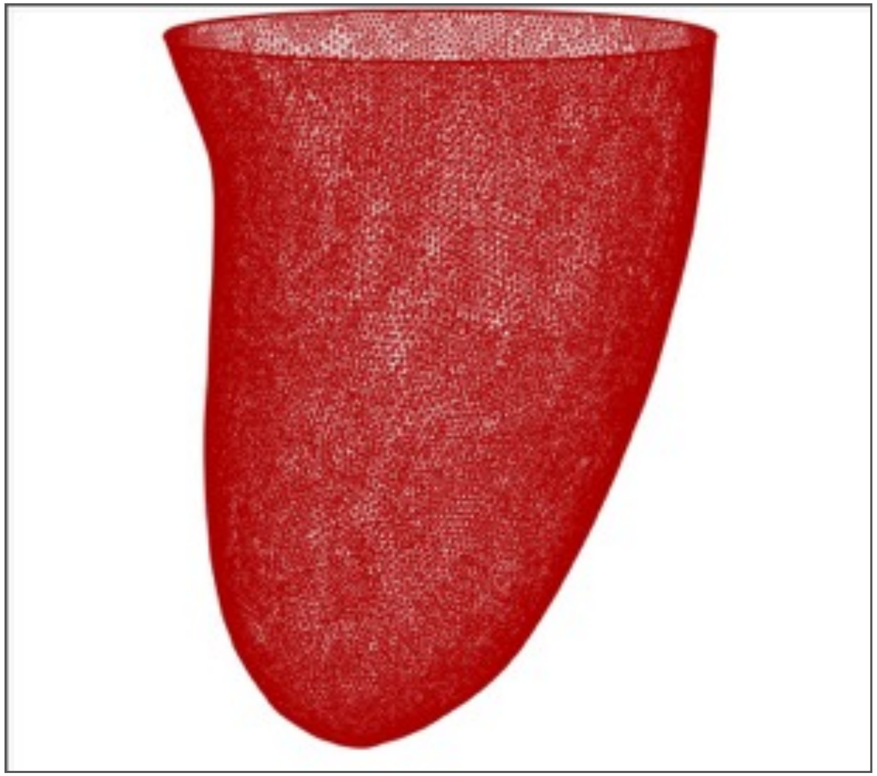

$$\Phi_i = \Phi_{ei} + \Phi_{bi} + \Phi_{Ali} + \Phi_{ATi} + \Phi_{Vi} + ..$$

$\Phi$ from interaction potential model (Fedosov et al., Comp. Methods in Appl. Mech. and Eng., 2010)

# Structure : the left ventricle

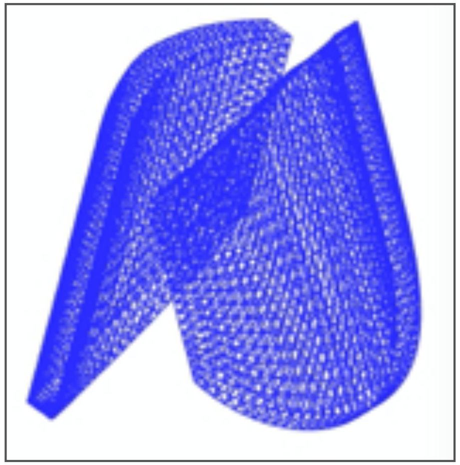
# and the mitral valve

Natural
mitral
valve



Left
Ventricle

Prosthetic
Mechanical
mitral valve



# Fluid-Structure interaction

## STRONG COUPLING

$$\frac{D\mathbf{u}}{Dt} = -\frac{\nabla p}{\rho} + \frac{1}{\rho}\nabla\cdot\tau + \mathbf{f}$$

$$\nabla\cdot\mathbf{u} = 0$$

$$M\frac{d^2\boldsymbol{x}}{dt^2} = \boldsymbol{F} \qquad \mathbf{F} = \int_s (\tau\cdot n - pn)\,dS$$

$$\boldsymbol{I}\frac{d^2\theta}{dt^2} = \boldsymbol{T} \qquad \mathbf{T} = \int_s \left[r\times(\tau\cdot n - pn)\right]dS$$

## LOOSE COUPLING

$$\frac{D\mathbf{u}}{Dt} = -\frac{\nabla p}{\rho} + \frac{1}{\rho}\nabla\cdot\tau + \mathbf{f}$$

$$\nabla\cdot\mathbf{u} = 0$$

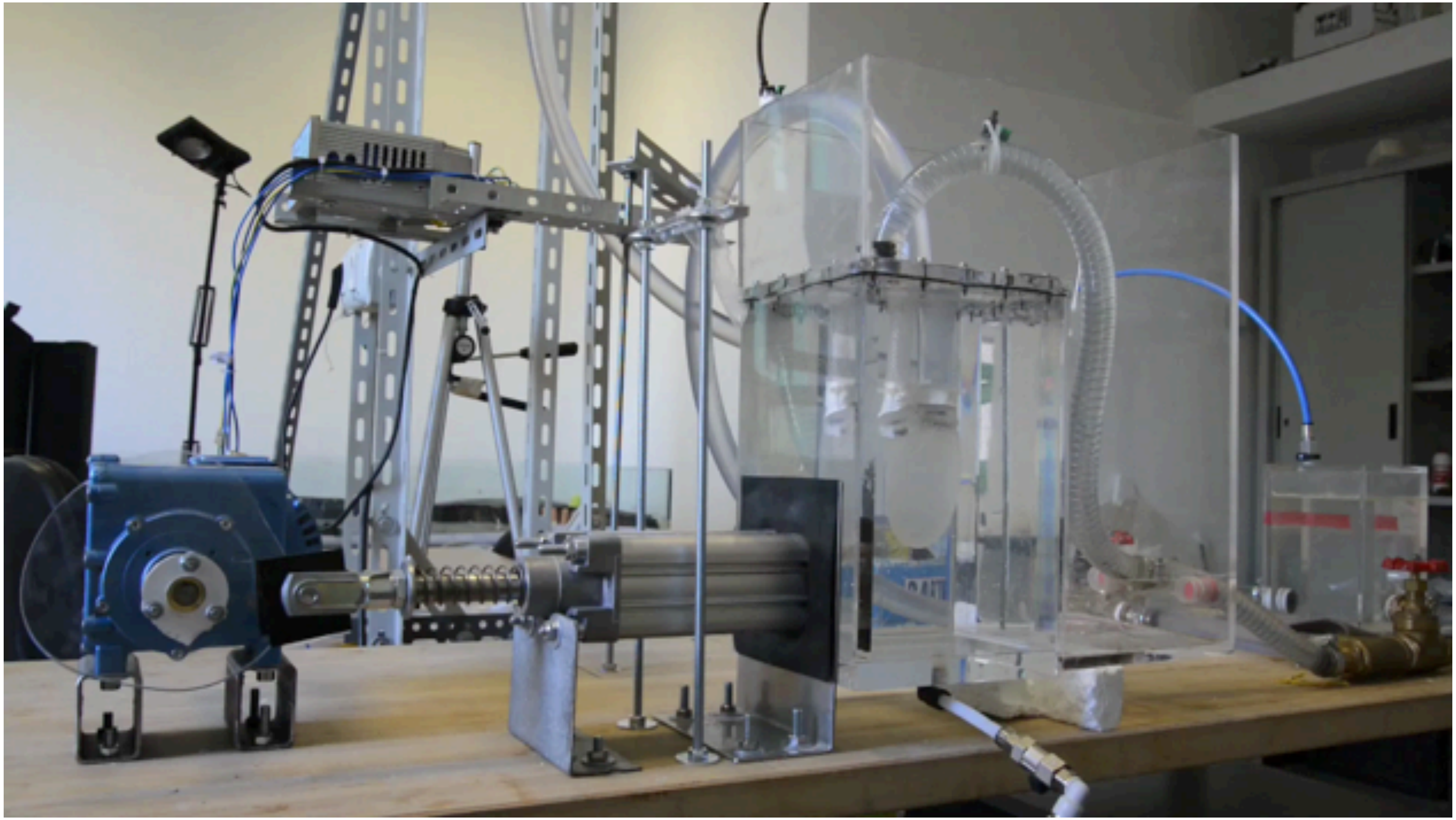
$$\nabla\cdot\sigma_s = \rho_s\frac{\partial^2 d_s}{\partial t^2} \qquad \sigma_s = CE_s$$

