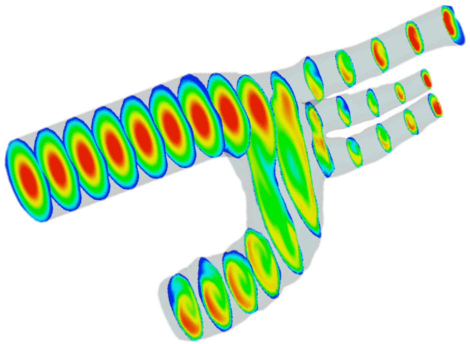
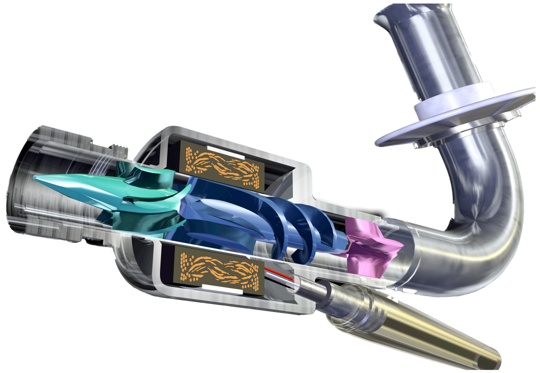




FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Numerical Analysis of Blood Flow in Human Arteries and Medical Devices

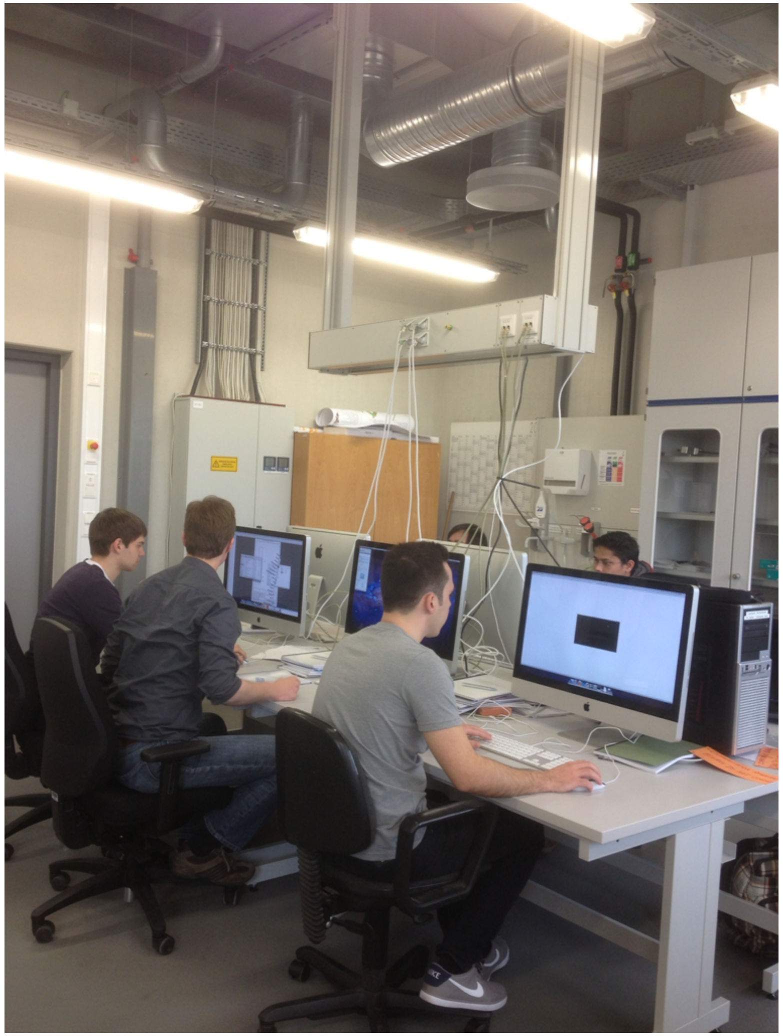
Prof. Dr.-Ing. Mehdi Behbahani

Faculty of Medical Engineering and Technomathematics
FH Aachen, Campus Jülich, Institute of Bioengineering,
Biomaterials Laboratory

Talk given at Club U, Paris, Chatou

April 9, 2013

Workgroup and Hardware



typically used is Apple`s 27" iMac:

Processor:

Quad-Core Intel Core i7 (Turbo Boost up to 3,9 GHz).

cores: 4 - 8

RAM: 8 - 20 GB 1600 MHzDDR3

GPU: NVIDIA GeForce GTX 675MX

Fluid Dynamics Group at FH Aachen

using code Saturne since 2012

CFD work

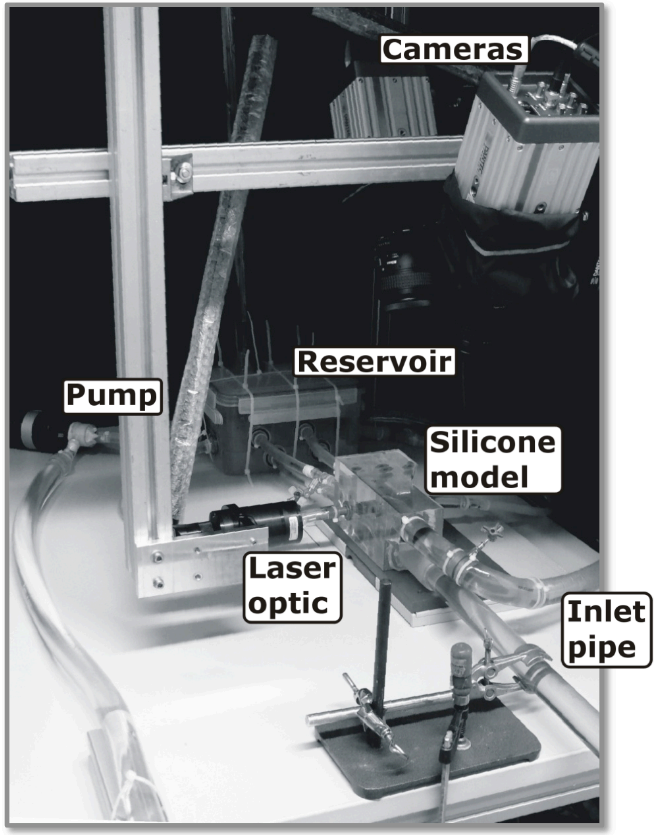
Aortic / Stenosed vessel flow

Abdomial aortic aneurysm

Organ conservation

Fluid structure interaction

Experimental work



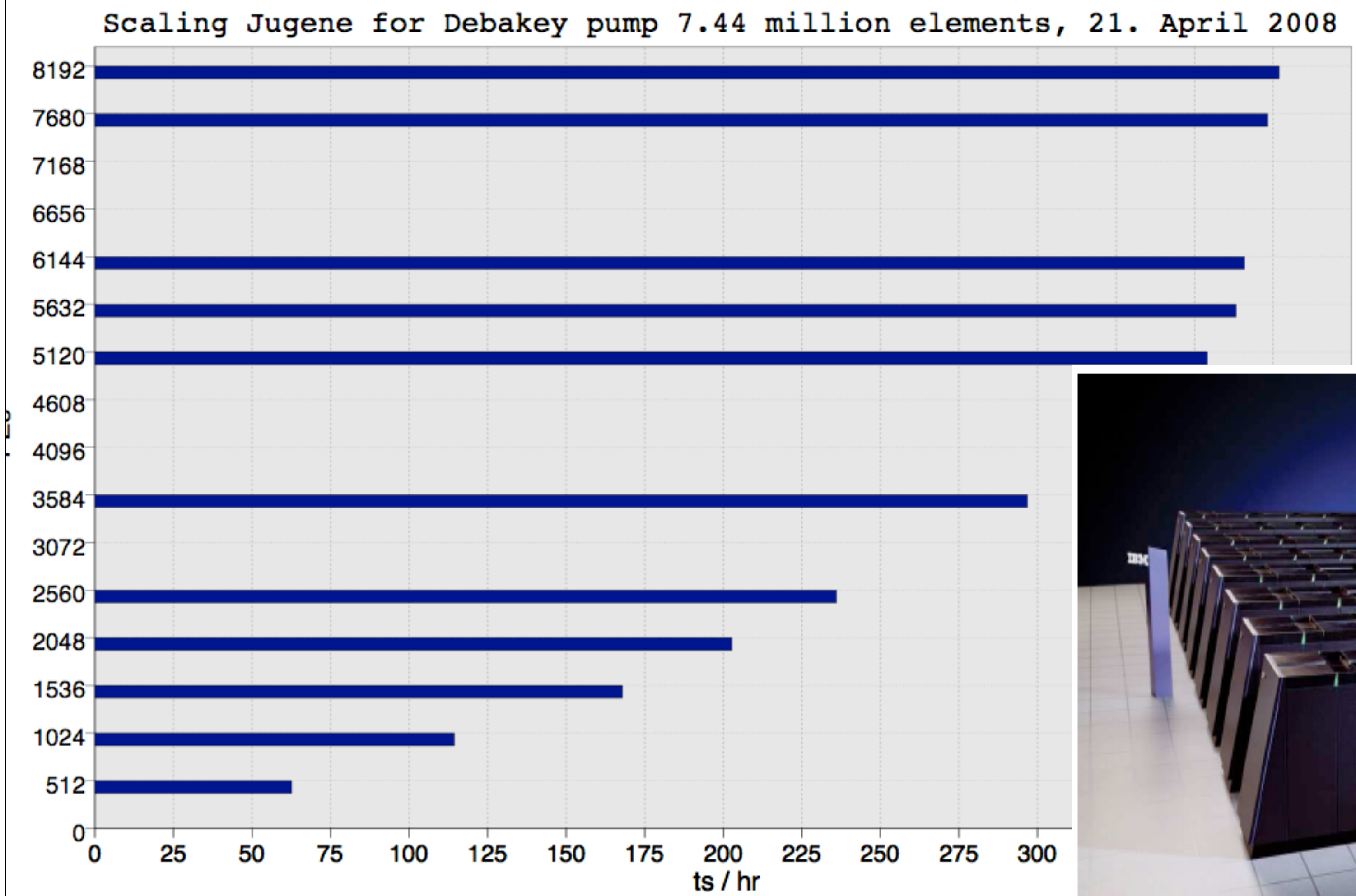
PIV [1]

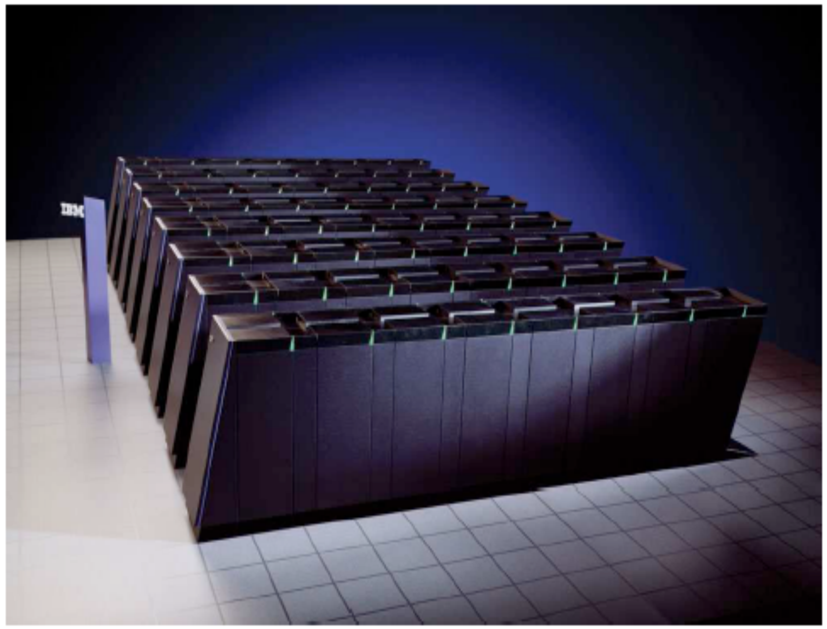
Flow experiments
(Couette flow, Taylor vortices, Non-Newtonian effects, ...)

