Institut de **M**athématiques et de
Modélisation de **M**ontpellier
UMR 5149 – I3M

Calcul Haute Performance en routine clinique: mythe ou réalité ?

Point de vue de la biomécanique cardio-vasculaire …

Franck NICOUD

Remerciements à :

I. Vignon-Clémentel, J.F. Gerbeau (INRIA), C. Taylor, A. Figueroa (Stanford Univ.), R. Moreno (INSERM), H. Rousseau (CHU Toulouse), B. Tayllamain (UM2), CERFACS/CFD

INTRODUCTION

- Recent progress in medical imaging techniques have induced advances in diagnosis of vascular disorders,
- Virtually no functional imaging available in many cases
- Therapeutic decisions heavily rely on heuristic criteria and/or non scientific elements
- Exemple: treatment of aneurysms based on their size but not on their load

TWO TYPES OF APPLICATIONS OF HPC

1. General purpose:
   - Increase our understanding of physical/medical observations
   - Optimizing medical systems, treatment protocols

2. Patient specific:
   - Allow a better diagnosis and/or treatment
   - More constraints

SOME “EXISTING” APPLICATIONS

1. General purpose:
   - Ventricular Assist Device – Aachen Univ. + Jülich Center
   - Virtual Heart - INRIA

2. Patient specific:
   - Pre-chirurgical planning – Stanford Univ.
   - Functional Imaging – UM2 + INSERM + ASA

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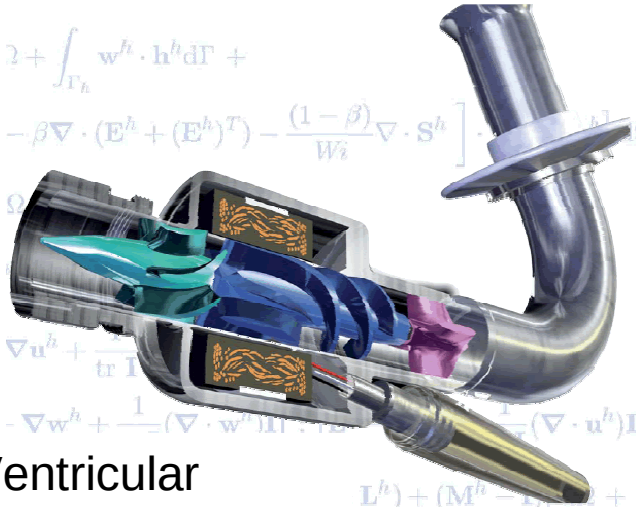
“PROSTHESIS” DESIGN



Ventricular
Assist **D**evice

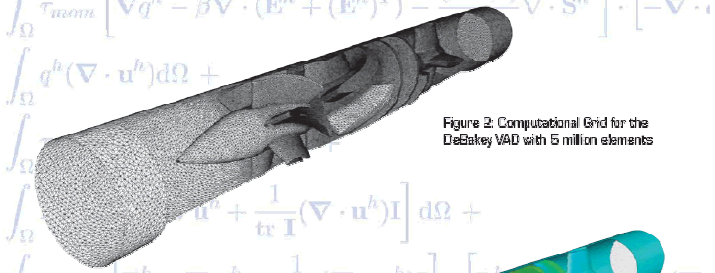


Figure 2: Computational Grid for the DeBakey VAD with 5 million elements

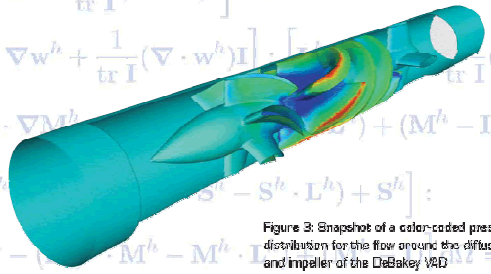
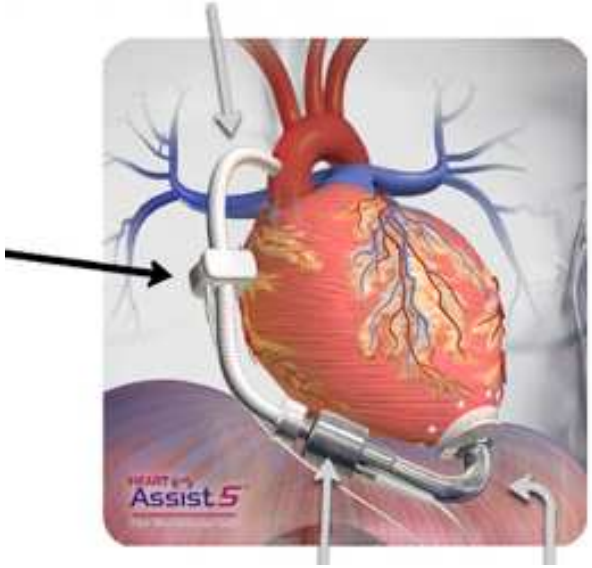
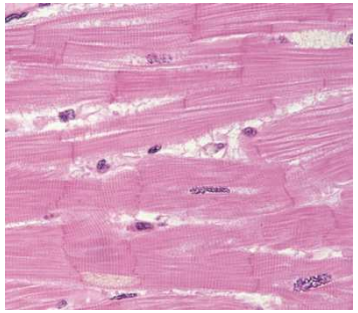


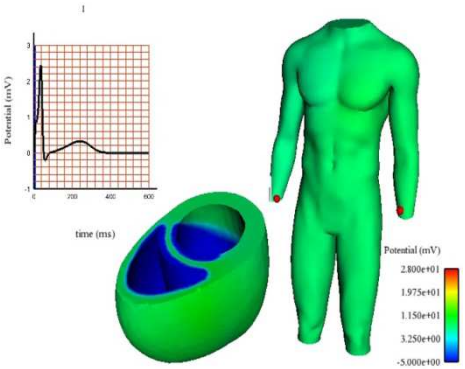
Figure 3: Snapshot of a color-coded pressure distribution for the flow around the diffuser and impeller of the DeBakey VAD



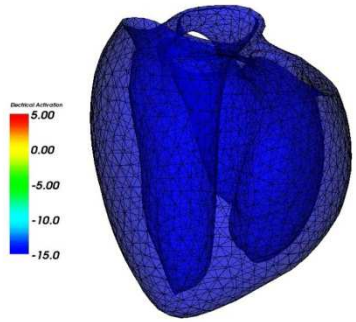
- **CFD code from Prof. Behr’s group at Aachen University**
- **5 Mnodes per geometry**
- **Optimization for minimizing both hemolysis and thrombosis**
- **4000 procs of the Bluegene/L at Jülich**

