Fluid Dynamics of Blood Flow – Modelling & Simulation

1. Masud Behnia * – Basics of Fluid Mechanics
2. Makoto Ohta ** – Experimental Modelling
3. Karkenahalli Srinivas * – Computational Fluid Dynamics
4. Toshio Nakayama ** – Sample CFD Results

* University of Sydney

** Tohoku University

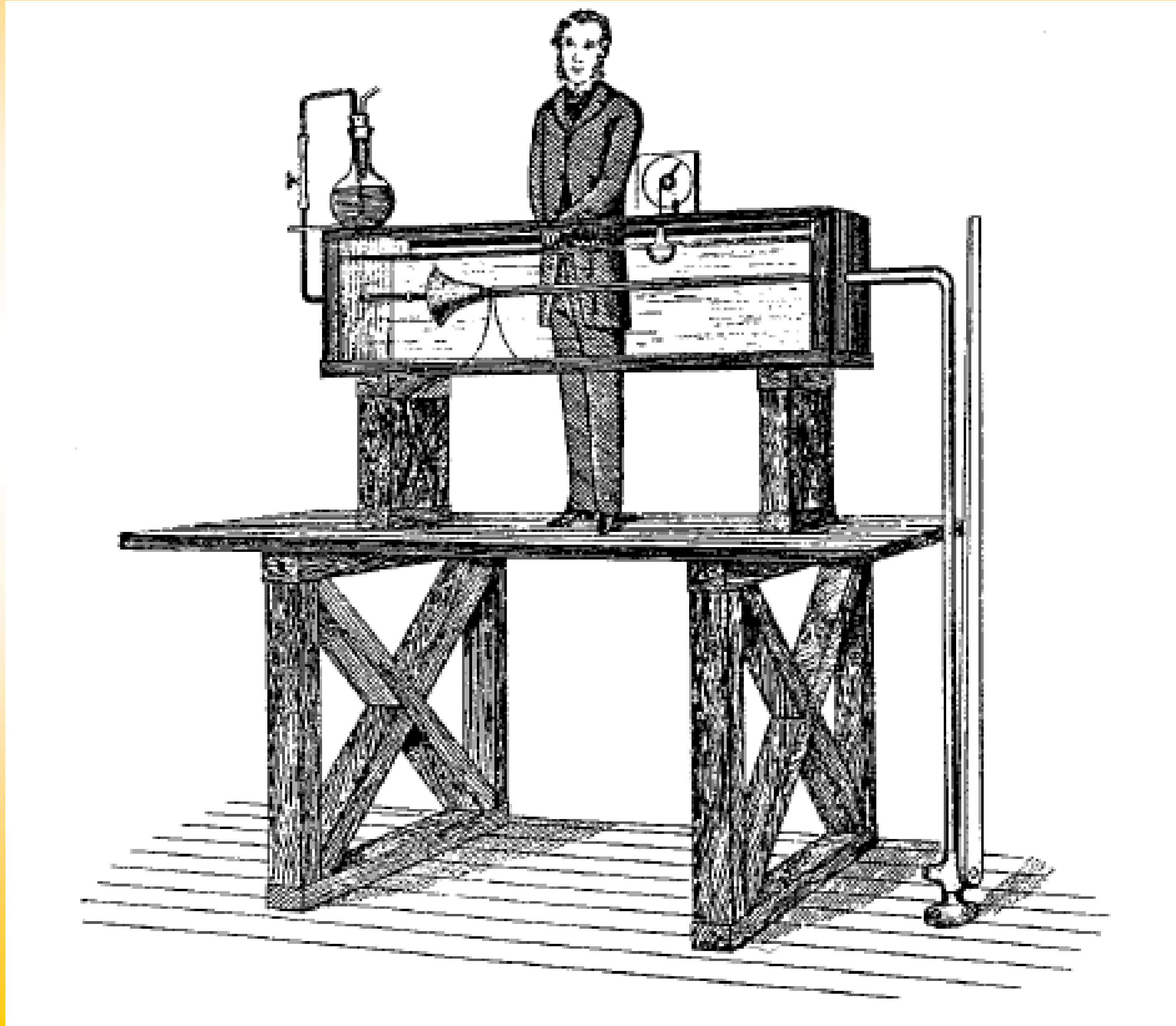
contact: m.behnia@usyd.edu.au

Types of Flow

- ✓ Laminar
- ✓ Turbulent
- ✓ Newtonian
- ✓ Non-Newtonian
- ✓ Steady
- ✓ Unsteady

Laminar & Turbulent

Reynolds, O.: *On the experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and the law of resistance in parallel channels*. In: Phil. Trans. Roy. Soc. 1883 (174), p. 935-982.