$$E_s = \frac{1}{2}\left[\nabla\cdot d_s + (\nabla\cdot d_s)^T + (\nabla\cdot d_s)^T\nabla\cdot d_s\right]$$

(de Tullio et al, 2009)

(Borazjani et al, 2008)

# Ad-hoc experimental set-up

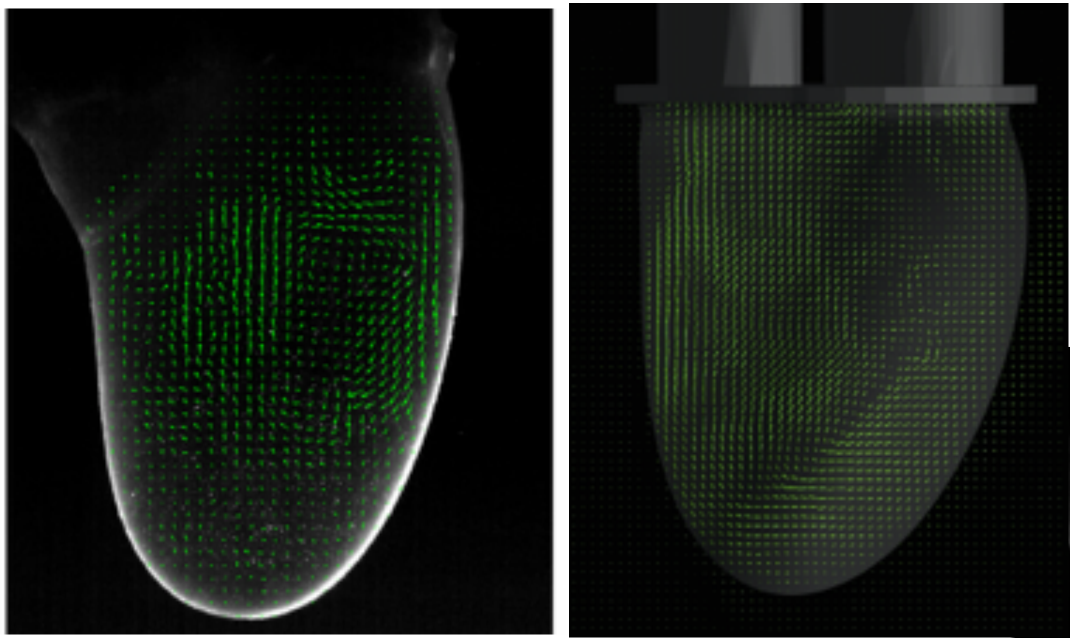


in collaboration with

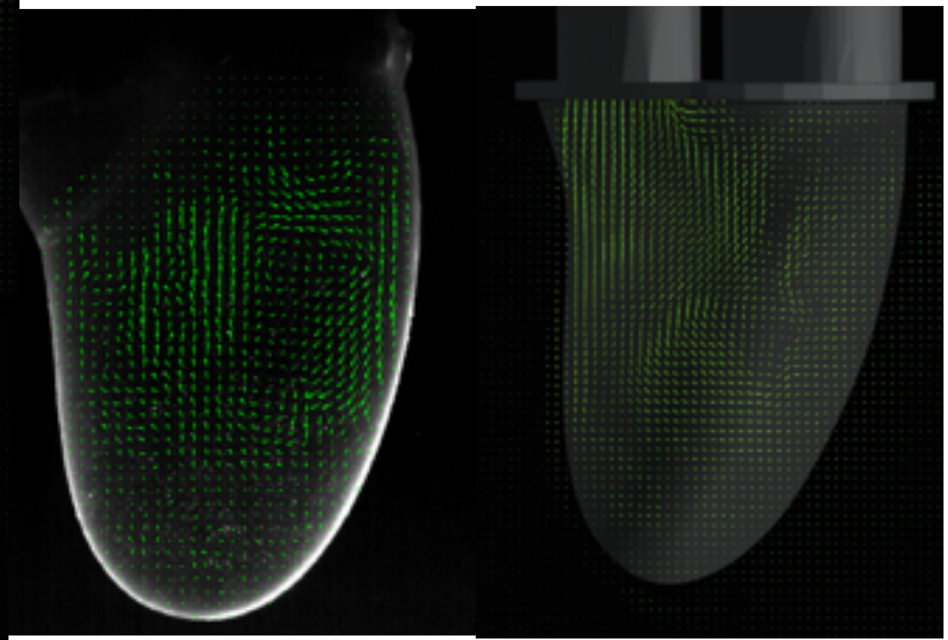
**Stefano Santamaria & Federica Sposato**

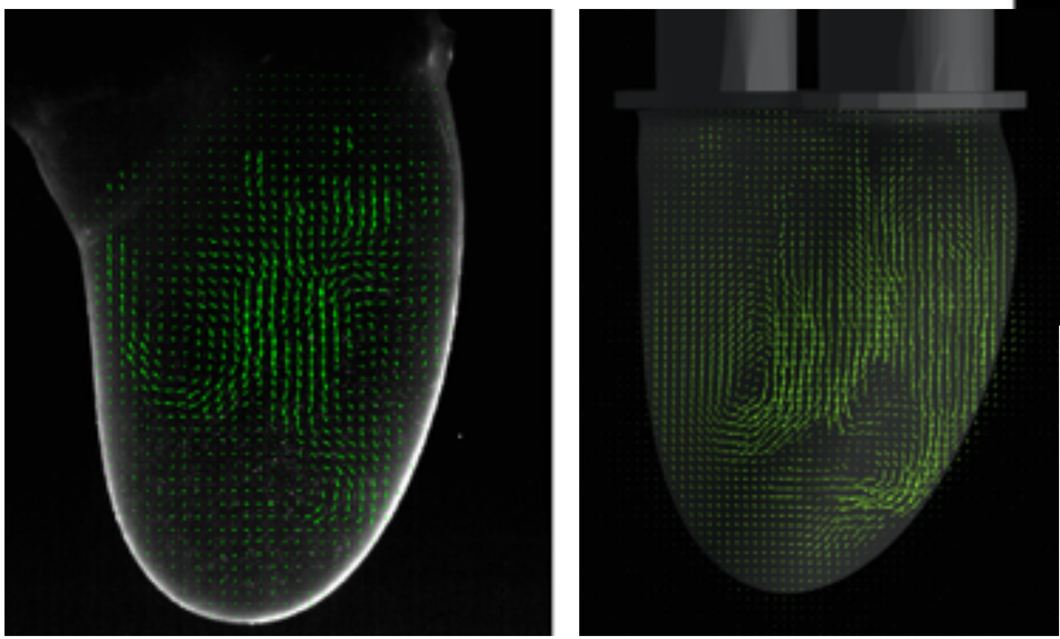
(Master Students of University of Roma Tor Vergata)