Virtual Heart

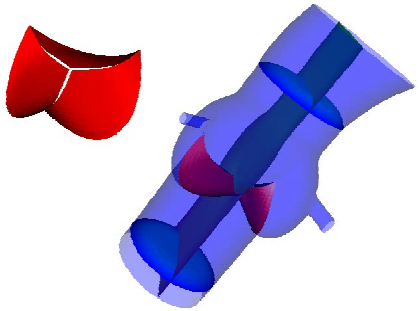




Electric activation

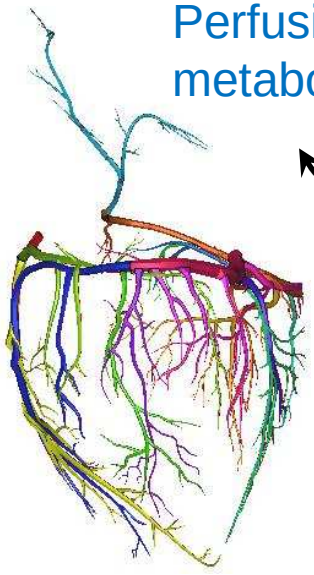


Myocard contraction



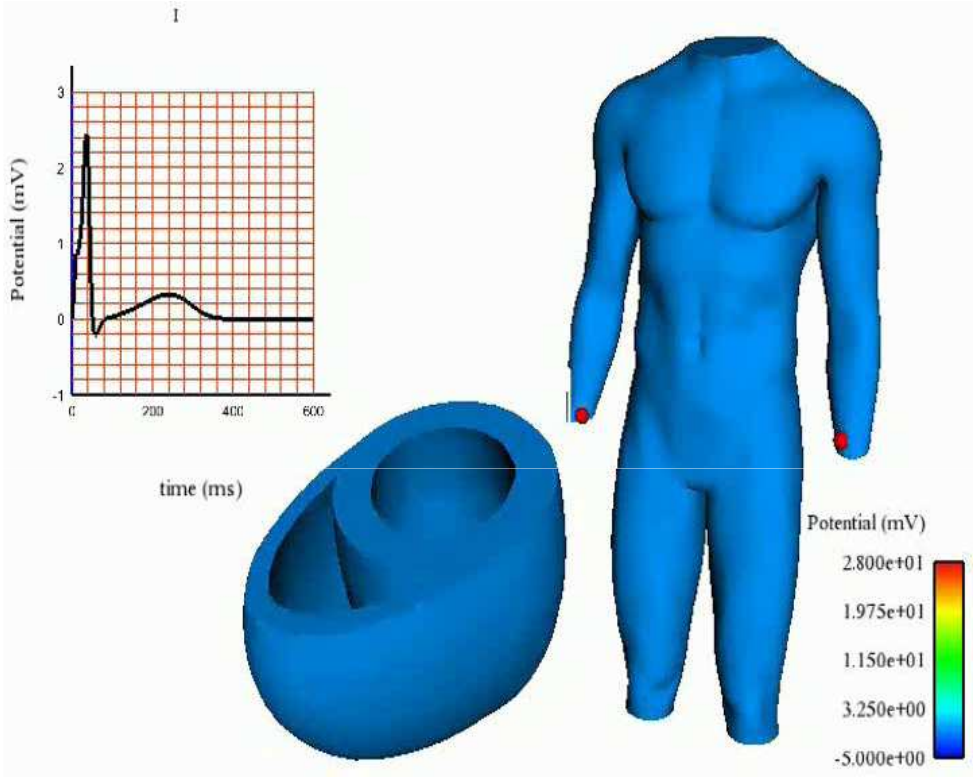
Blood flow

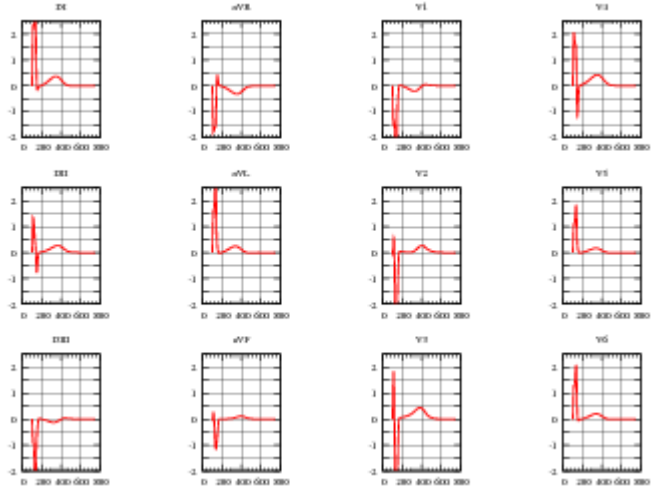
Perfusion and metabolism



CardioSense3D (Equipe-projets Asclepios, Macs, Reo, Sisyphe)

Virtual Heart - ECG





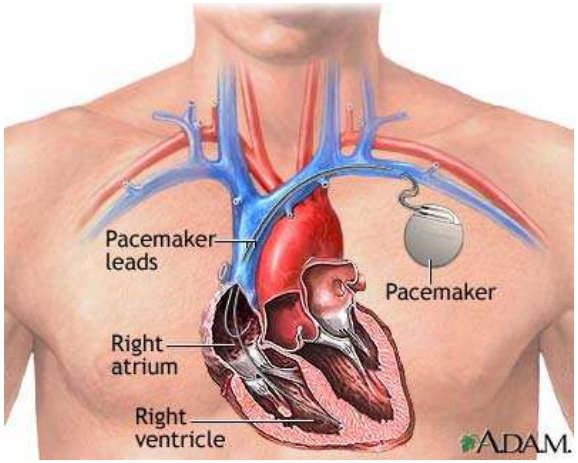
Computed ECG

Actual ECG

CardioSense3D (Equipe-projets Asclepios, Macs, Reo, Sisyphe)

Multisite resynchronization

- Heart desynchronization is a major cause of cardiac deficiency
- Possible treatment: Pacemaker based multisite stimulation (Dr. Cazeau, 1995)

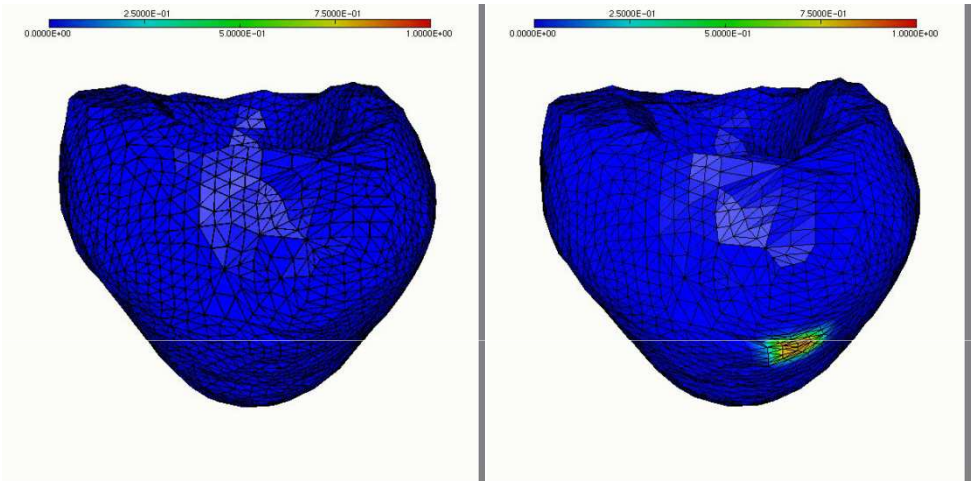


Where stimulate ?

When ?

Which criteria ?

Reference case **Pathologic case**



Computations allow to address the following questions:

- Positions of the stimulation probes ?
- Which criteria should be used for the diagnostic ?