Reynolds Experiment

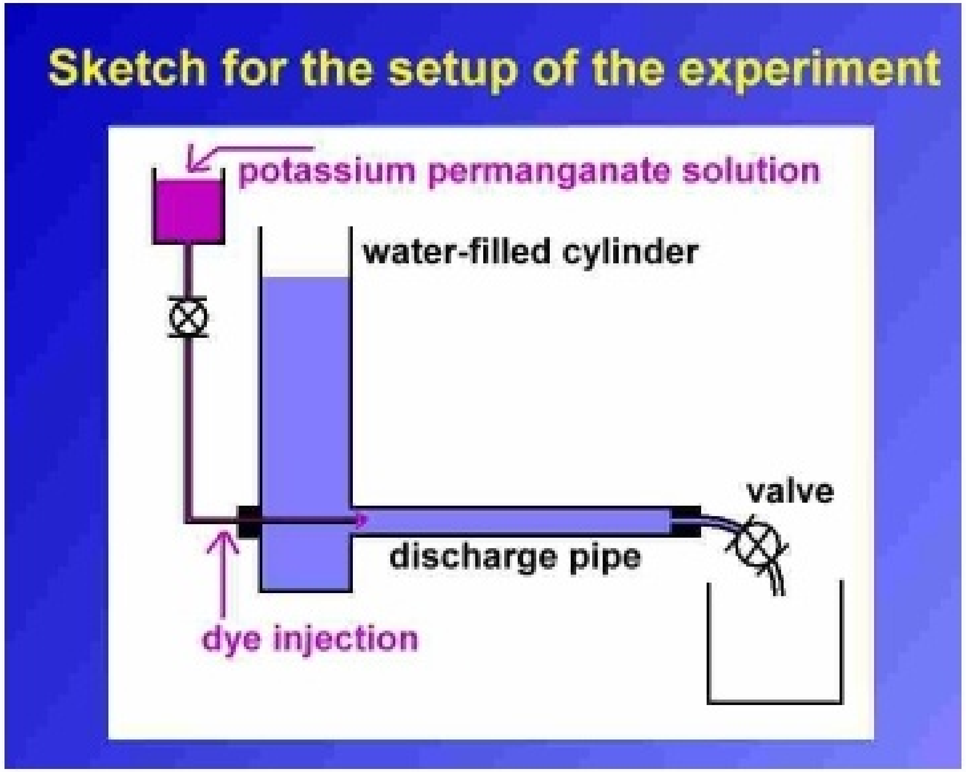


Fig. 1: Schematic sketch for the setup of the Reynolds number experiment

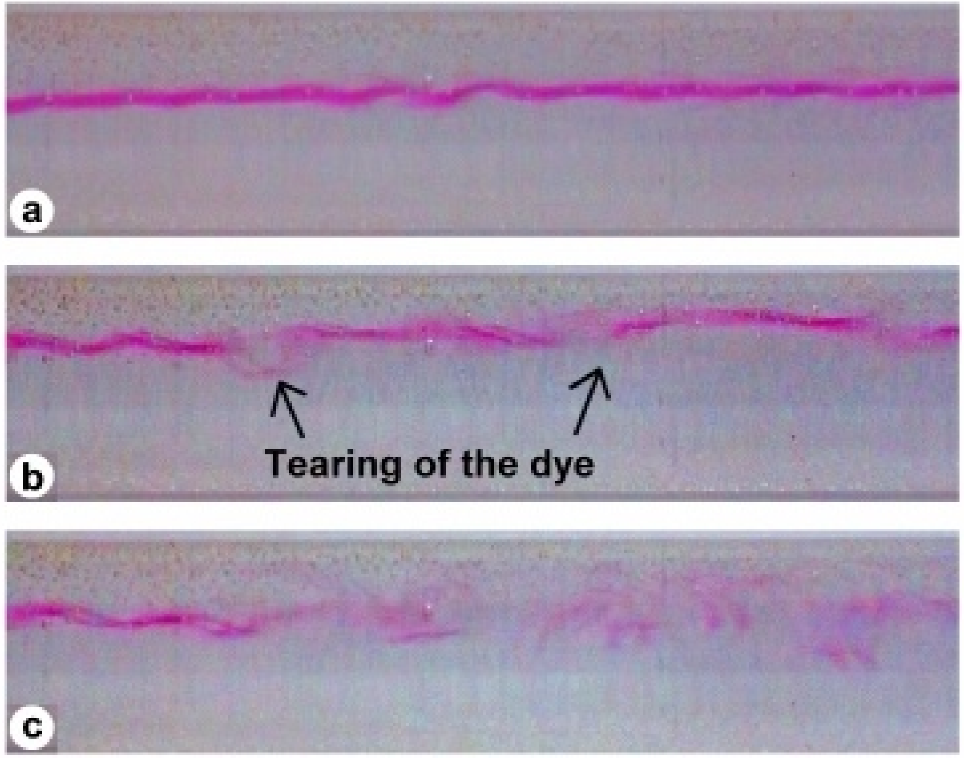


Fig. 2: a) red line of the dye at laminar flow, b) fluctuations and breaking of the dye thread at the transition point, c) unordered movement of the dye at turbulent flow