# Experimental vs Numerical



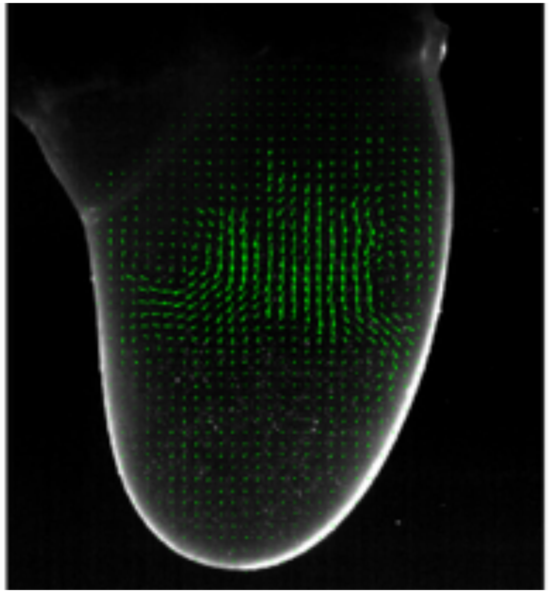
Strong cycle-to-cycle variation (small scales) but the large-scale features are

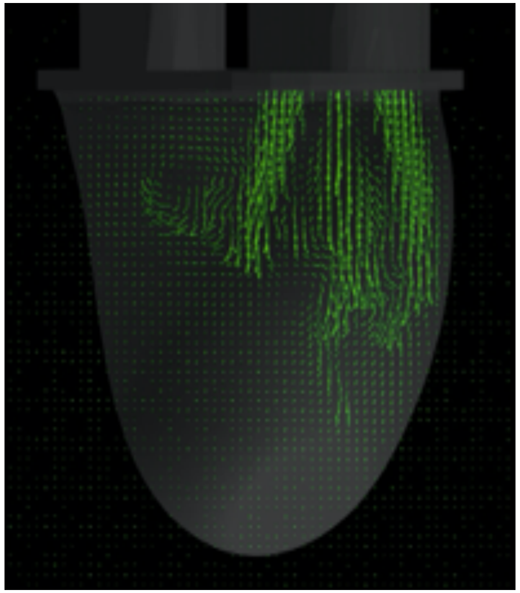


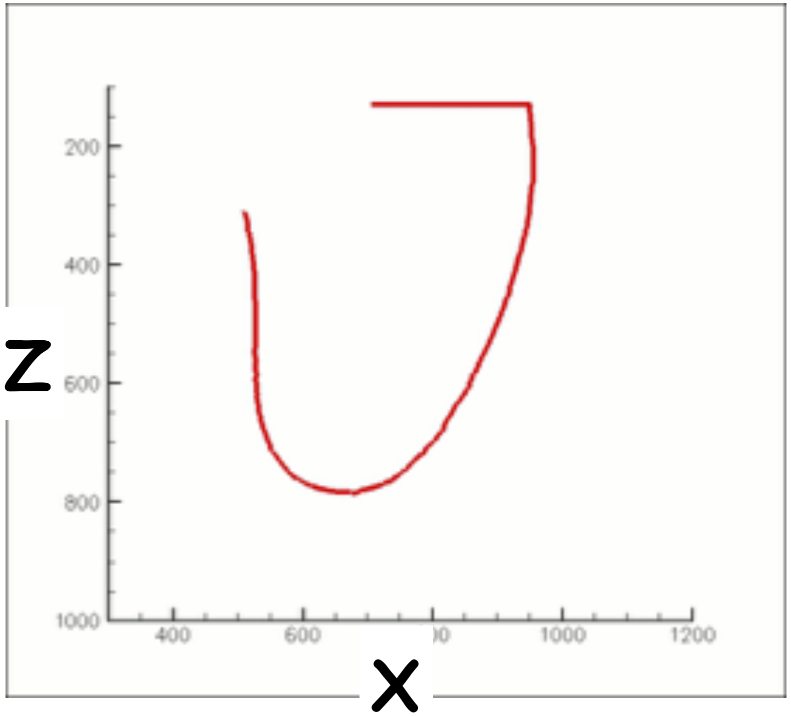


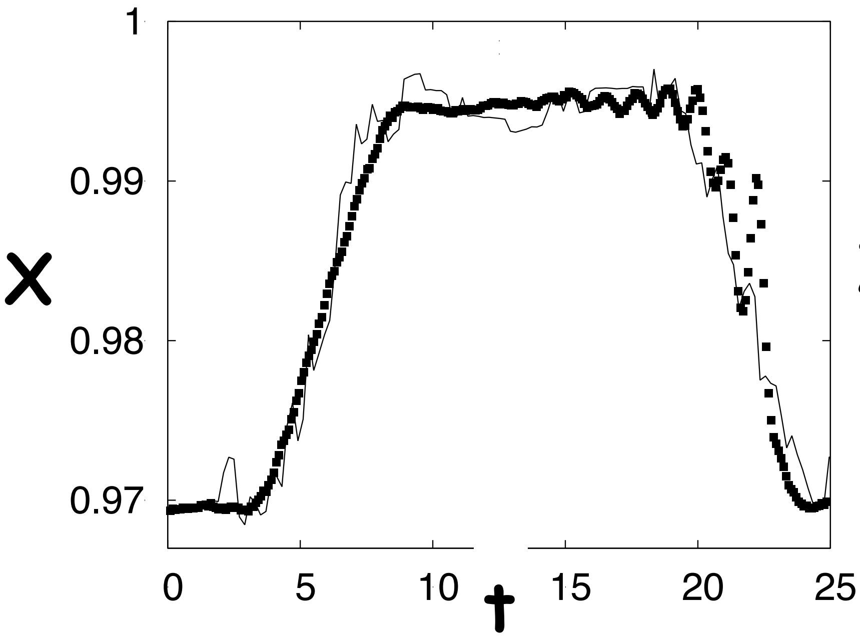
(Instantaneous velocity fields)