XNS, FE-based simulation code

parallel computing

Earlier used code XNS scaled well up to 5000 processors





[2]

Code Saturne, FE-based simulation code

future goal: massive parallel computing

Future possibility to use code Saturne with BlueGene/G super computer at Juelich research facility

BlueGene/G

JUQUEEN [3]

- 28 racks (7 rows à 4 racks) - 28,672 nodes (**458,752 cores**)
  Rack: 2 midplanes à 16 nodeboards (16,384 cores)
  Nodeboard: 32 compute nodes
  Node: 16 cores
- Main memory: 448 TB
- Overall peak performance: **5.9 Petaflops**
- Linpack: > 4.141 Petaflops

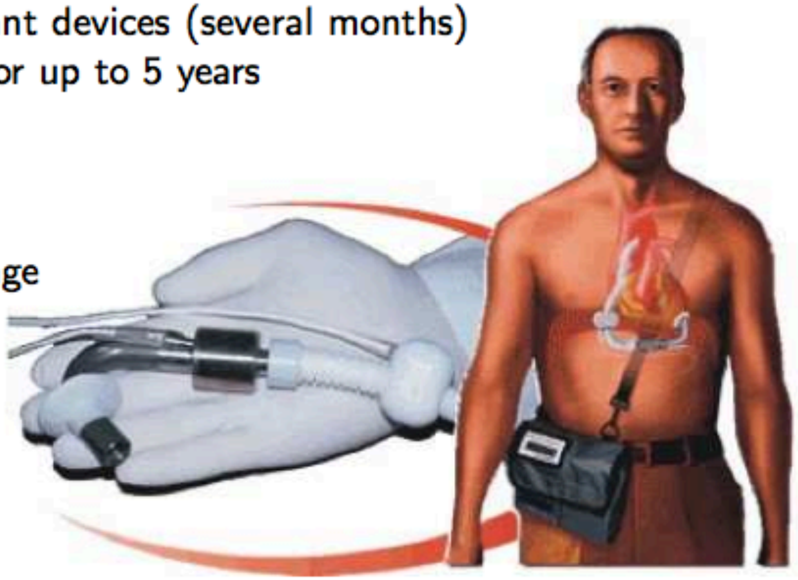
Overview

- Motivation
  - Prediction of Blood flow and Thrombosis in Medical Devices
  - Prediction of Blood Flow and Thrombosis in the Human Circulation
- Numerical Analysis of Blood Flow in Medical Applications using code XNS / code Saturne
  - Sudden Expansion
  - Dialysis
  - Micromed DeBakey LVAD
- Numerical Analysis of Blood Flow in Human Circulation using code Saturne
  - Shear Stress and Shear Rate in Vessel Flow
  - Steady and Pulsatile Blood Flow through Aorta
  - Fourier Representation of the Physiological Blood Flow through Aorta
  - Blood Flow in the Carotid Bifurcation Arteries
  - Blood Flow in an Abdominal Aortic Aneurysm (AAA)
- FDA Study

FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

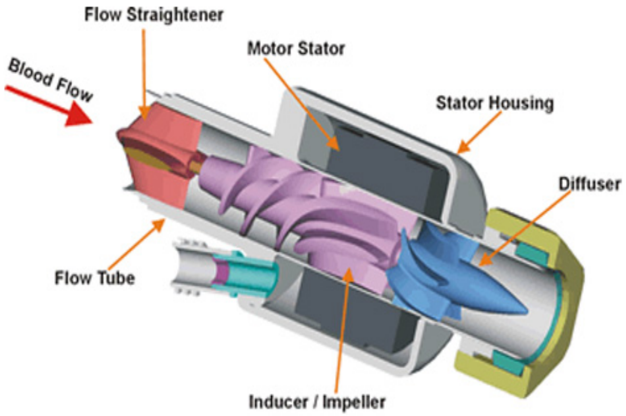
Motivation

- Heart disease
  - "number one killer" of adults in Europe and worldwide
  - 20 million cases of heart disease reported
  - $> 100,000$ patients could benefit from a new heart
  - donor hearts available for only 5% of patients
- Ventricular Assist Devices (VAD):
  - replace the pumping function of the heart
  - presently: bridge to transplant devices (several months)
  - in future: long-term assist for up to 5 years
- Challenges:
  - good hydraulic performance
  - minimization of blood damage

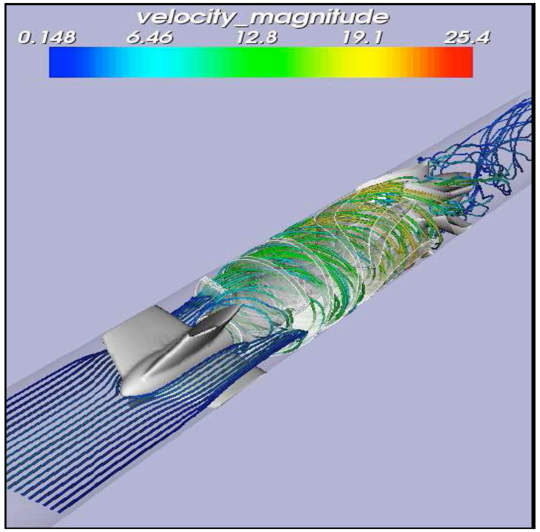


Numerical Analysis of Blood Flow in Medical Applications

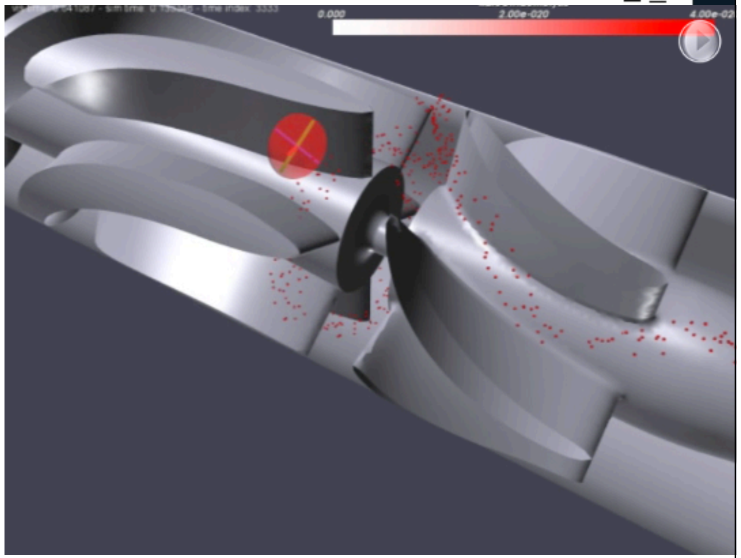
Micromed DeBakey LVAD



Design of MicroMed DeBakey blood pump [4]



Flow simulation



Computation of red blood cell trauma

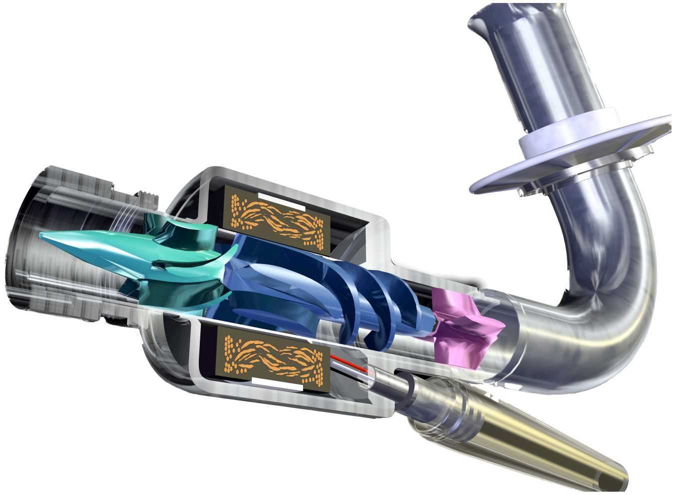
Thrombus formation and embolization is far more dangerous to the patient than hemolysis.

How is it possible to model and simulate the complex reactions of platelets ?

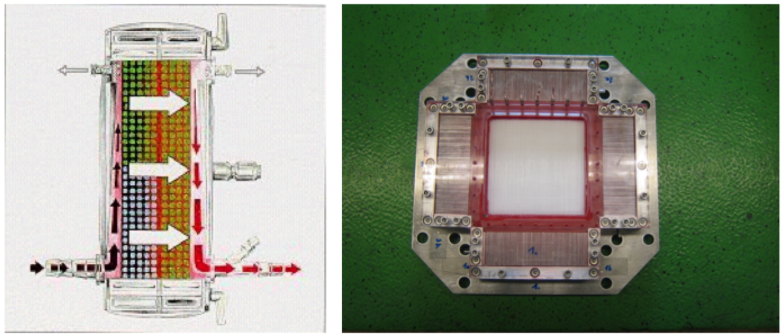
Motivation

Prediction of Thrombosis in Medical Devices

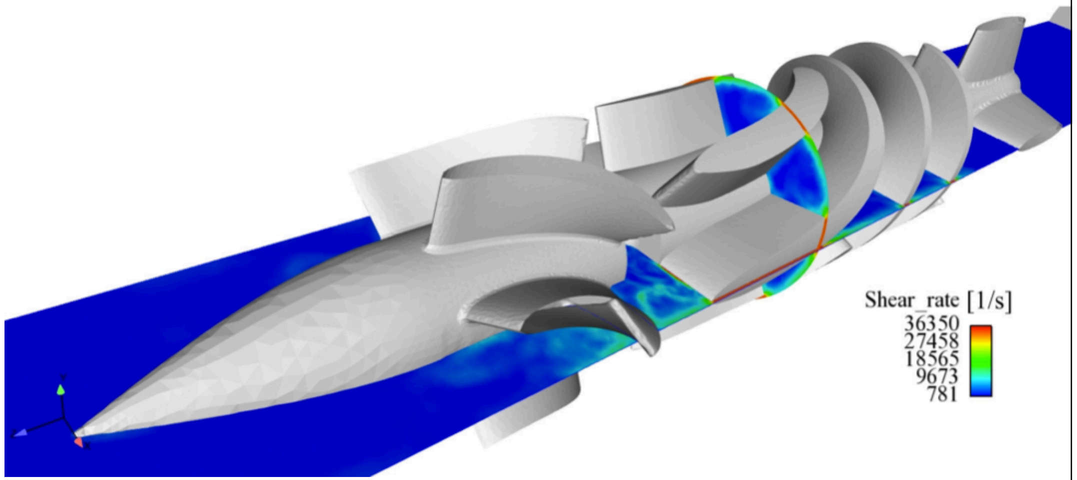
Bjork-Shiley heart valve



Micromed DeBakey LVAD [5]



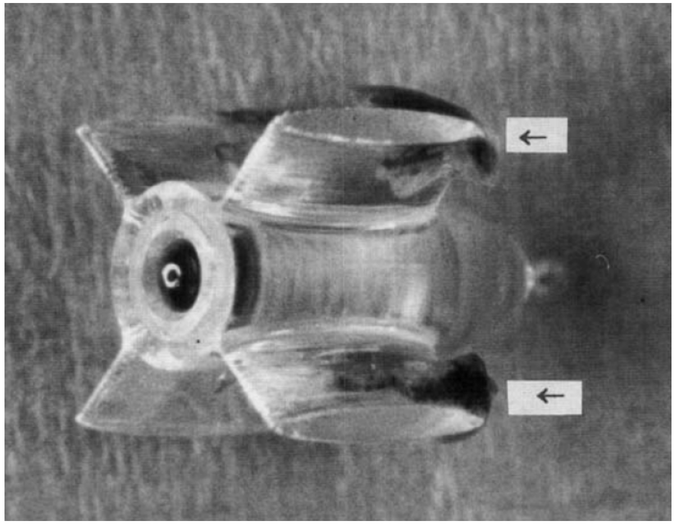
Oxygenators,
left commercially available model,
right with defined hollow fiber arrangement