CardioSense3D (Equipe-projets Asclepios, Macs, Reo, Sisyphe)

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PRE-OP SURGICAL PLANNING

- In case of complicated or multi-level disease, the optimal vascular reconstruction procedure might not be obvious
- Thanks to CFD, different options can be evaluated a priori regarding their hemodynamics consequences
- Numerical hemodynamics can provide an aid to discriminate between different possible therapeutic interventions

PRE-OP SURGICAL PLANNING

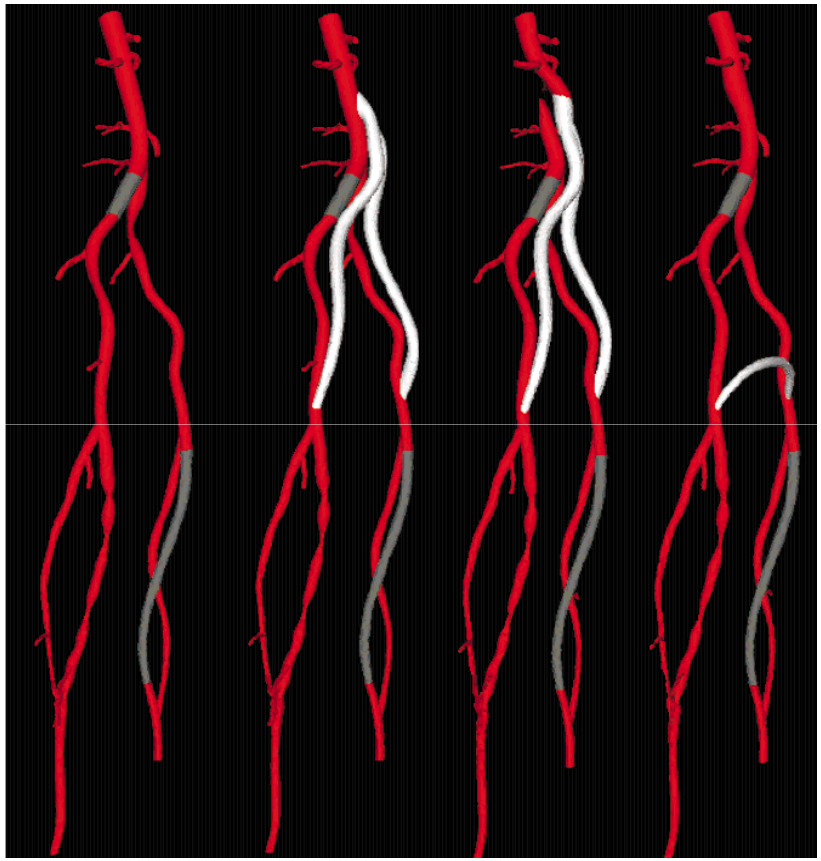
- Proof of concept done in the Stanford Group

- Specific case:
  - occluded right iliac artery,
  - partially occluded left iliac artery,
  - occluded left profunda
  - diffusely diseased right superficial femoral artery

- Blood flow solutions are obtained under pre and different virtual post-operative conditions

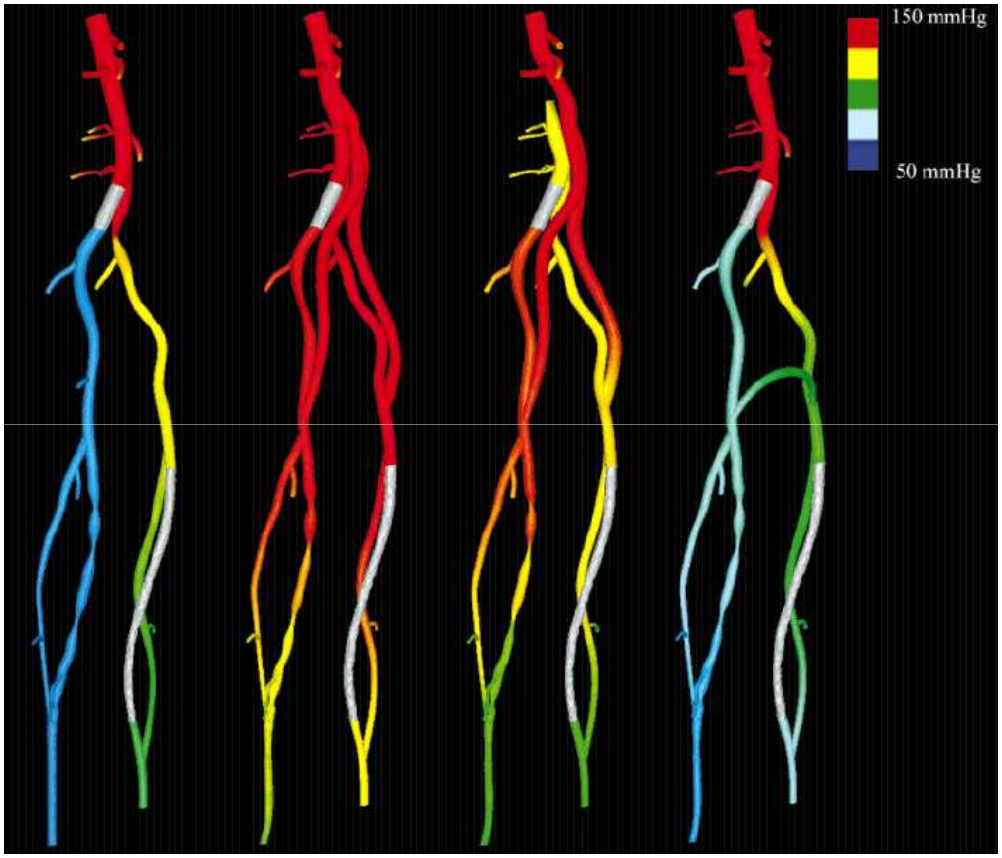
PRE-OP SURGICAL PLANNING

Geometry



Pre-op # 1 # 2 # 3

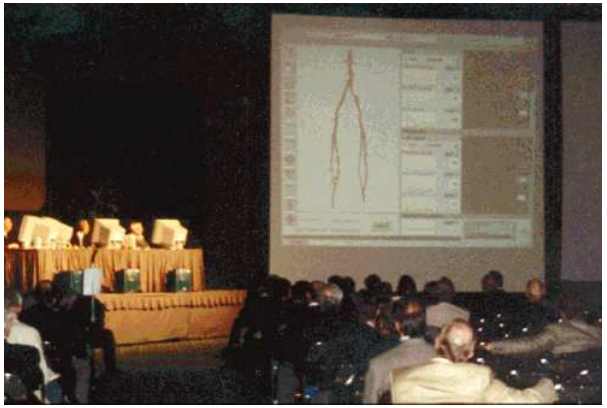
Pressure at peak



Pre-op # 1 # 2 # 3

Taylor et al., 1999

PRE-OP SURGICAL PLANNING



Proof of concept OK but may not be used by clinicians before a long, long time ...

- Models for long term evolution are not yet available

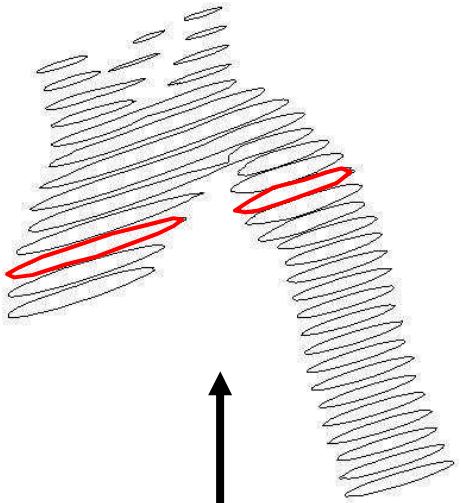
- Hemodynamic is certainly only one part of the story. What about the unavoidable injuries, the chemical aspect, the endothelium response, the vessel remodelling, etc ...

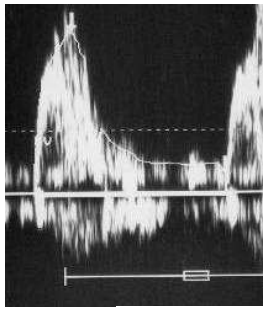
- Even if classical mechanics were the only/major factor: would it be possible to perform predictive simulations ? Yes, in theory ...