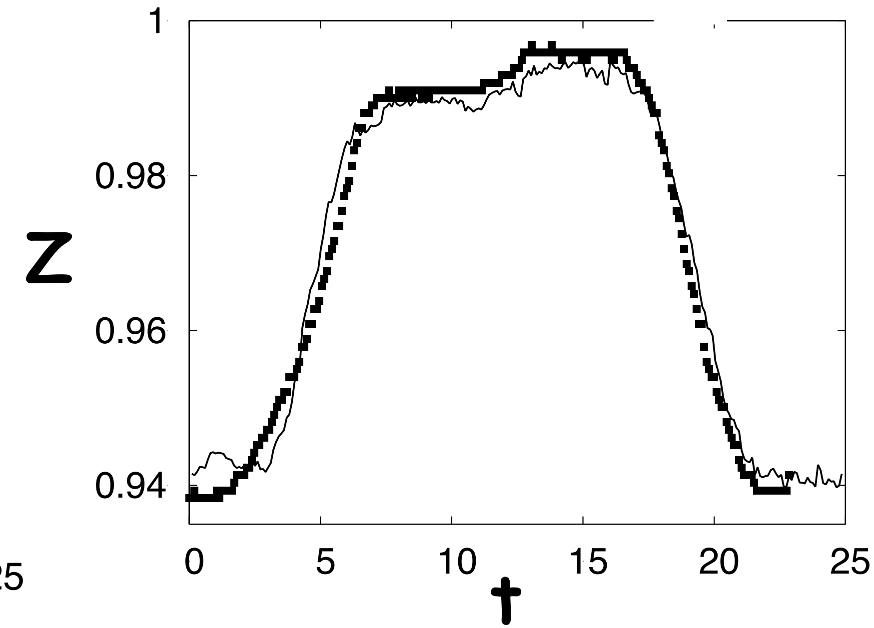
# Experimental vs Numerical







# Mitral valve and left ventricle

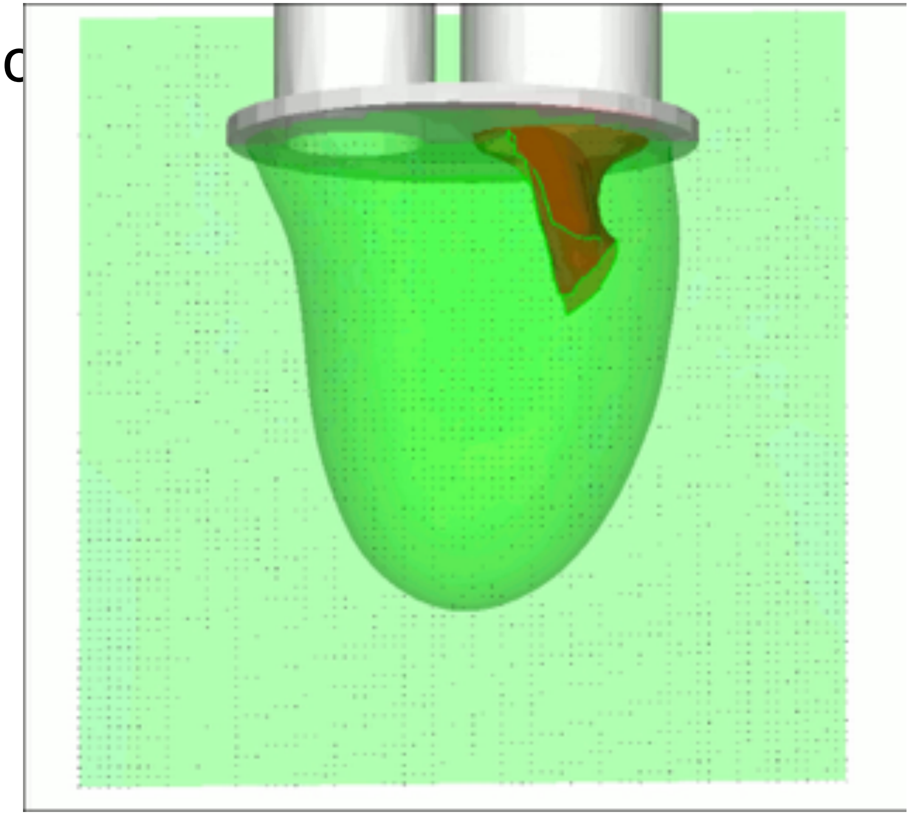
Ejection Fraction (EF), pumping efficienc
of the left ventricle

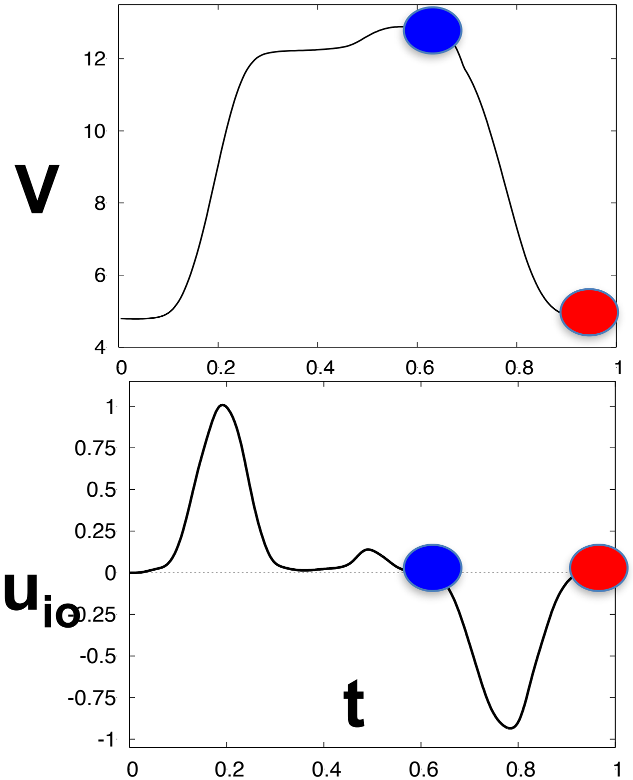
$$EF = \frac{V_{max} - V_{min}}{V_{max}} * 100$$