Motivation

Prediction of Thrombosis in Medical Devices

Thrombus growth due to unphysiological flow conditions



Thrombus adhesion at the straightener (in the area of the arrows) [6]

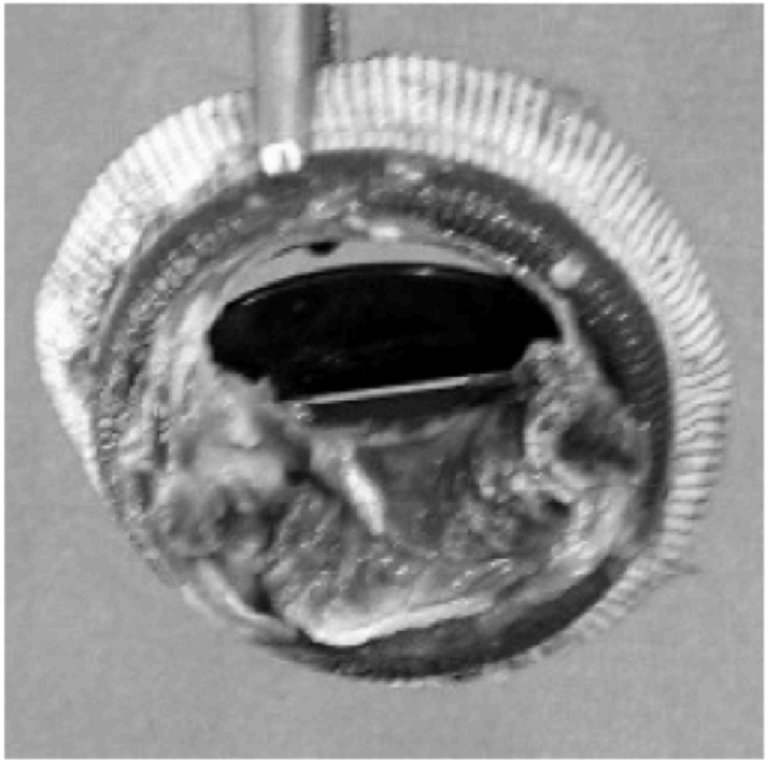
Thrombus adhesion due to blood contact with thrombogenic material

Inlet cannula to blood pump [7]

Motivation

Prediction of Thrombosis in Medical Devices

(a) Frontal view.



(b) Rear view.

Figure 3.7. The shown thrombus developed within a few days after implantation of a mechanical bi-leaflet heart valve and an emergency operation was necessary to save the patient's life. The histologic examination of the obstructing material showed fibrin mass in which erythrocytes, leukocytes, and platelets were entrapped [8]. Pictures taken from [8].

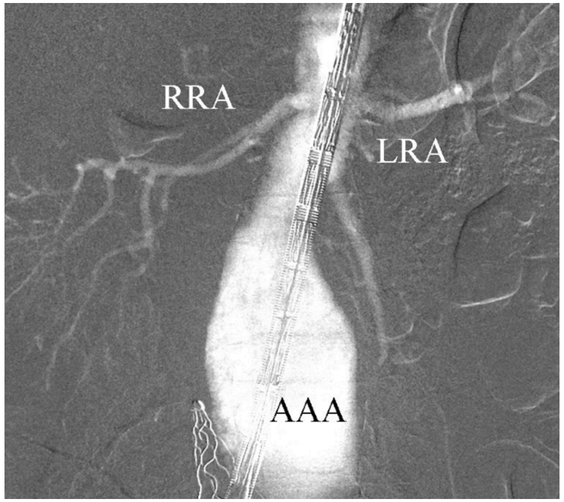
© FH AACHEN

FH AACHEN UNIVERSITY OF APPLIED SCIENCES

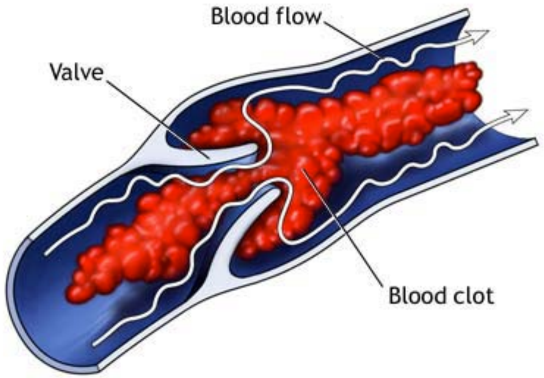
Motivation

Prediction of Thrombosis in the Human Circulation

Arterial thrombosis (stenosed arteries)

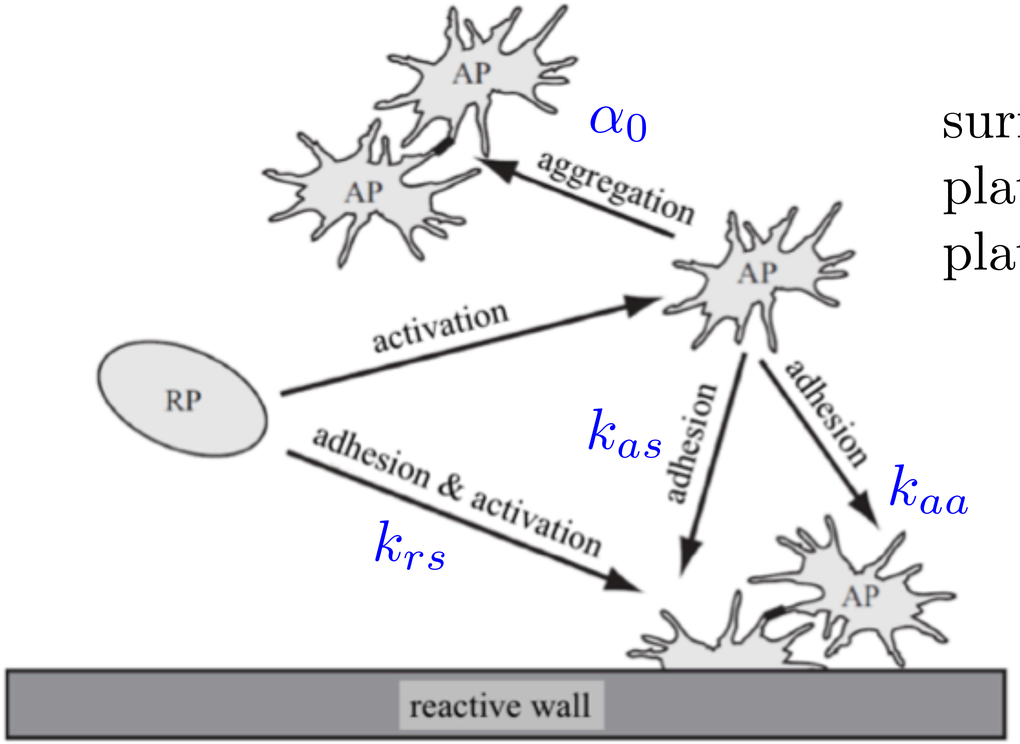


Interdependence of aneurysm and thrombus growth



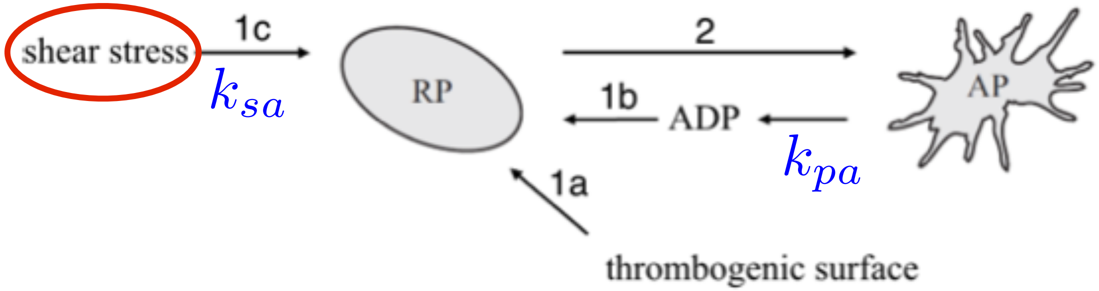
Blood clotting in the heart or in veins

A mathematical model describing platelet reactions



surface-platelet adhesion rates (k_{rs}, k_{as}),
platelet-platelet adhesion rate (k_{aa}),
platelet-platelet aggregation rate (α_0),

platelet activation rates (k_{pa}, k_{sa})



A mathematical model describing platelet reactions

advection - diffusion - reaction approach

$$(1) \quad \frac{\partial [C_i]}{\partial t} + (\mathbf{u} \cdot \nabla)[C_i] = \nabla \cdot (D_i \nabla [C_i]) + R_i$$

Equation (1) is written for $[RP], [AP]$ and $[ADP]$.
The resulting 3 equations are coupled via reaction terms R_i.

$$(2) \quad R_{RP} = -k_{pa}[RP] - k_{sa}[RP]$$

rate of chemical platelet activation due to ADP

rate of mechanical platelet activation due to high shear

$$(3) \quad R_{AP} = +k_{pa}[RP] + k_{sa}[RP] - \frac{16\alpha_0 \dot{\gamma} b^3 [AP]^2}{3}$$

AP aggregation term

$$(4) \quad R_{ADP} = +\lambda_{ADP}(k_{pa} + k_{sa})[RP]$$

amount of ADP released per platelet

Boundary conditions at the reactive wall (fluxes J_i to and from the wall depend on available free surface $S(\mathbf{x}, t)$)

$$(5) \quad J_{RP} = S(\mathbf{x}, t) k_{rs}[RP]$$

$$(6) \quad J_{AP} = (S(\mathbf{x}, t) k_{as} + (1 - S(\mathbf{x}, t) k_{aa}))[AP]$$

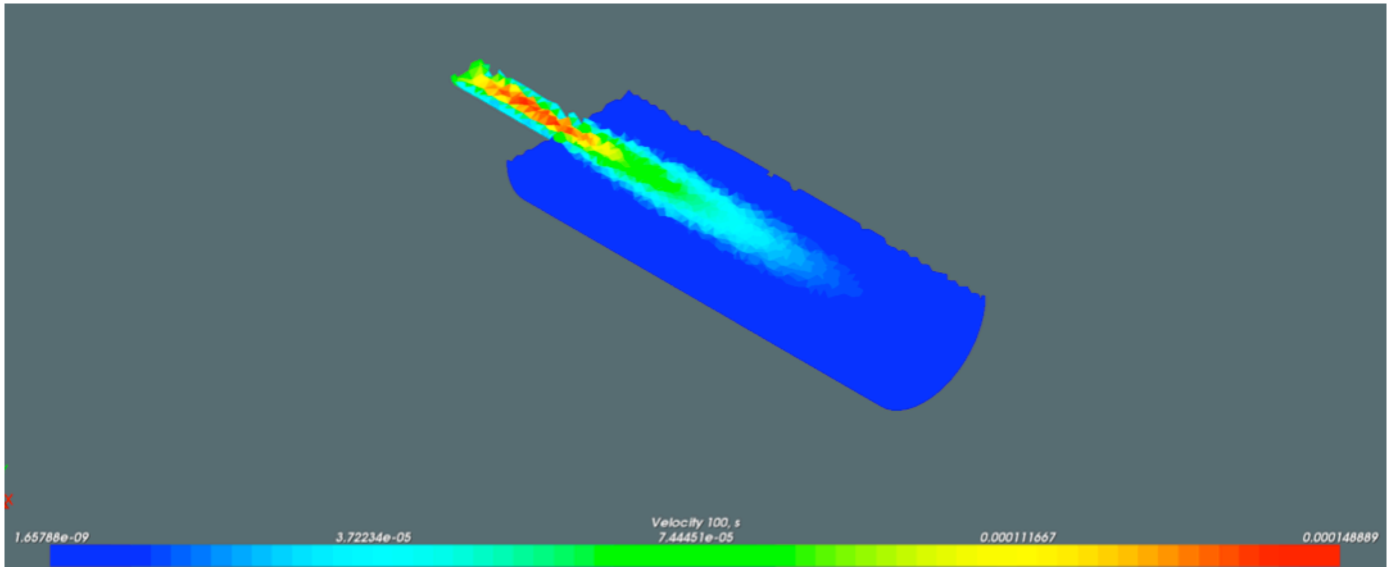
$$(7) \quad J_{ADP} = -\lambda_{ADP} S(\mathbf{x}, t) k_{rs}[RP]$$