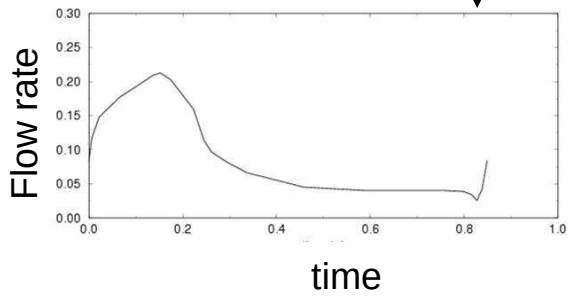
Fluid-Struct. Interaction methodology

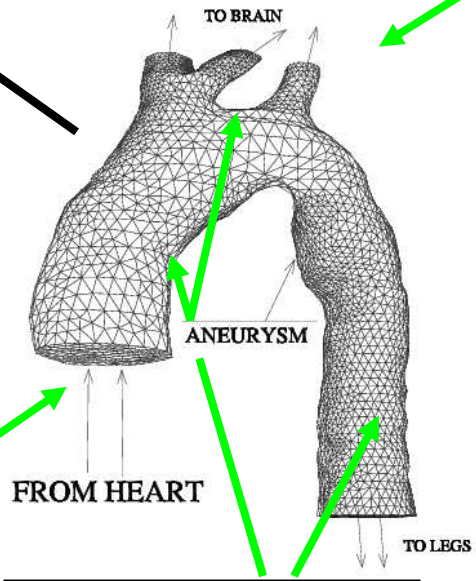
CODE FOR
FLUID + SOLID

3D mesh

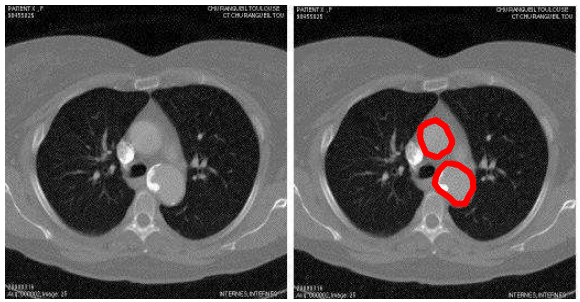








DATA ABOUT
THE VESSEL
RHEOLOGY AND
ENVIRONNEMENT



Fluid-Struct. Interaction: Related issues

- This is not an easy task:

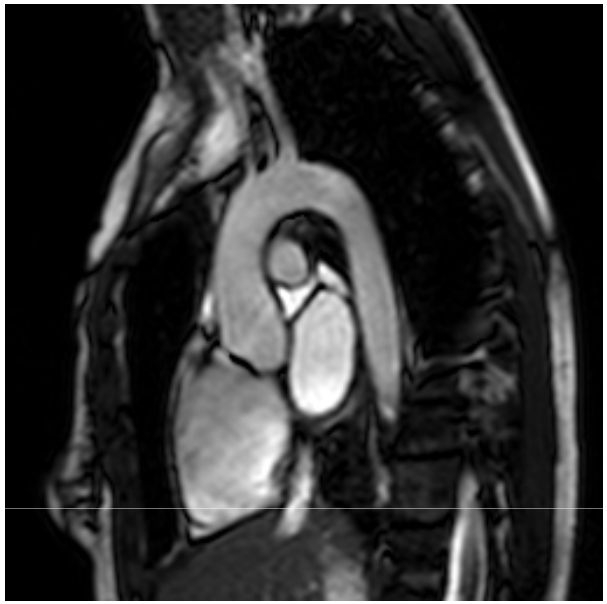
☺ – Strongly coupled problem because the density ratio is close to unity,

☺ – The deformations may be large, and not elastic

? – What is the rheology of the arteries ?

?? – What are the outer Boundary Conditions ?

The biggest issue: the outer conditions

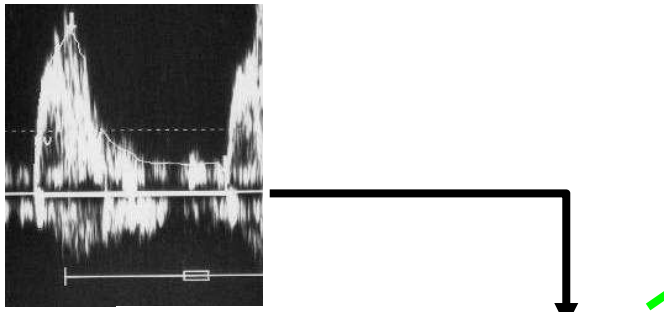


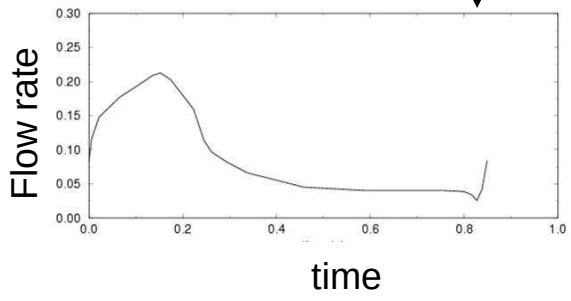
- The aorta and the pulmonary artery are sometimes in contact during the cycle …
- Should we compute both to get the wall motion right ?
- What about other organs such as the rachis, trachea, ligamentum arteriosum, … ?

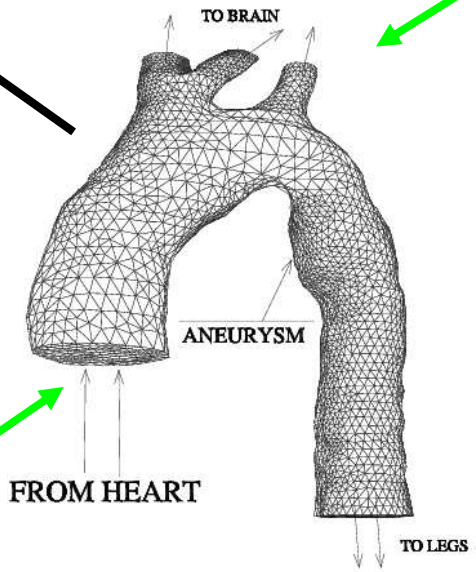
“Uncoupled” methodology

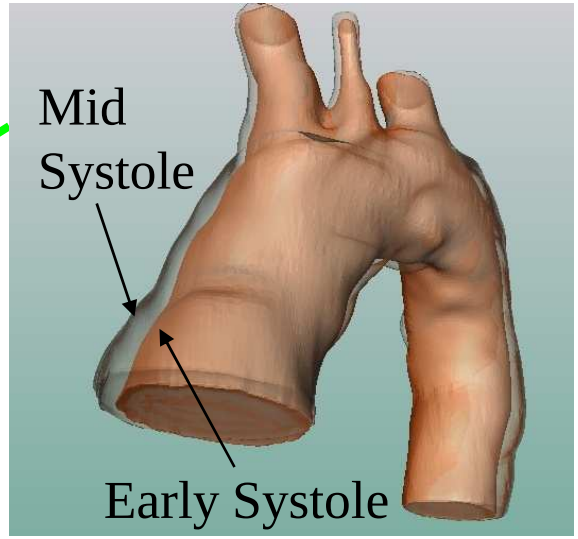
CODE FOR FLUID ONLY

4D mesh





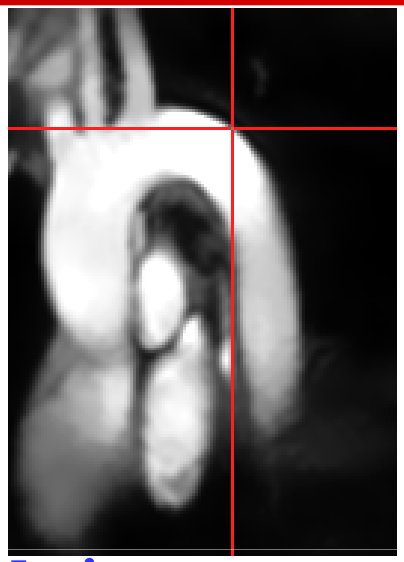




Phase locked imaging (ECG)