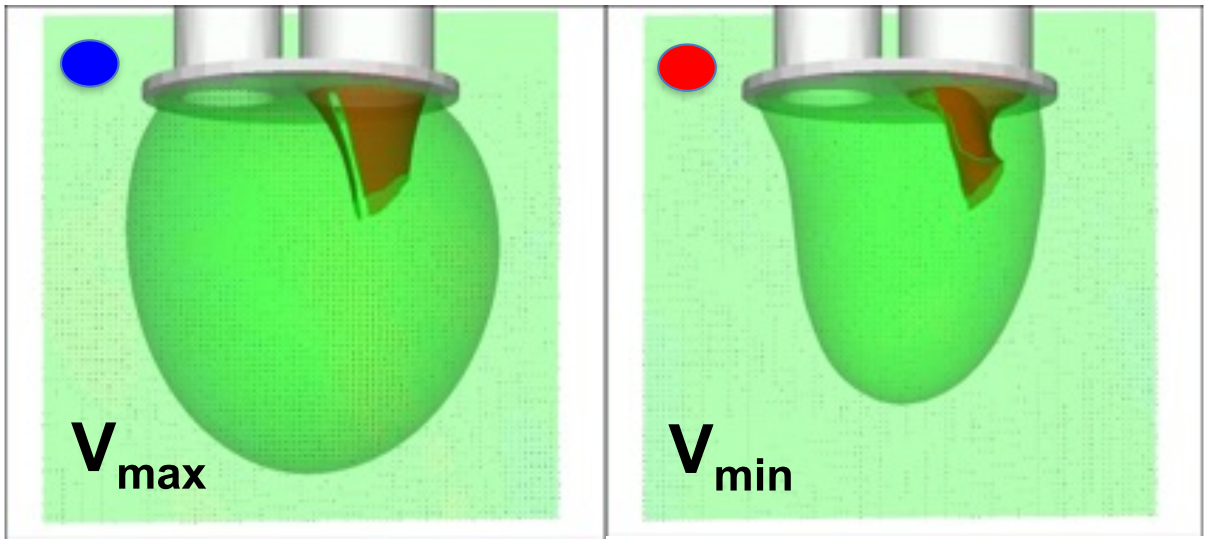
EF=55-70% (good efficiency)

40% <EF< 50% (pathologic)

EF< 35% (life threatening)



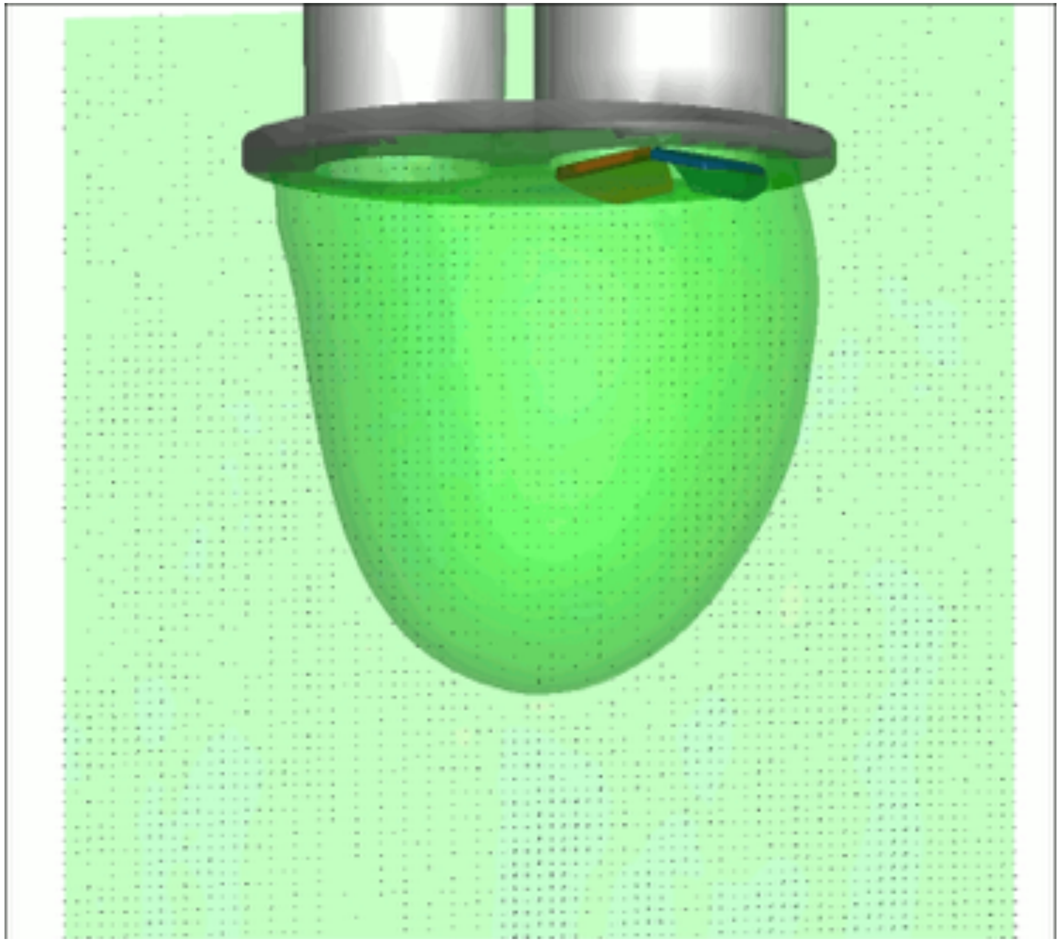


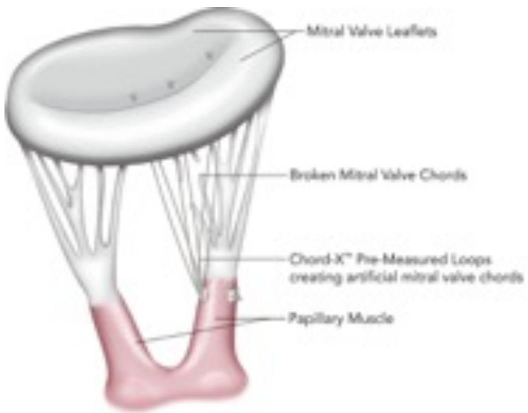
# Mechanical Mitral valve

## ‘Healthy’ left ventricle (EF 60%)

Similarly to the aortic valve, also in the mitral position  the leaflets perturb the flow downstream