Numerical Analysis of Blood Flow in Medical Applications

Sudden Expansion - Velocity Profile (coarse mesh using code Saturne)

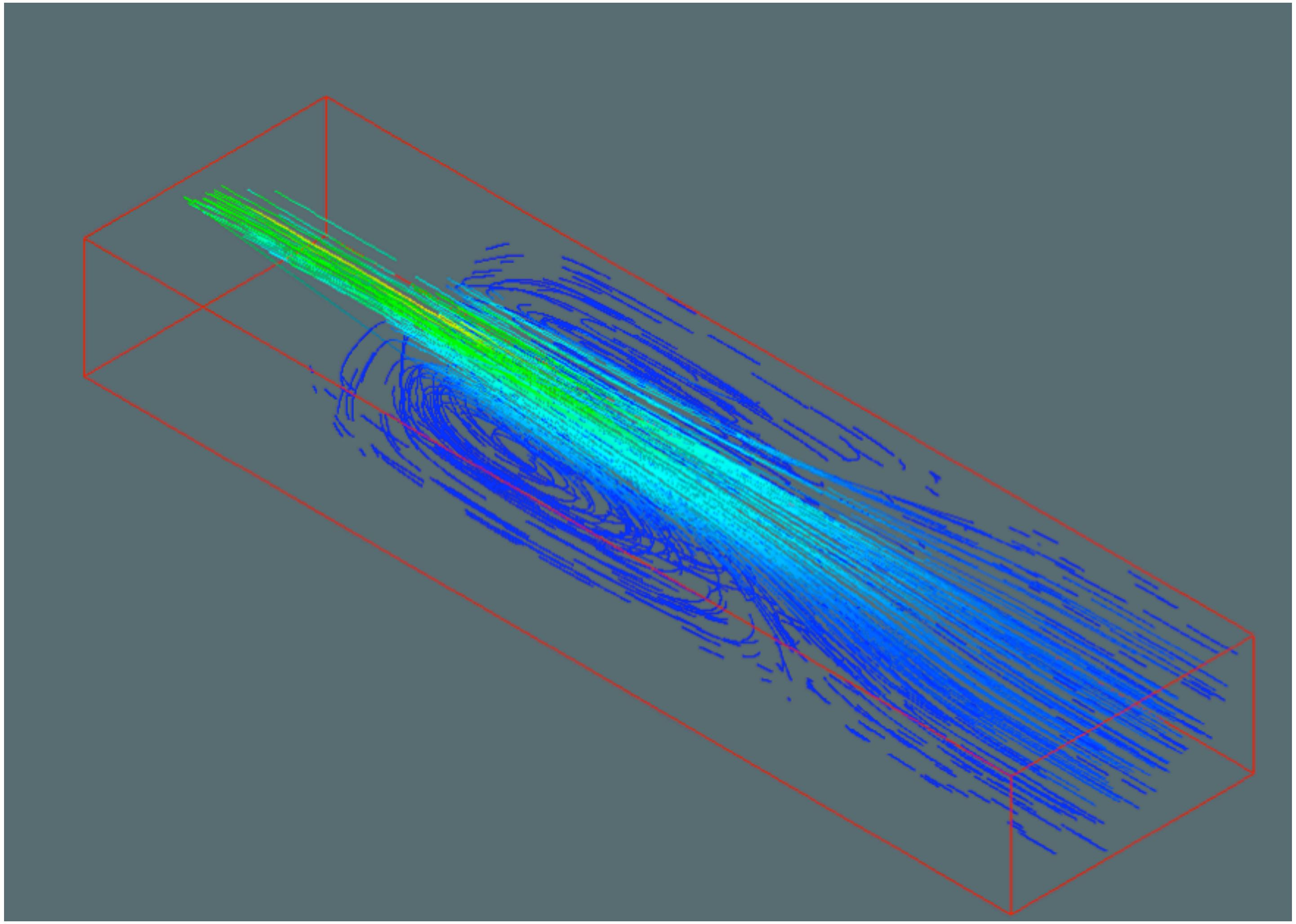
- <u>applications in the Biomedical field include</u>:
  - analyzing phenomena of stagnation areas and blood cell distribution
  - analyzing the transport of platelets in blood flow

In order to be able to validate the CFD results, we did a comparism to those results reported in the paper "Applied Mathematical Modelling" (Whaba, 2007).



Sudden Expansion - Velocity

Sudden Expansion - Stream Lines (coarse mesh using code Saturne)



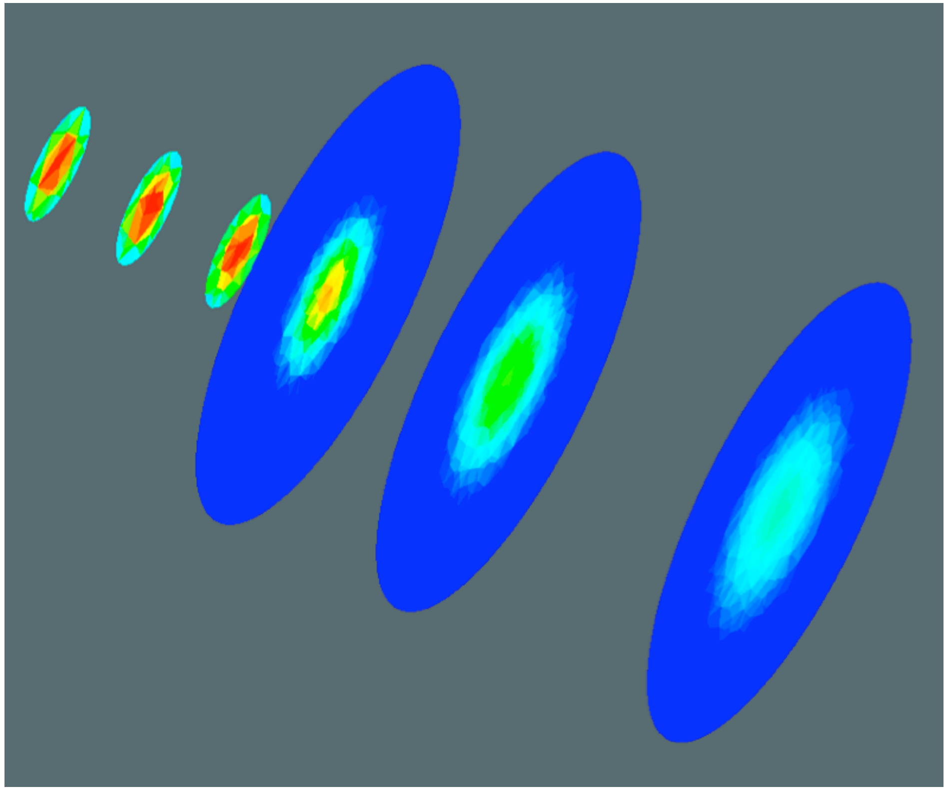
Sudden Expansion - Stream Lines

Numerical Analysis of Blood Flow in Medical Applications

Sudden Expansion - Velocity Profile (coarse mesh using code Saturne)

Even with a coarse mesh a first reasonable estimate of the real solution can be achieved

finer meshes required for precise resolution

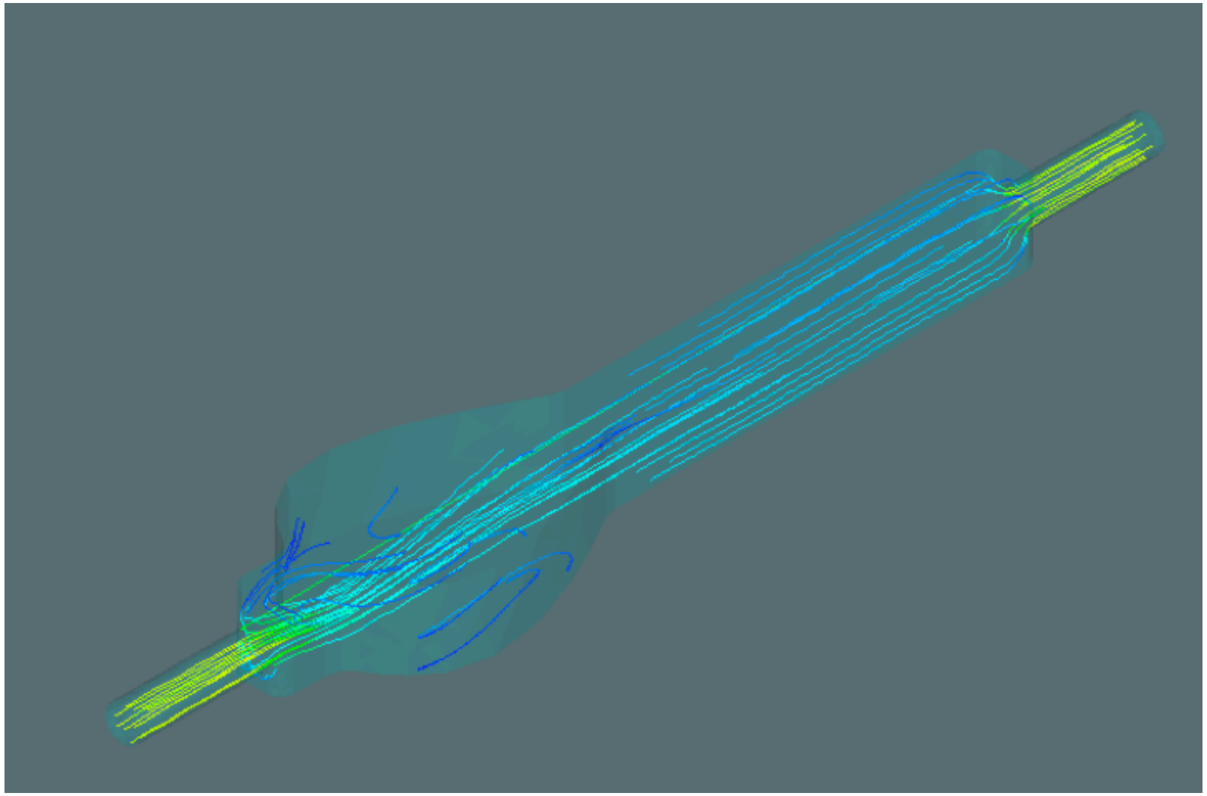


Sudden Expansion - Velocity

Numerical Analysis of Blood Flow in Medical Applications

Dialysis (coarse mesh using code Saturne)

- dialysis tube used for volumetric flow measurements using a temperature sensor
- sensor is positioned around the tubing and has a shape, which exactly fits the geometry of the dialysis tube



Dialysis Tube

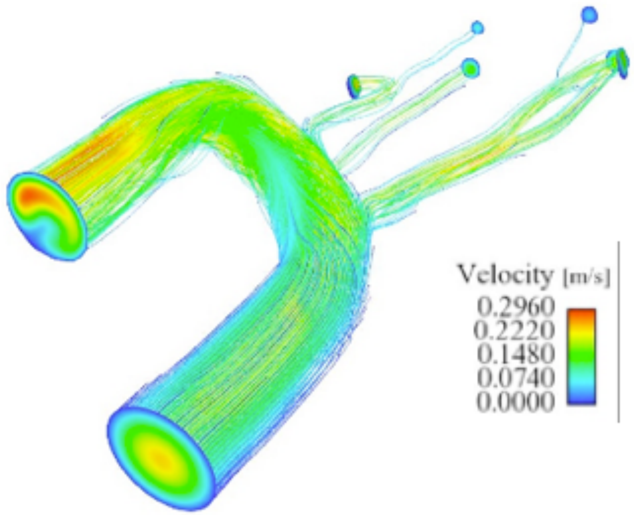
FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Shear stress and shear rate in vessel flow

FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

complex vessel flow

$$\boldsymbol{\mathcal{T}} = \mu \begin{pmatrix} 2\frac{\partial u}{\partial x} & \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) & \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \\ \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) & 2\frac{\partial v}{\partial y} & \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \\ \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) & \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) & 2\frac{\partial w}{\partial z} \end{pmatrix}$$



$$\begin{aligned} II_{\boldsymbol{\mathcal{T}}} &= \\ &= -\frac{1}{2} tr(\boldsymbol{\mathcal{T}}^2) \\ &= -\frac{1}{2}(\boldsymbol{\mathcal{T}}_{11}^2 + \boldsymbol{\mathcal{T}}_{22}^2 + \boldsymbol{\mathcal{T}}_{33}^2 + \boldsymbol{\mathcal{T}}_{12}\boldsymbol{\mathcal{T}}_{21} + \boldsymbol{\mathcal{T}}_{13}\boldsymbol{\mathcal{T}}_{31} + \boldsymbol{\mathcal{T}}_{21}\boldsymbol{\mathcal{T}}_{12} + \boldsymbol{\mathcal{T}}_{23}\boldsymbol{\mathcal{T}}_{32} \\ &\quad + \boldsymbol{\mathcal{T}}_{31}\boldsymbol{\mathcal{T}}_{13} + \boldsymbol{\mathcal{T}}_{32}\boldsymbol{\mathcal{T}}_{23}) \\ &= -\frac{1}{2}\boldsymbol{\mathcal{T}} : \boldsymbol{\mathcal{T}} \end{aligned}$$

$$\tau_{scalar} = (-II_{\boldsymbol{\mathcal{T}}})^{\frac{1}{2}} = \left(\frac{1}{2}\boldsymbol{\mathcal{T}} : \boldsymbol{\mathcal{T}}\right)^{\frac{1}{2}}$$

$$\tau_{scalar} = \mu G$$

a **scalar comparative shear stress** can be computed from velocity gradients of the **three dimensional deviatoric stress tensor**

Numerical Analysis of Blood Flow in the Human Circulation

Physiological shear rate ranges

FH AACHEN UNIVERSITY OF APPLIED SCIENCES

Non-pathological

in large arteries, capillaries, venous circulation 40 - 600 1/s

(shear thinning / viscoelastic and laminar flow)

in small arteries and arterioles 1,000 - 3,000 1/s

(Newtonian and laminar behavior)

Flow conditions in the human circulation according to [9]

Gefäß	Durchmesser (mm)	Mittlere Wand-Scherrate (s^{-1})	Wand-Schubspan-nung (Pa)
Aorta ascendens	23 – 43,5	45 – 305	2,5
Femoralarterie	5	302	2,4
Aorta carotis communis	5,9	253	o. A.
Sinus caroticus	5,2	240	o. A.
Arteria carotis externa	3,8	331	o. A.
Kleine Arterie	0,3	1335	3,8
Arteriole	0,025	1600	7,5
Kapillare	0,012	560	11,1
Venole	0,021	o. A.	0,2
Große Vene	6	o. A.	0,4
Vena cava	12,5	o. A.	1,3

Pathological

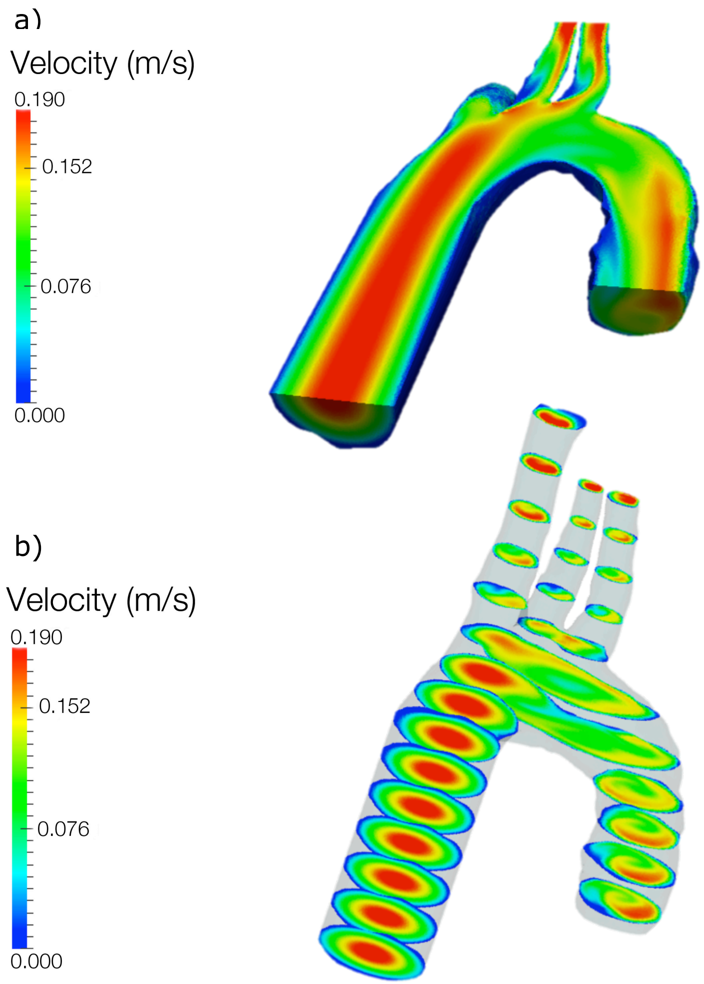
in arteries with severe stenosis 10,000 - 40,000 1/s

(Newtonian and turbulent behavior)

Numerical Analysis of Blood Flow in the Human Circulation

Steady Blood Flow through Aorta (fine mesh using code Saturne)

- the aortic arch geometry was created using MRI scans of a patient geometry creating a **mesh of 2.47 million elements**
- parabolic inflow at a constant flow rate of 3.371 L/min
- inflow diameter of 2.8 cm
- blood density of 1085 kg/m^3
- dynamic viscosity of 0.0036 Pas
- steady laminar flow conditions at Re = 770

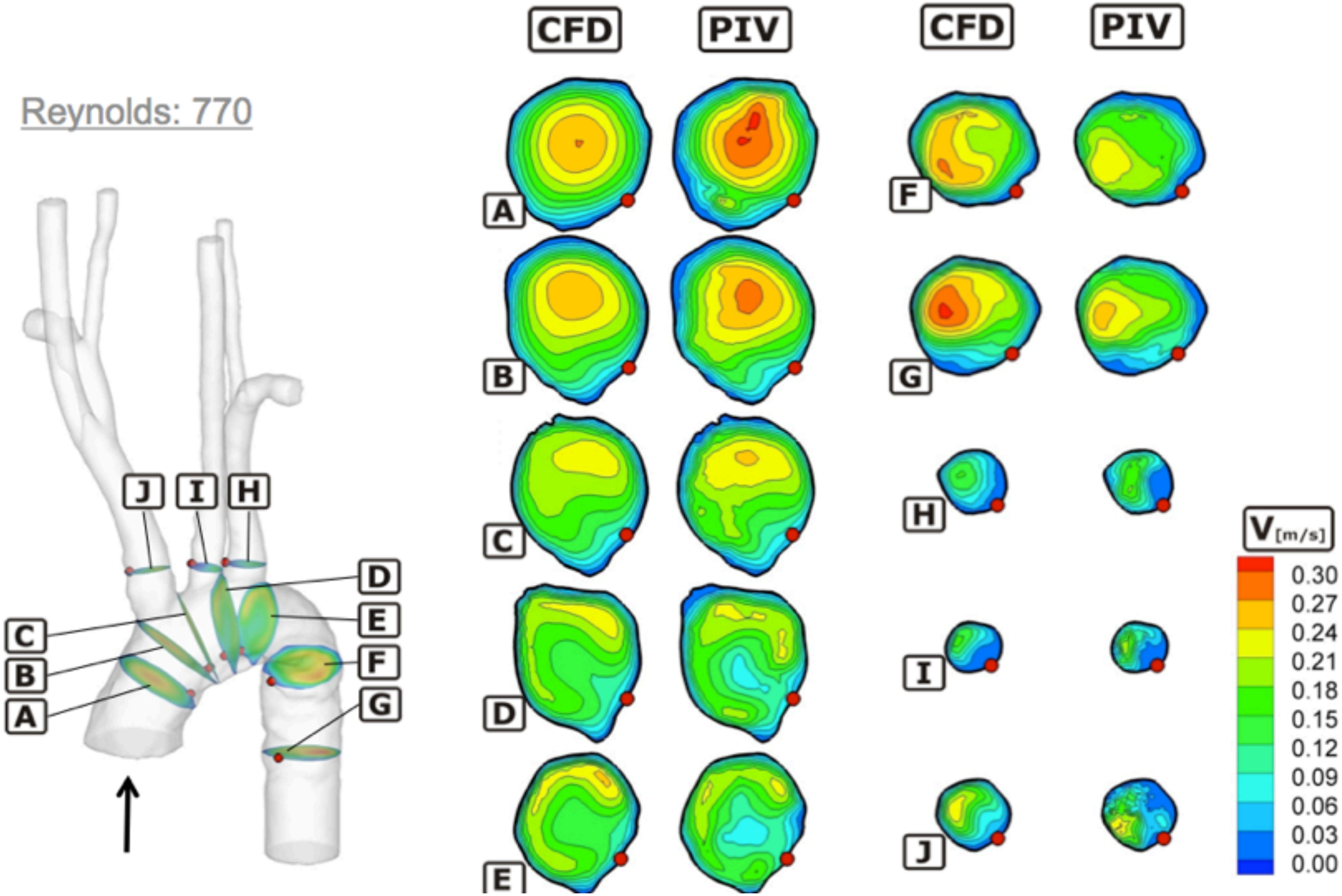


a) Longitudinal section of the velocity flow profile in the aortic arch
b) Cross sections of the velocity flow profile in the aortic arch

© FH AACHEN

Numerical Analysis of Blood Flow in the Human Circulation

Steady Blood Flow through Aorta (Comparison CFD and experimental PIV)



FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Numerical Analysis of Blood Flow in the Human Circulation

Fourier Representation of the Physiological Blood Flow through Aorta

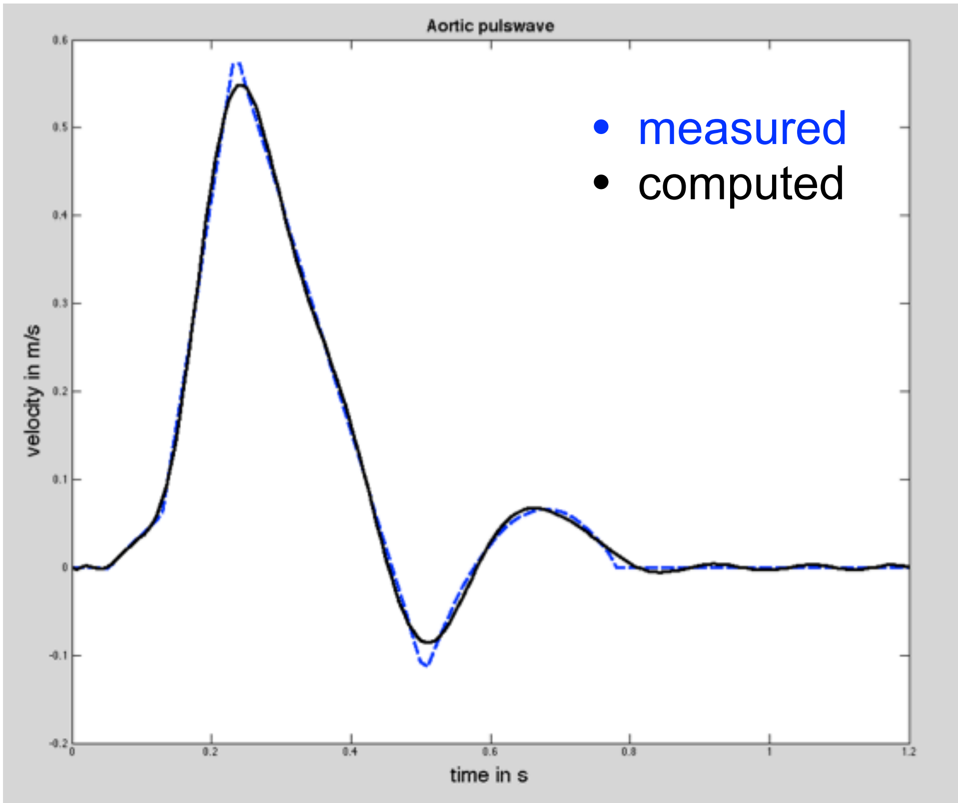
$$v\,(r,t) = A_0 + \sum_{k=1}^{N} (A_k \cdot \cos 2\pi k t + B_k \cdot \sin 2\pi k t)$$