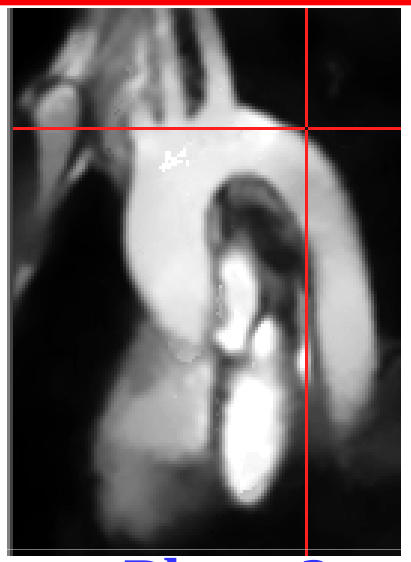
CFD/MRI-based Functional Imaging

Generation of the 4D mesh



T1

T2

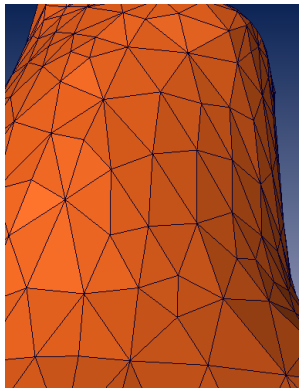


Native geometry

Phase 1

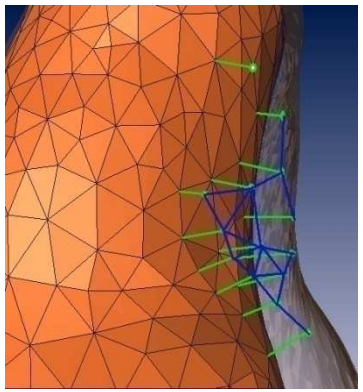
Phase 2

Native mesh



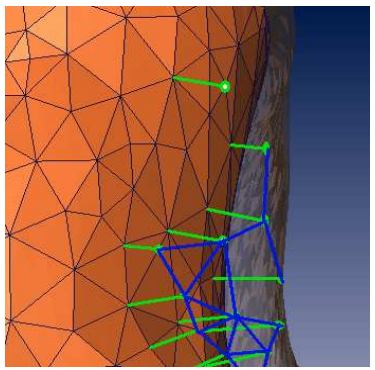
T1

Mesh 1

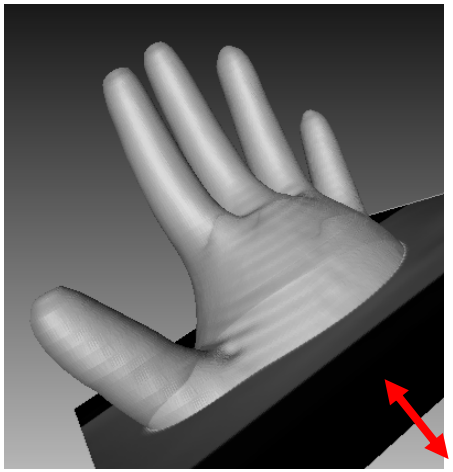


T2

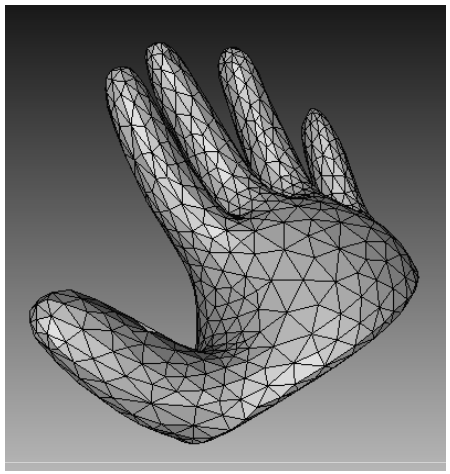
Mesh 2

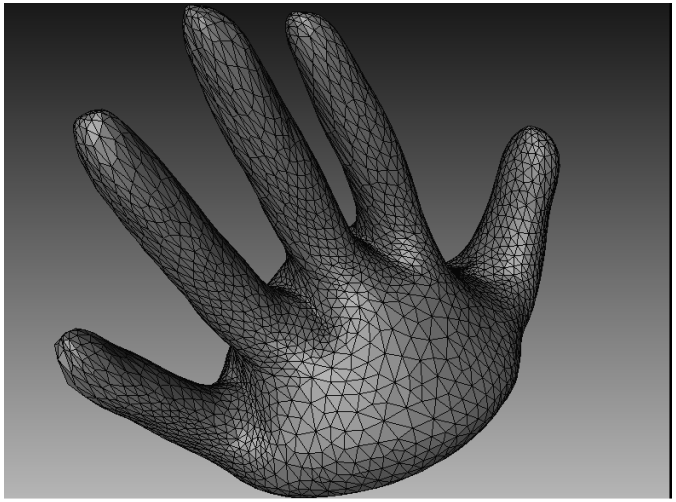


The hand glove model



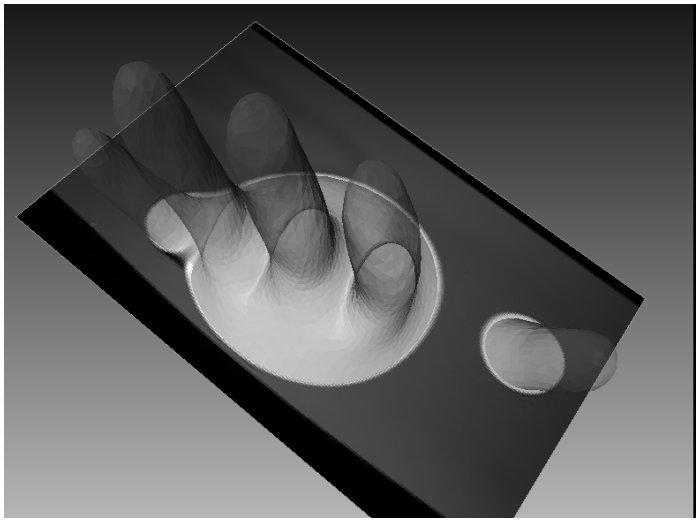
Native mesh





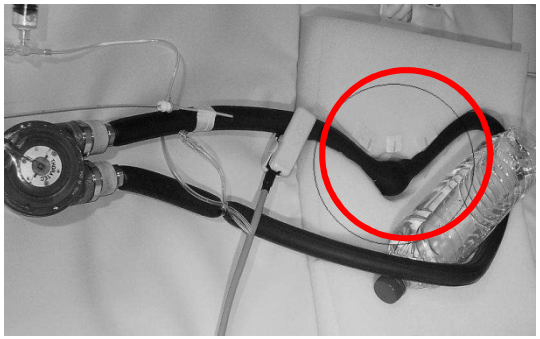
4D mesh

<u>Phantom model</u>
hand glove with a sinusoidal flux

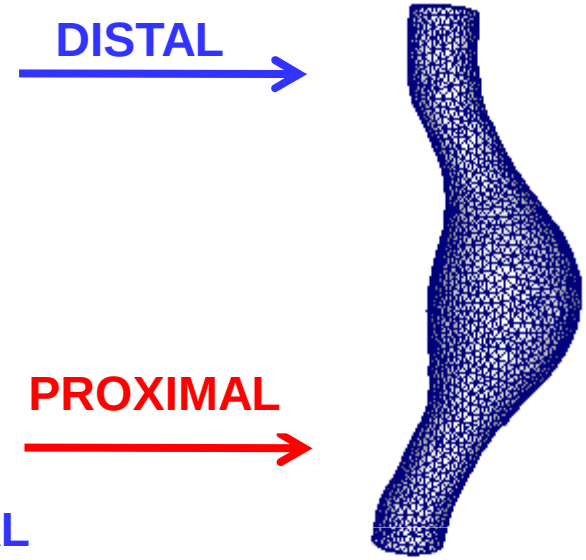


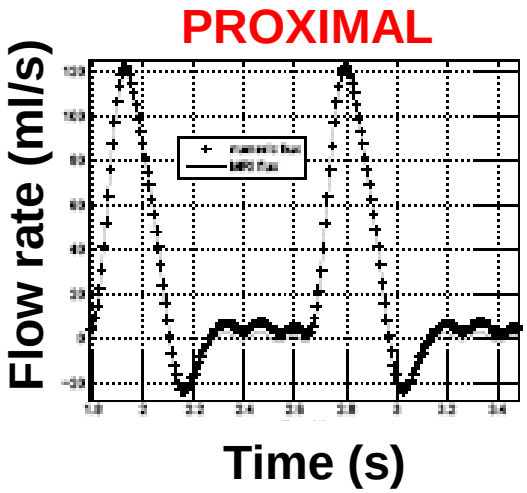