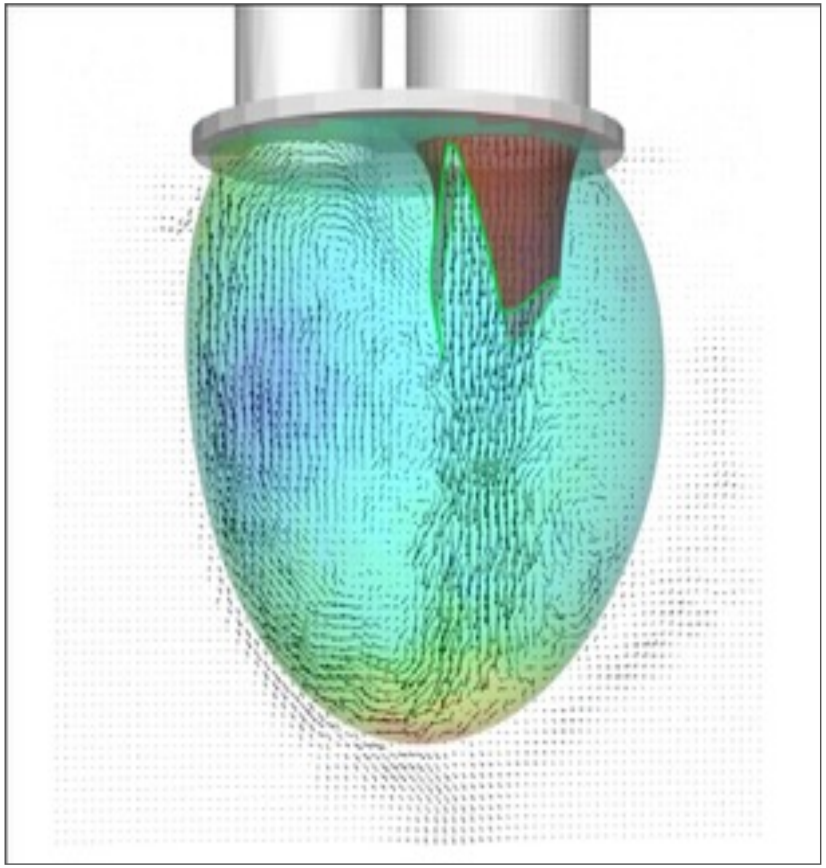


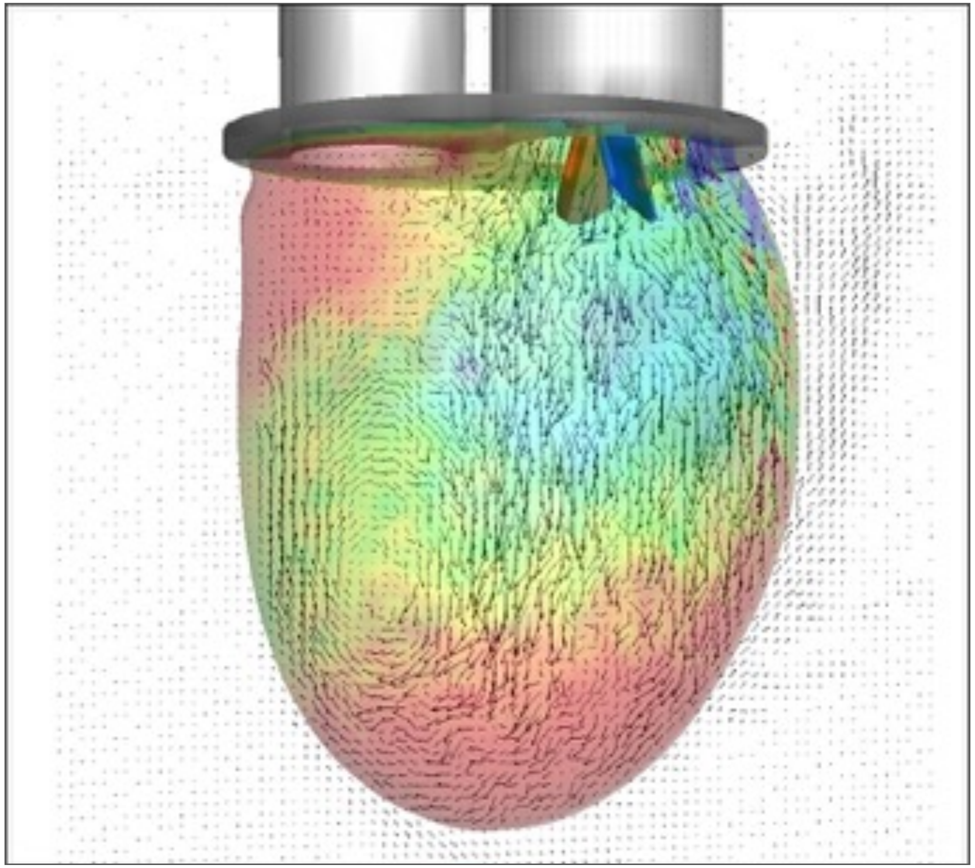
The ventricular flow is strongly changed by the prosthetic valve