<u>one cycle</u>

➡ t = 1 s

<u>coefficients A and B</u>

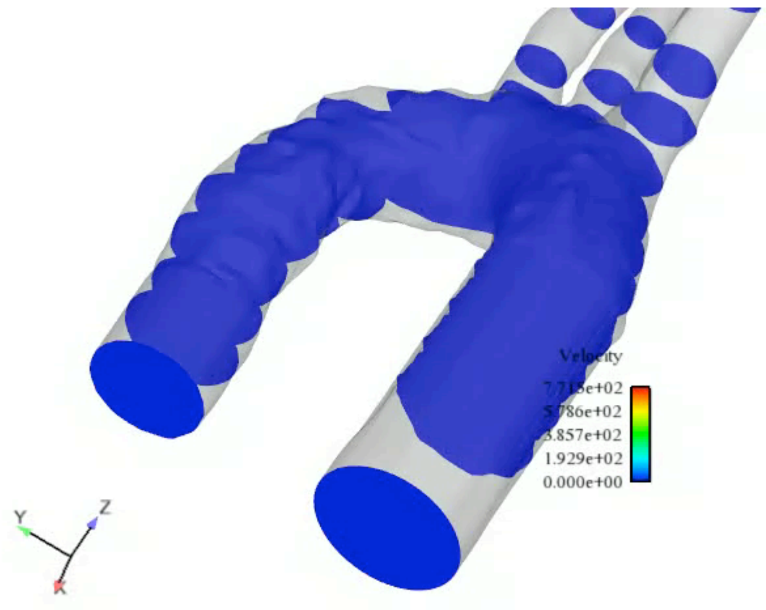
➡ required for representation of pulse wave form of aortic flow

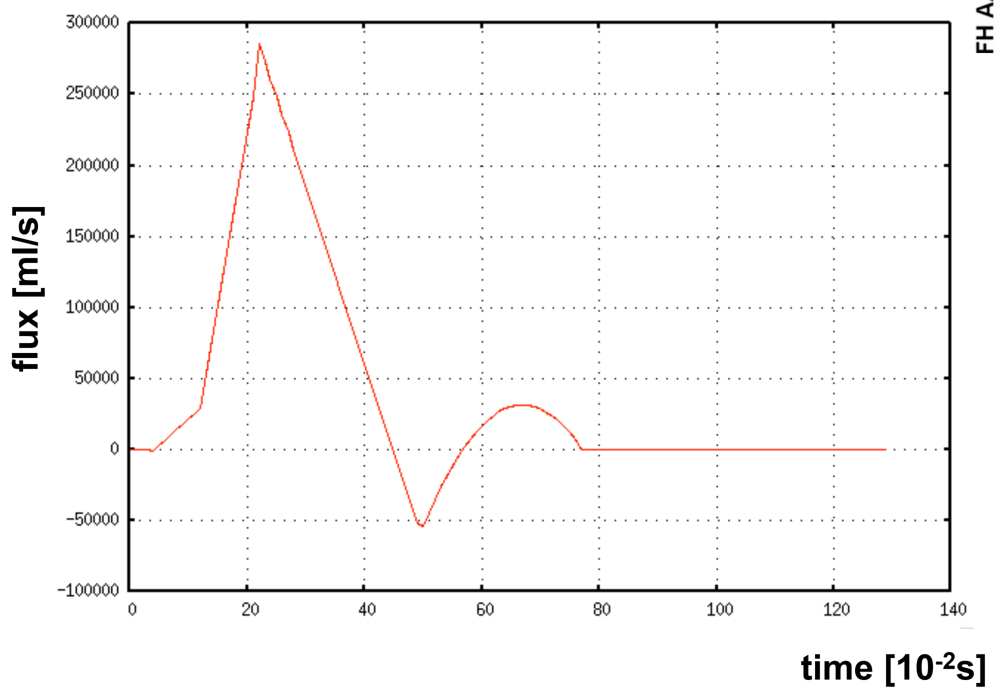


Pulse Wave Form Chart of Aortic Blood Flow

Numerical Analysis of Blood Flow in the Human Circulation

Pulsatile Blood Flow through Aorta using Heaviside Function





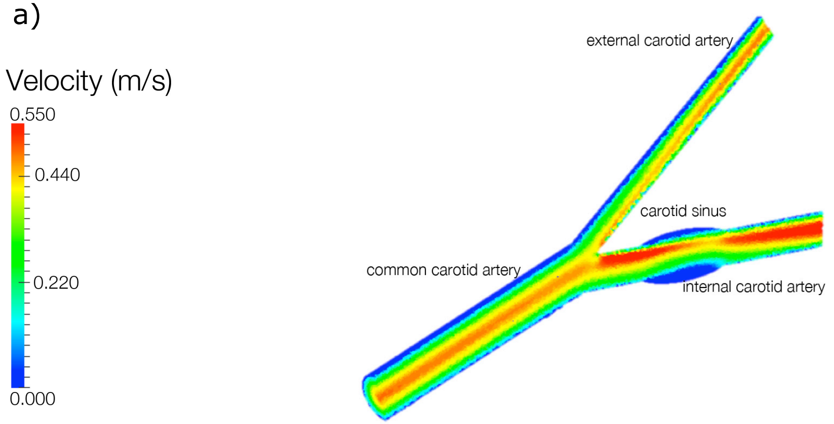
- simulate pulsatile blood flow in aorta (possibly include Windkessel function)

Numerical Analysis of Blood Flow in the Human Circulation

Blood Flow in the Carotid Bifurcation Arteries (moderate size mesh using code Saturne)

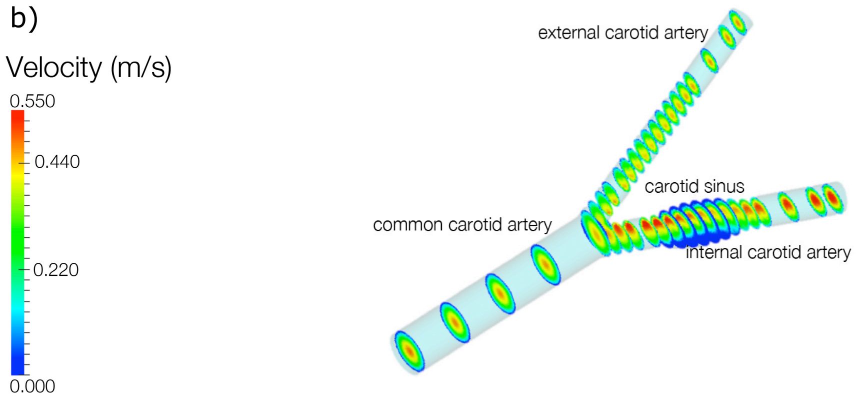
- the carotid artery geometry is based on a model by Kien T. Nguyen [1] used to create a mesh with **0.45 million elements**
- parabolic inflow at a constant flow rate of 0.742 L/min
- common carotid artery (CCA) inflow diameter of 8 mm
- blood density of 1030 kg/m^3
- dynamic viscosity of 0.004 Pas
- steady laminar flow conditions at Re = 498

a)



Longitudinal section of the flow profile in healthy carotid arteries

b)



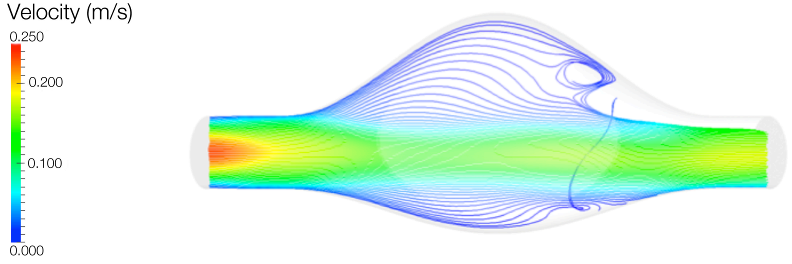
Cross sections of the velocity flow profile in healthy carotid arteries

Numerical Analysis of Blood Flow in the Human Circulation

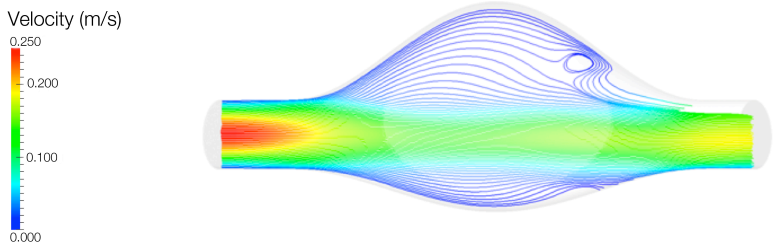
Blood Flow in an Abdominal Aortic Aneurysm (AAA) (fine mesh using code Saturne)

- the geometry for the abdominal aortic aneurysm is based on a model by Scotti [3] similar to the CT scan of a patient geometry shown to the right, creating a **mesh of 1.58 million elements**
- inflow diameter of 2 cm
- diameter of the sacular aneurysm is 3 cm
- blood density of 1050 kg/m3
- dynamic viscosity of 0.0035 Pas
- laminar, pulsatile flow conditions at Re = 702 modelled using a Fourier expansion

a)



b)



a) Longitudinal section of the flow profile of the AAA geometry at time t=2.65s showing the velocity profile and streamlines

b) Longitudinal section of the flow profile of the AAA geometry at time t=2.71s showing the velocity profile and streamlines

- **Currently analysis using a patient geometry and code Saturne with a fine mesh of 11 million elements is ongoing on a 4-processor machine, computation took 10 days => parallel computing becomes necessary**

Conversion from DICOM to Saturne readable Mesh Format

T. Le, C. Hengefeld, S. Jiménez, M. Behbahani

FH AACHEN UNIVERSITY OF APPLIED SCIENCES

Objective

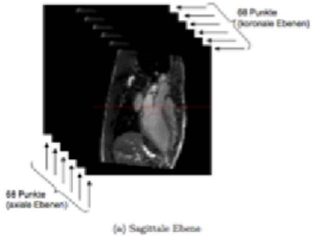
- **study of blood flow** in human arteries
- this technique allows for the utilisation of real **patient data** gained from imaging technologies such as computed or magnetic resonance tomography in order to create a mesh that can be used for the consequent numerical study of blood flow
- **visualization** of gathered flow data in common visualisation software