Consistency with MRI

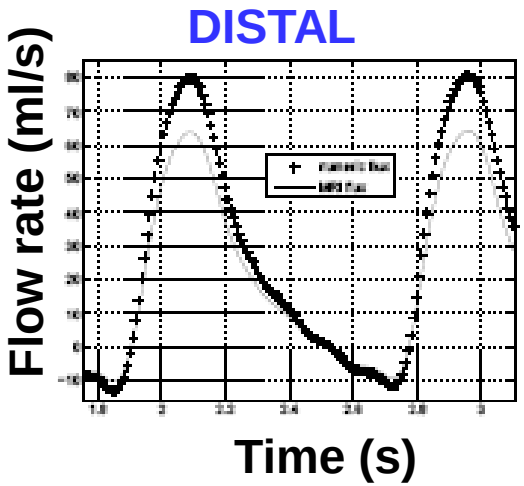
Windkessel effect



TAA Phantom

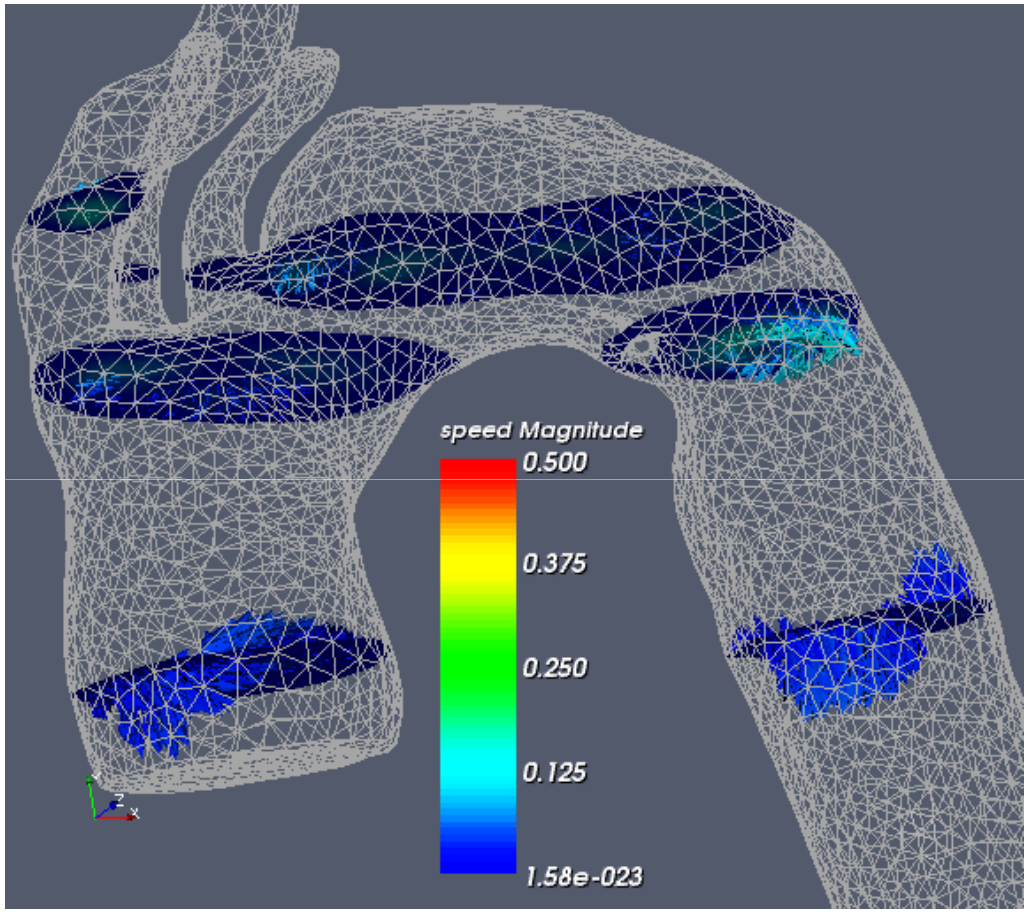






Computations done with the AVBP code from CERFACS

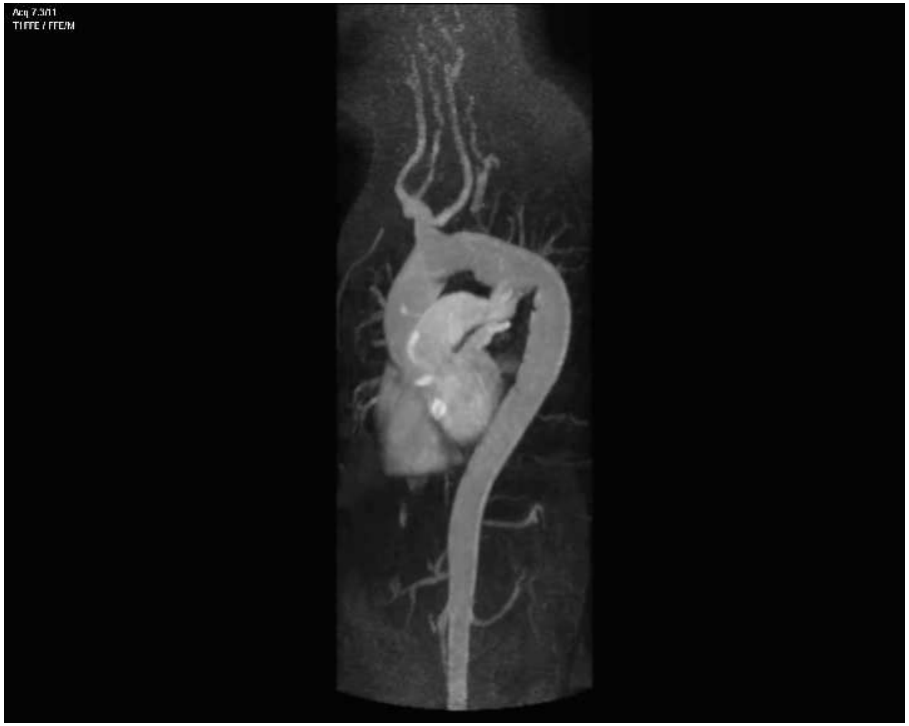
Windkessel effect – Actual geometry



Computation done with the AVBP code from CERFACS
Moreno – CHU Toulouse - 2007

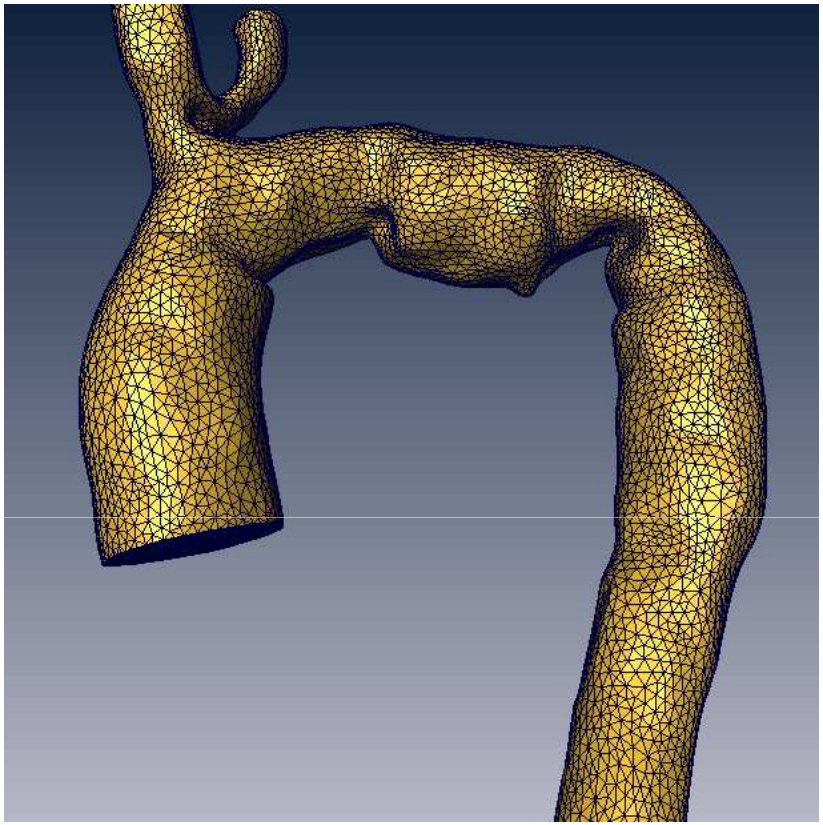
An actual physiologic case

CT after stenting

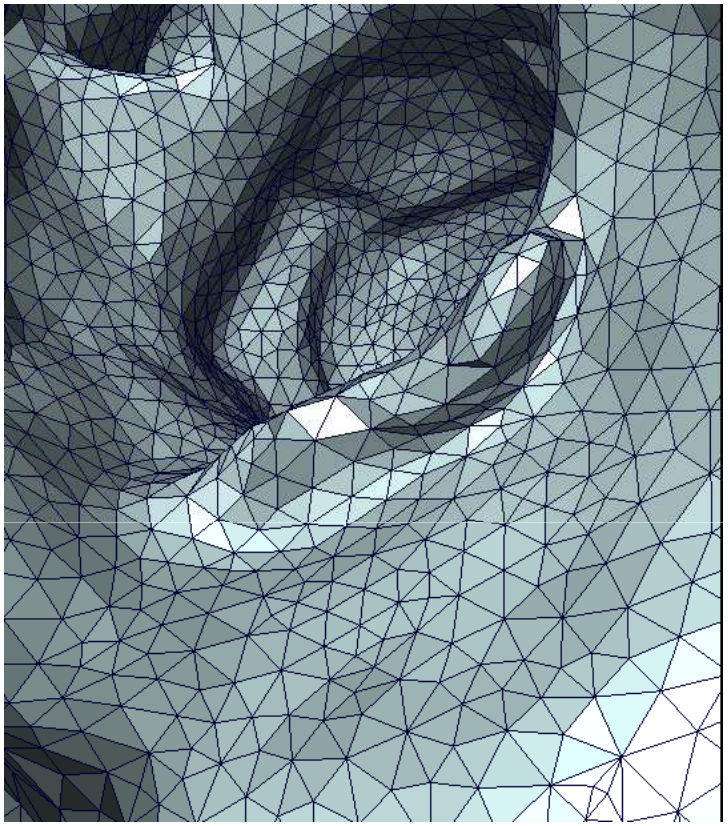


CE-MRI

MRI/CFD based functional imaging



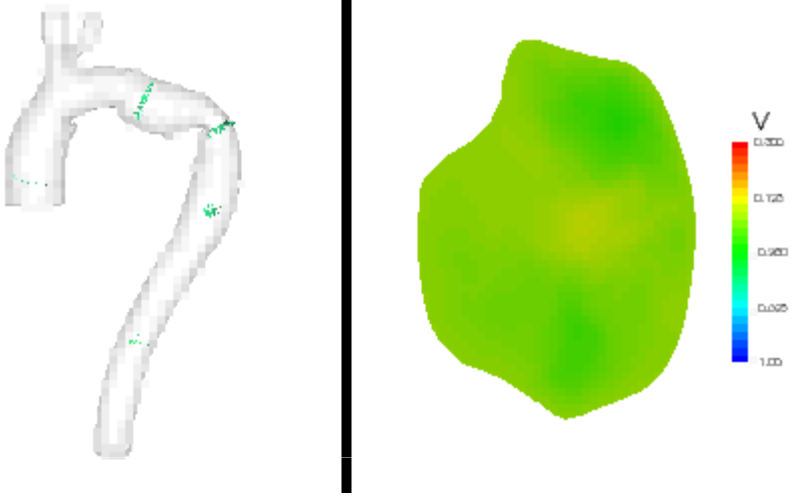
Moving mesh



From inside …

Moreno – CHU Toulouse - 2007

Qualitative validation

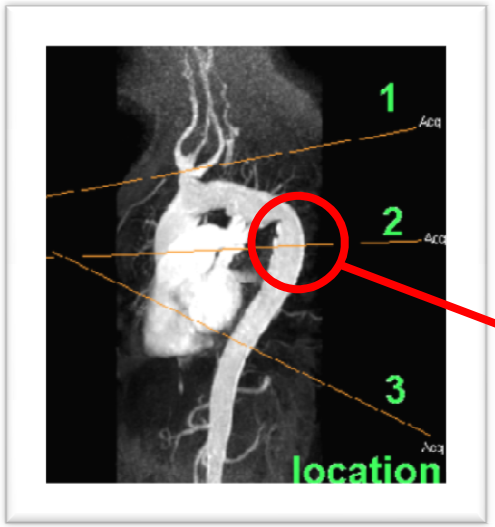


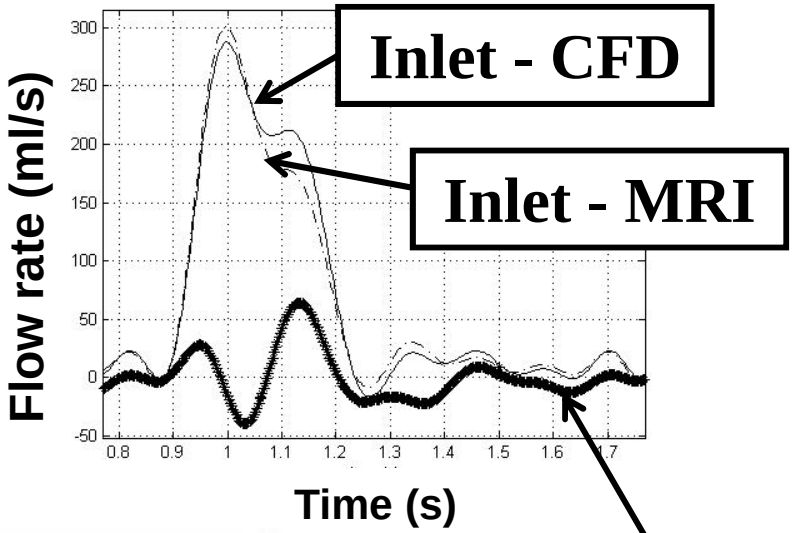