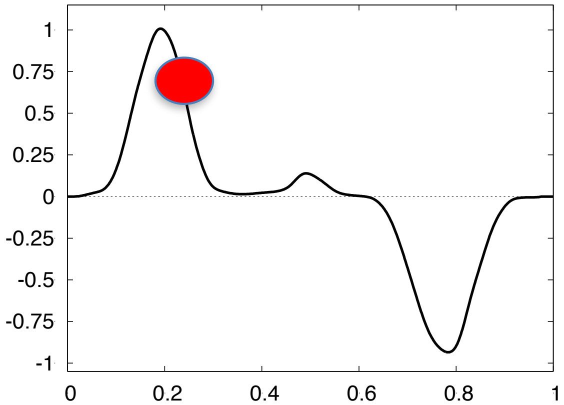


# Natural vs Mechanical Mitral valve

## ‘Healthy’ left ventricle (EF 60%)



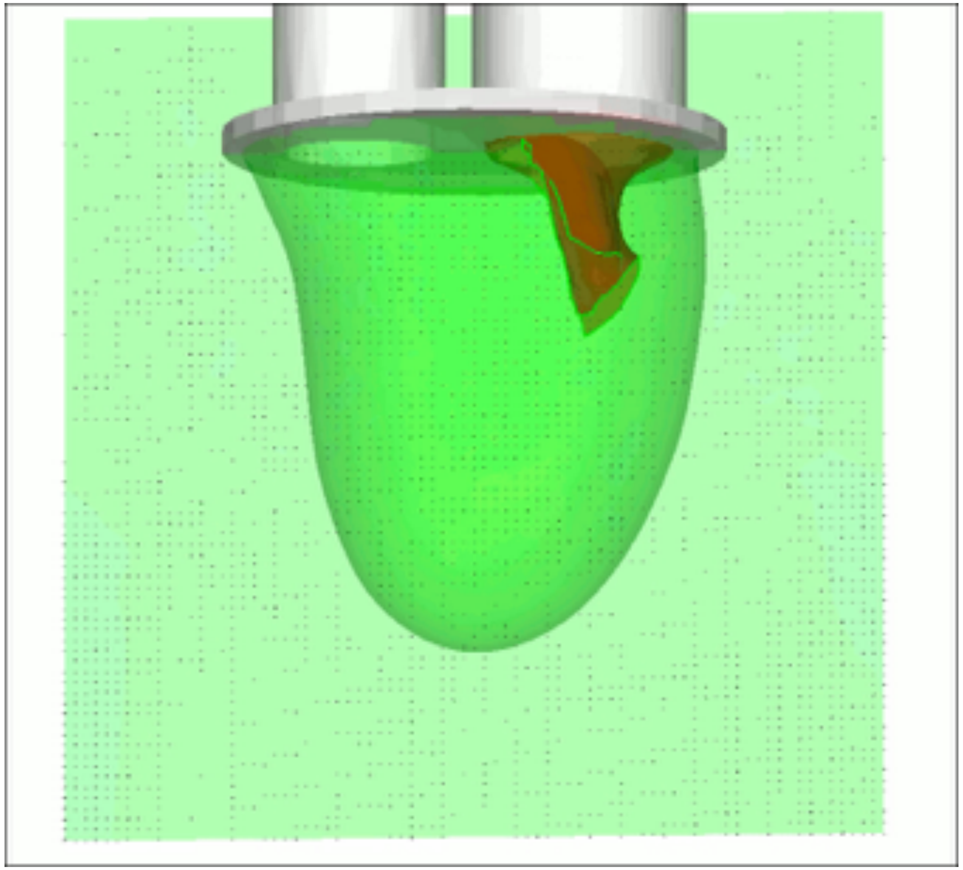




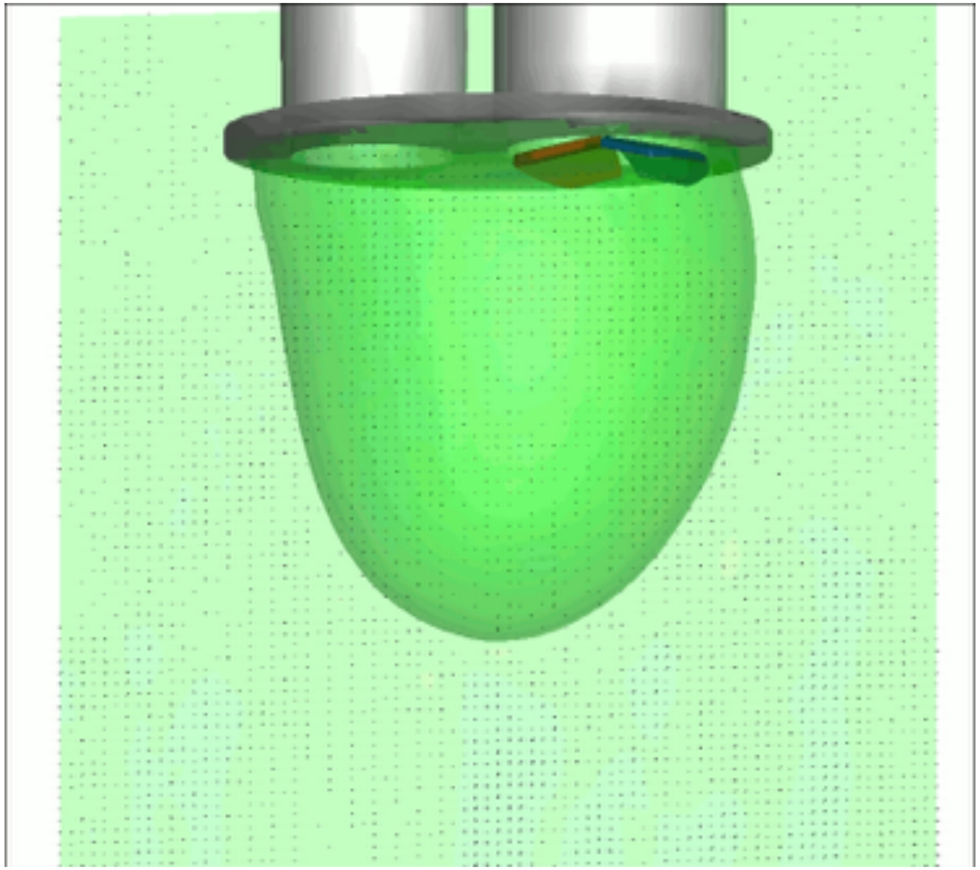

The disturbance produced by the mechanical valve considerably alters the flow and the shear stresses on the inner ventricle surface