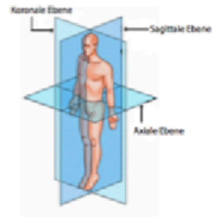
Workflow

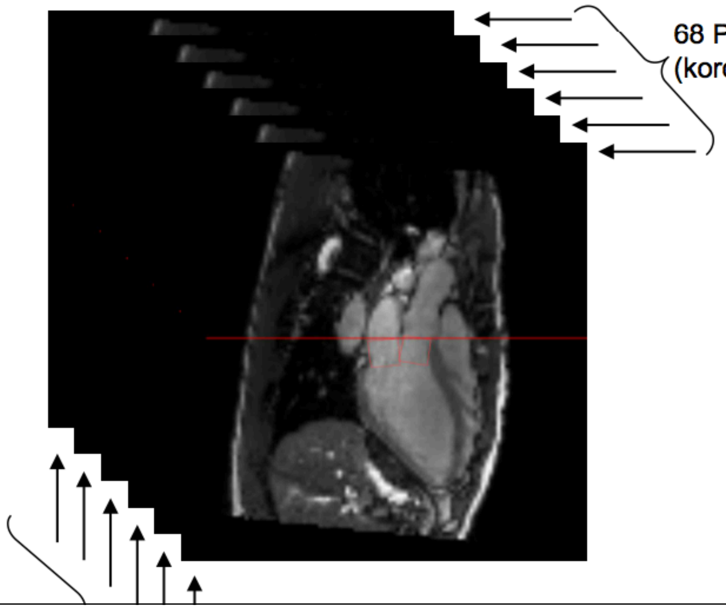
1. MRT/CT Data in DICOM Format

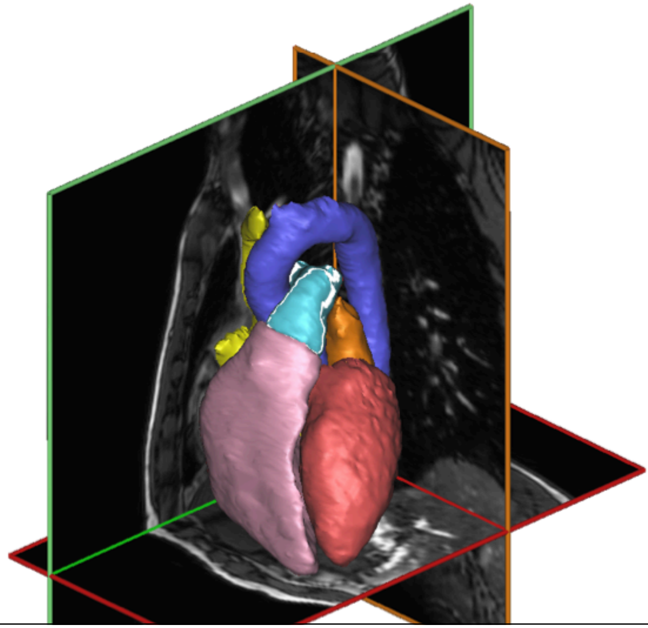
Digital **I**maging and **CO**mmunications in **M**edicine (DICOM):
basic datafile for computed and magnetic resonance tomography images in FEM and CFD work

- consists of a header and image data set packed into a single file
- information within header is organized as a constant and standardized series of tags
- extracting data from these tags gives access to important patient and study information









© FH AACHEN

2. OsiriX

image processing software dedicated to DICOM files for navigation and visualization of multimodality and multidimensional (3D + temporal and functional dimensions) images

1. visualization and rendering
2. data management

3. itk snap

software application used to segment structures in 3D medical images providing semi-automatic segmentation using active contour methods as well as manual delineation and image navigation

1. crop region of interest (ROI)
2. create 3D geometry

4. GIMIAS

workflow-oriented environment for solving advanced biomedical image computing and individualized simulation problems, which is extensible through problem-specific plug-ins

1. cut away irrelevant regions
2. define closer region of interest
3. smoothen surface
4. produce watertight model
5. export to .stl-file format

5. DeVide

software framework for the rapid prototyping, testing and deployment of visualisation and image processing algorithms

1. .stl -> .vtk -> .stl
2. further mesh processing
3. reduce file size by 75 - 90% depending on application

6. InStep V2.0 Beta

software application used to convert various file formats into STEP format

1. convert surface mesh to solid geometry .stl -> .stp
2. in case of detection of redundant faces or multiple bodies, return to step 4.

SOLVEERING LLC

7a. SALOME Meshing Module

software application that provides a generic platform for pre- and postprocessing for numerical simulations; the meshing module allows for importing, creating and editing mesh CAD models

1. check if dimensions of imported geometry are correct; scaling by a constant factor might be required
2. choose appropriate coordinate system
3. meshing

7b. MATLAB

numerical computing environment and fourth-generation programming language allowing matrix manipulations, plotting of functions and data, implementation of algorithms and creation of user interfaces

1. establish pulsatile flow conditions described by Fourier expansion using curve fitting

8. Code_Saturne Solver Module

Navier-Stokes equations solver based on a co-located finite volume approach accepting meshes composed by cells of any type

1. solving by parallel computing (using METIS for optimised partitioning results)

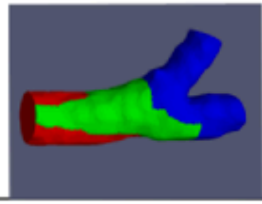


Figure 1: METIS Partitioning Result

9. Paraview

data analysis and visualization application

1. visualization and analysis of the flow profile

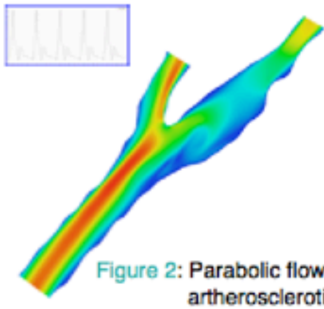
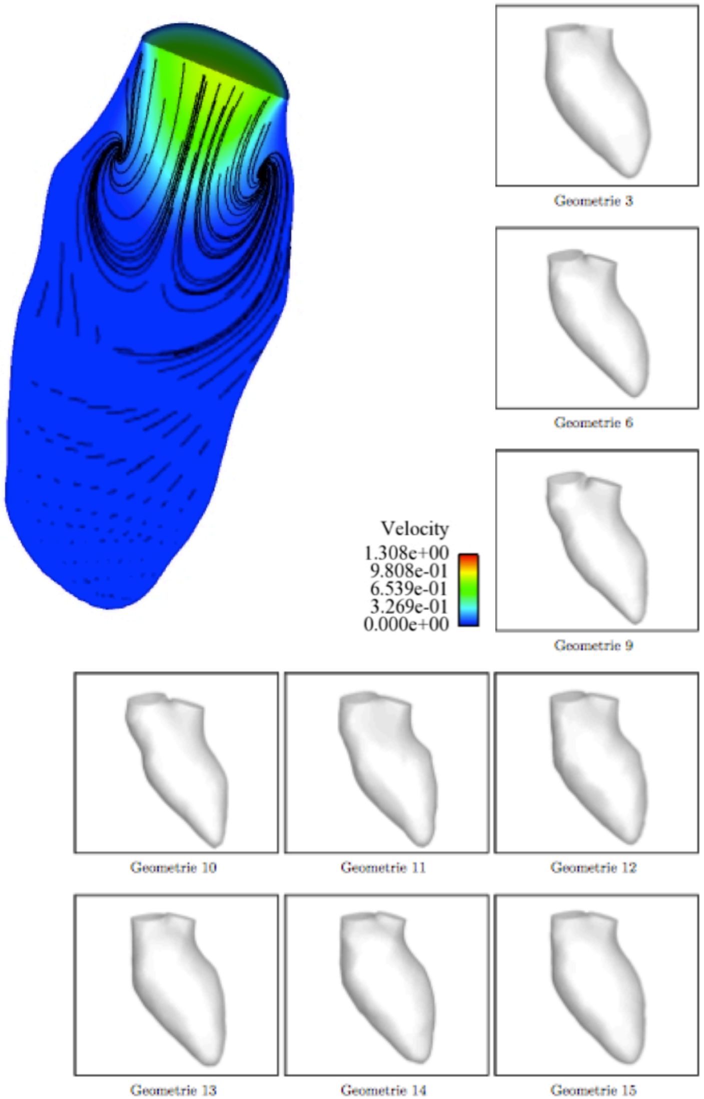
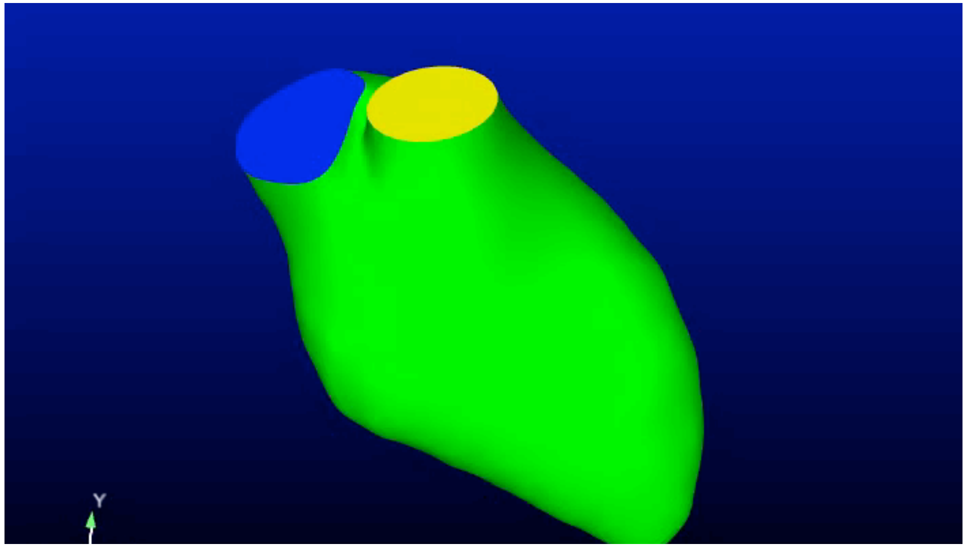


Figure 2: Parabolic flow in an artherosclerotic artery

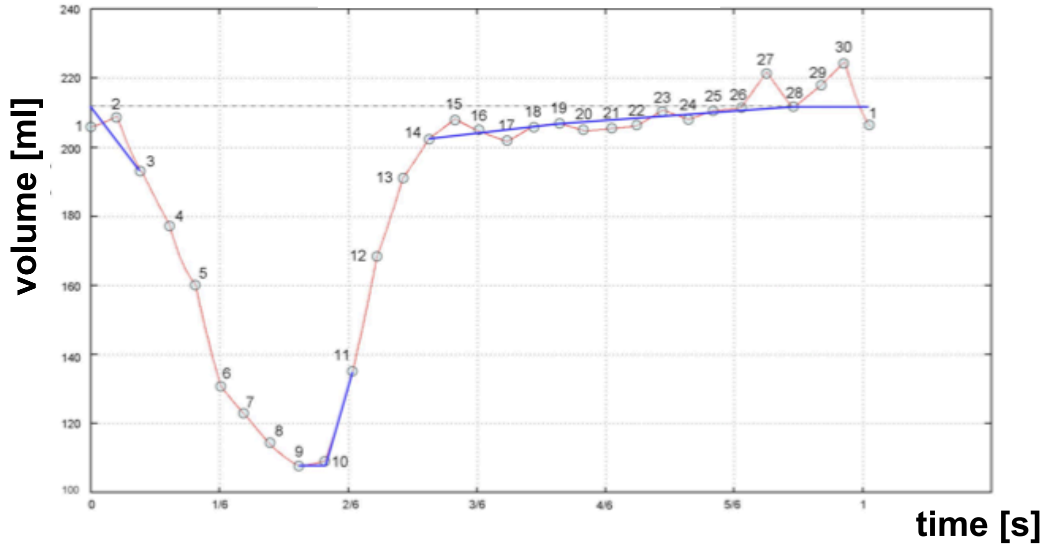
Future challenges: Deforming meshes

Blood Flow in the beating human heart (examples using code XNS, in the future code Saturne shall be used)