MRI/CFD

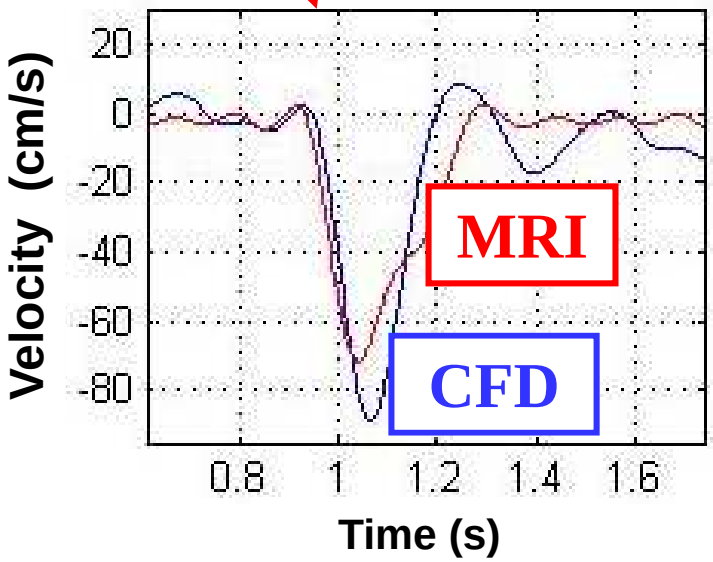
Both MRI and CFD indicate positive/negative vertical velocity in this region

Phase Contrast MRI Vertical velocity

Further validation







Sum – CFD

Integrates to zero

Functional Imaging in clinical routine ?

☺ • Computations should be performed in situ next to the MRI or CT facilities

☺ • Should provide useful data at low extra cost
A 30 procs server costs approx. 5 % of a modern MRI system ...

? • Fast enough to provide results within a few hours,

?? • Simple enough to be operated by clinicians ...

?? • Trustable by clinicians

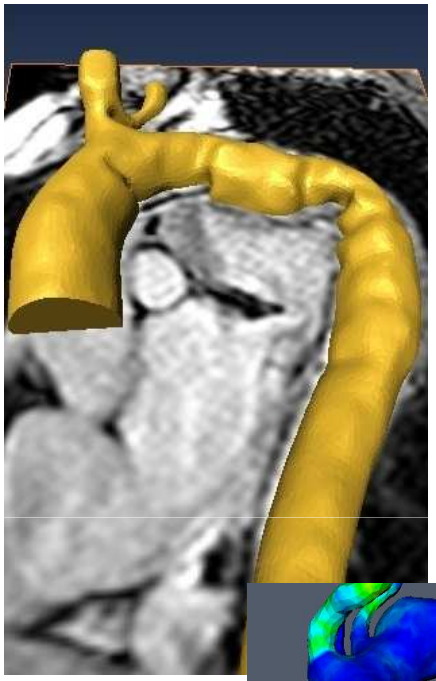
Functional Imaging in clinical routine ?

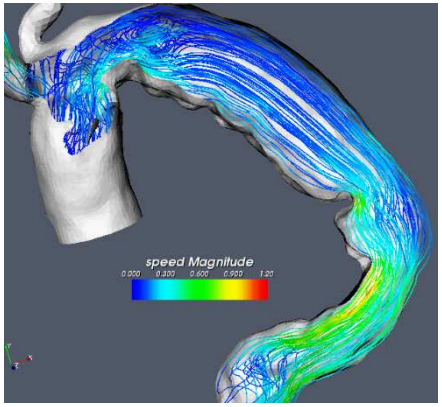