# Natural vs Mechanical Mitral valve

## ‘Healthy’ left ventricle (EF 60%)



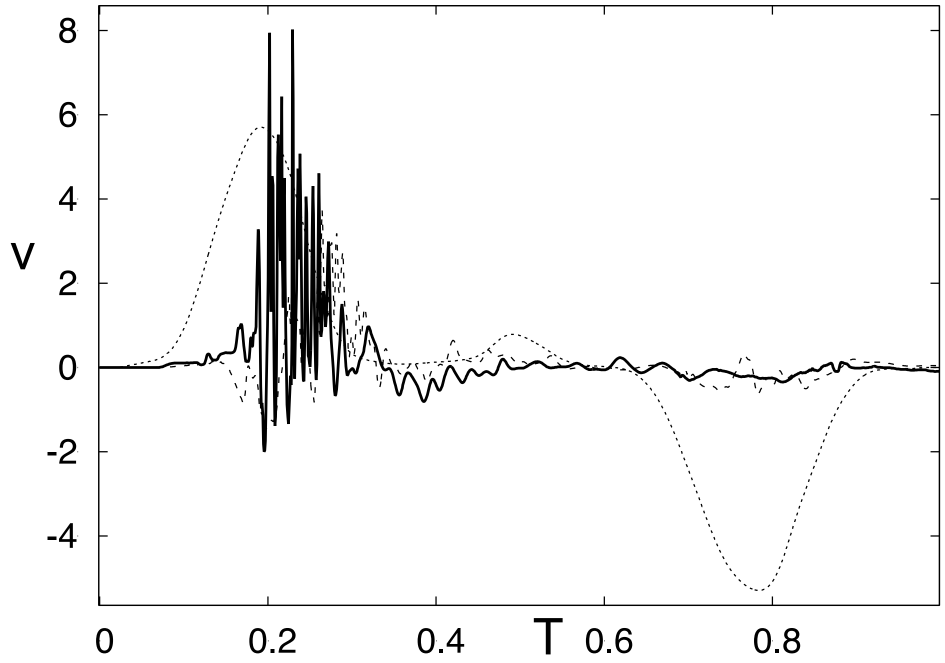
Natural valve

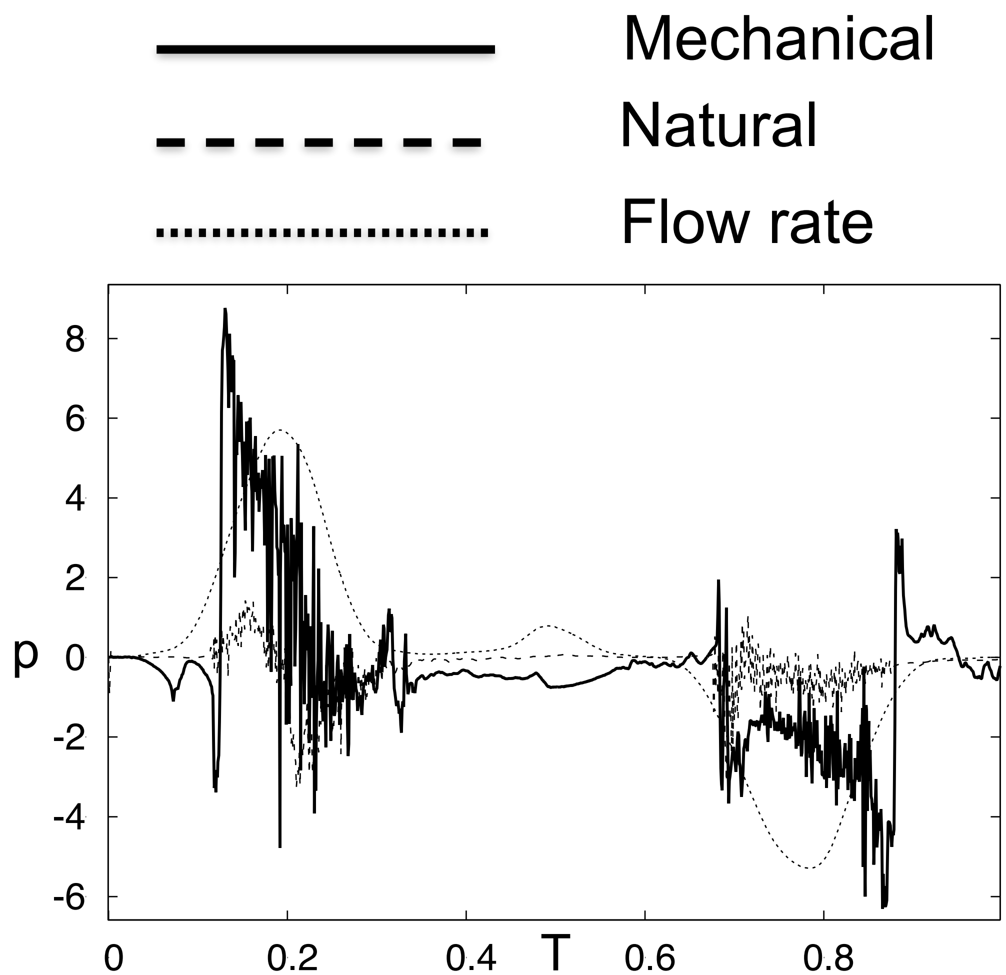


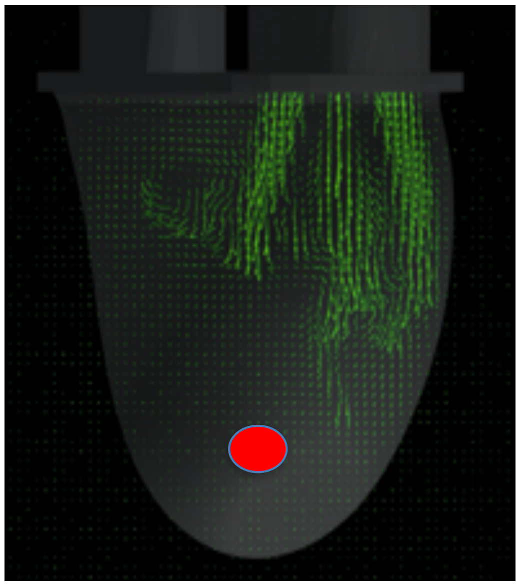
Mechanical valve

# ‘Healthy’ left ventricle (EF 60%)

More than 60 numerical probes are fit into the ventricle to sample in time velocity, pressure, vorticity …

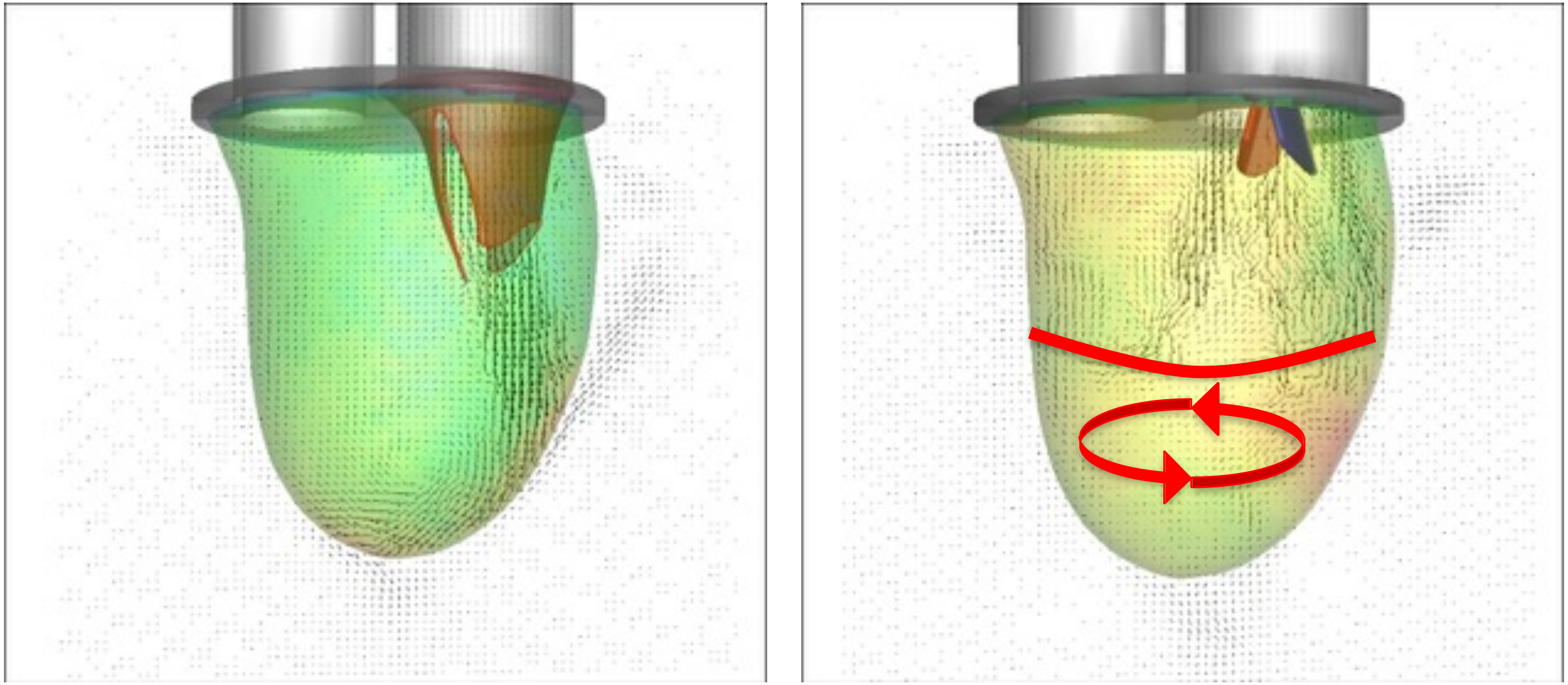


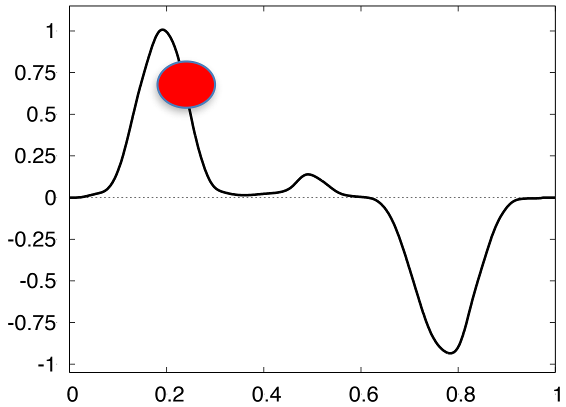



Both, velocity and pressure have much more intense fluctuations for the mechanical valve

# Natural vs Mechanical Mitral valve
## Failing left ventricle (EF 30%)






The pressure drop across the mechanical valve and the increased dissipation of the flow prevents the mitral jet from penetrating up to the ventricle apex

# Ongoing work and future perspectives

Effect of physical cordae tendinae
(not only their constrains)

Effect of trabeculae in the left ventricle (surface is not smooth)

Use the computational model to simulate different cardiac pathologies and intervention measures

Modelling the complete heart

*European Hospital, Rome,IT*

*Univ. of Twente NL*

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