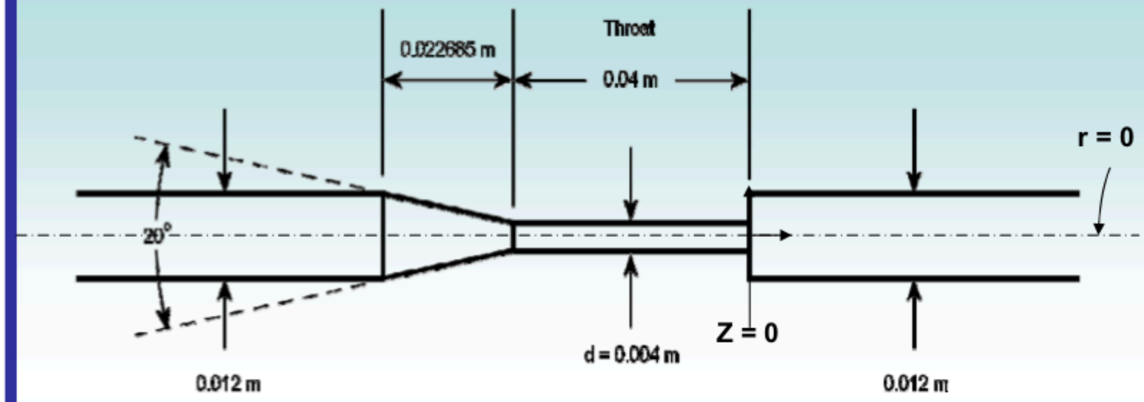
heart volume over time



FDA Study [10]

American Food and Drug Administration launched a worldwide benchmark to evaluate today's possibilities of CFD, 27 groups participated

CFD Benchmark Flow Model Specifications



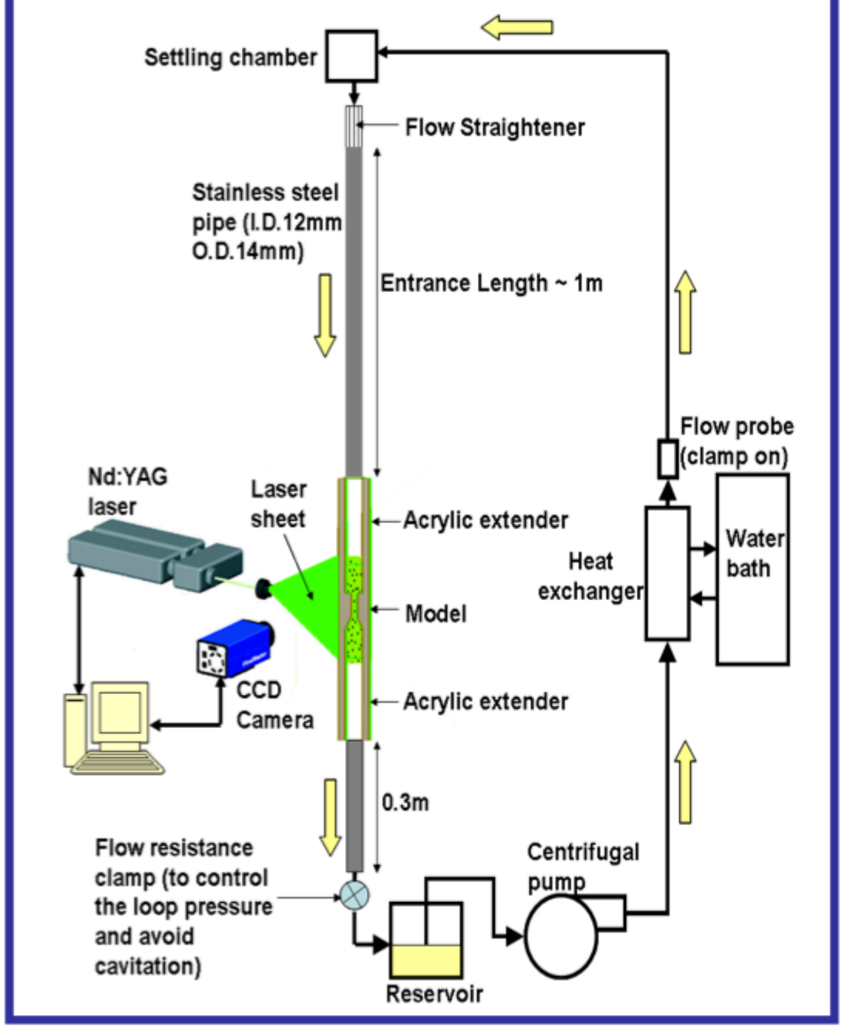
- Throat Reynolds numbers: 500, 2000, 3500, 5000, 6500
- Flow Rate range: 0.3 – 4.0 L/min
- Fluid Density = 1056 kg/m^3
- Dynamic Viscosity = 0.0035 $N \cdot s/m^2$ (3.5 cP)
- Simulations were performed in both flow directions

FDA Study

Abstract

Computational fluid dynamics (CFD) to assess device safety in new device submissions to the FDA is limited due to the lack of reliable standardized techniques. To determine suitability of CFD for evaluating device safety, participants from academia, industry, and FDA have begun a study of a benchmark flow model, which consists of a nozzle with a sudden contraction (or expansion) and a conical diffuser (or concentrator, depending on the flow direction). With the aid of ASAIO and other biomedical and computational societies, our project website (www.fda.gov/cdrh/cfd/index) received over 120 requests for information from around the world. Over 40 groups signed up to perform simulations and predict levels of blood damage in the model under different flow conditions. As data was received from participants, the information was blinded and analyzed using statistical techniques appropriate for CFD validation. This presentation will provide preliminary results of the submitted CFD data, compared to quantitative flow visualization measurements obtained in three independent laboratories. These comparisons, along with *in vitro* blood damage experiments, will help to determine how best to extrapolate CFD engineering results to predict the blood damage potential of medical devices.

Schematic of PIV flow system



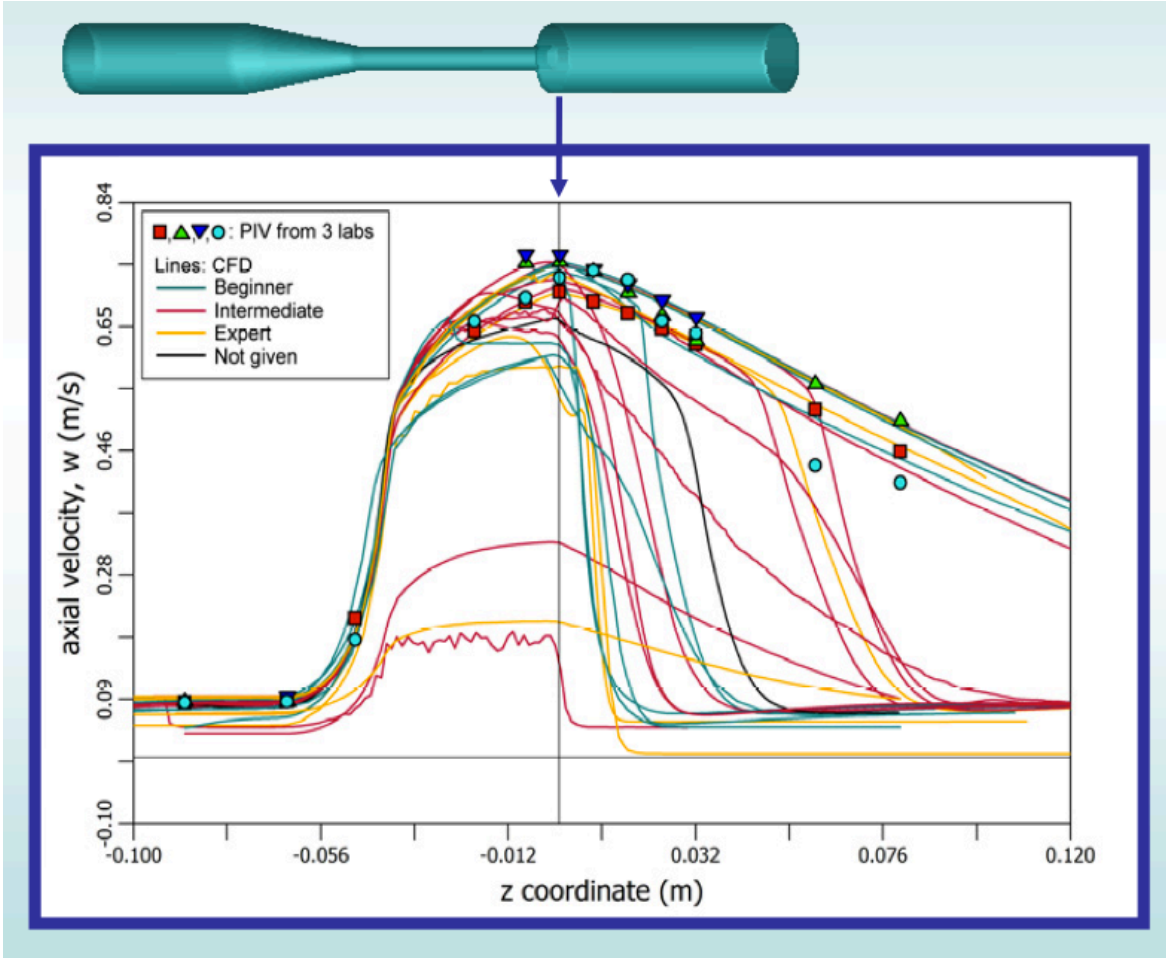
FH AACHEN UNIVERSITY OF APPLIED SCIENCES

FDA Study

Velocity Analysis (2.5 million mesh using XNS code)

Good results obtained for laminar flow in the FDA study with code XNS will have to be repeated with code Saturne

It is hoped to obtain also good results for turbulent flow using code Saturne turbulence models



Virtual Reality Techniques

How will VR contribute to blood pump design optimization?

- Pump design context:
  - enhanced analysis of the flow field in blood pumps,
  - insight into regions that are not easily accessible.
- Hematological design context:
  - tracking of RBCs along pathlines,
  - possibility for interaction,
  - visualization of blood cell morphology and hemoglobin release.

Outlook / Future Objectives with Code Saturne

- using moderate and massive parallel computing ressources
- coupling of code saturne with code Aster to perform fluid structure interactions
- learning to use code Saturne for complex rotating geometries
- implementation of material laws (viscoelastic blood behavior)
- implementation of a platelet advection-diffusion-reaction model

HVAD HeartWare

References

[1] photograph of PIV set up from Helmholtz Aachen Cardiovascular Eng. Group

[2] http://www.fz-juelich.de/portal/DE/Forschung/Informationstechnologie/Supercomputer/JUGENE.html

[3] http://www.fz-juelich.de/ias/jsc/EN/Expertise/Supercomputers/JUQUEEN/JUQUEEN_node.html

[4] http://www.medgadget.com/2006/10/apple_solution.html

[5] http://inside.hlrs.de/htm/Edition_01_07/article_06.html

[6] M. Rothenburger, M. Wilhelm, D. Hammel, C. Schmidt, T. Tjan, D. Böcker, H. Scheld, and C. Schmid. Treatment of thrombus formation associated with the MicroMed DeBakey VAD using recombinant tissue plasminogen activator. Circulation, 106(12):189–192, 2002.

[7] K. Kawahito, R. Benkowski, S. Ohtsubo, G.P. Noon, Y.Nosé, and M.E. DeDakey. Improved flow straighteners reduce thrombus in the NASA/DeBakey axial flow ven- tricular assist device. Artificial Organs, 21(4):339–343, 1997.

[8] A. Roscitano, F. Capuano, E. Tonelli, and R. Sinatrad. Acute dysfunction from thrombosis of a mechanical mitral valve prosthesis. Journal of Applied Physiology, 20(1):88–90, 2005.

[9] Goldsmith and Karino 1992 and Schmid-Schönbein 1988

[10] https://fdacfd.nci.nih.gov

© FH AACHEN

Thank you very much for your attention!

FH AACHEN
UNIVERSITY OF APPLIED SCIENCES