- OCFIA: Optimized Computational Functional Imaging for Arteries

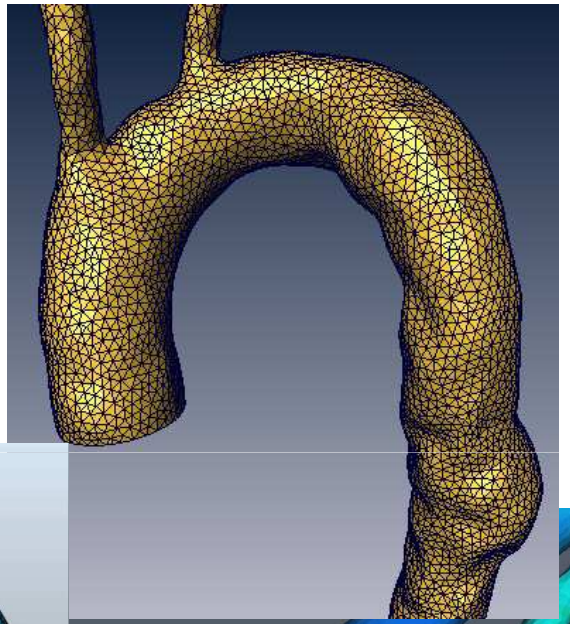
- ANR AAP CI 2007 - Kick-off meeting Feb. 2008
  UM2 / ASA / CHU Toulouse / INSERM
  - 24 h total ‘elapsed’ time, computer + human
  - All the computations done in situ
  - “One-Click” technology

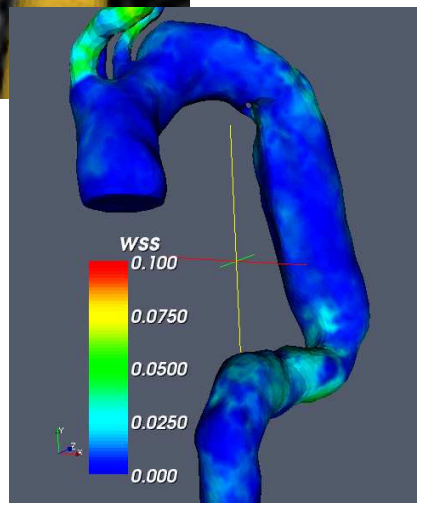
- DARI 2009: New CT « Simulation Biomédicale et Applications à la Santé »

QUESTIONS ?




speed Magnitude

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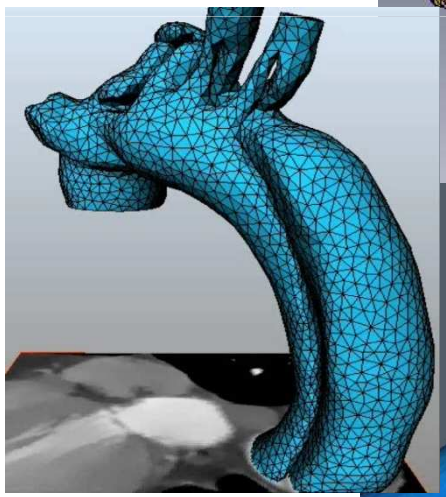
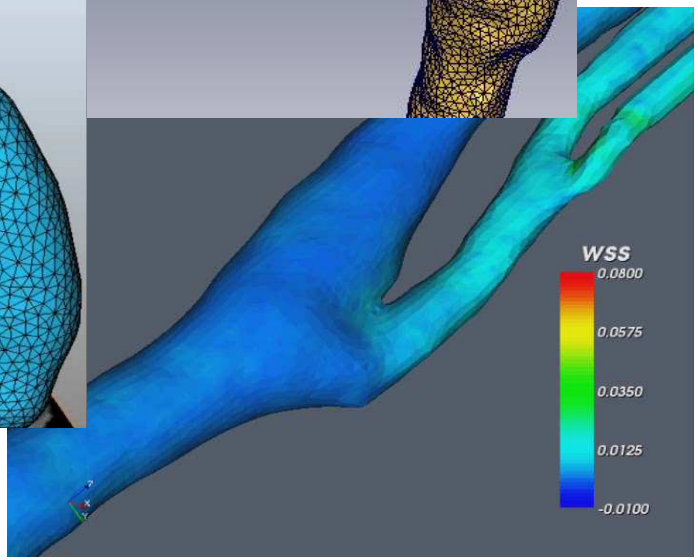
0.0250
0.000

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0.0125
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