Turbulence Film Clip

- Film showing transition from laminar to turbulent flow

Laminar to Turbulent Transition

- ✓ **Flow in a pipe**

$$Re = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$

- ✓ **Re is Reynolds number, V is the average velocity=Q/A (volumetric flowrate/area)**
- ✓ **Transition occurs at Re of 2300**

Kinematic Viscosity

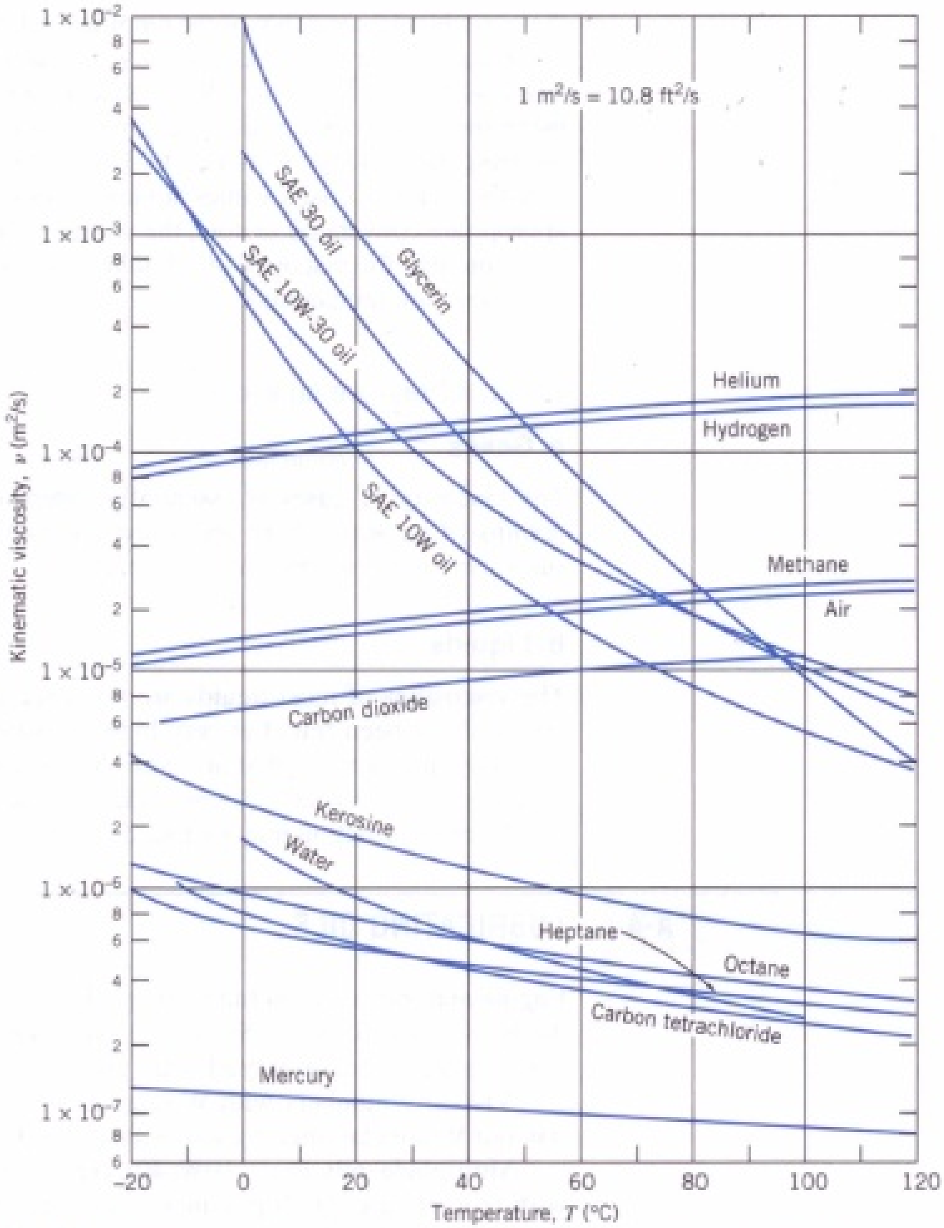


Fig. A.3 Kinematic viscosity of common fluids (at atmospheric pressure) as a function of temperature. (Data from [1, 6, and 10].)

Example Calculations

Re_{water} & Re_{blood}

Flow rate = 0.9g/s

$$\mathrm{Re} = \frac{VD}{\nu} = \frac{4Q}{\pi D \nu}$$

$\nu_{water} = 8.9 \times 10^{-7}\ m^2/s$, $\nu_{blood} = 3.3 \times 10^{-6}\ m^2/s$

$V_{water} = 0.382$ m/s, $V_{blood} = 0.36$ m/s

$\mathrm{Re}_{water} = 1288$, $\mathrm{Re}_{blood} = 327$

Turbulent Velocity Profiles in Fully Developed Pipe Flow

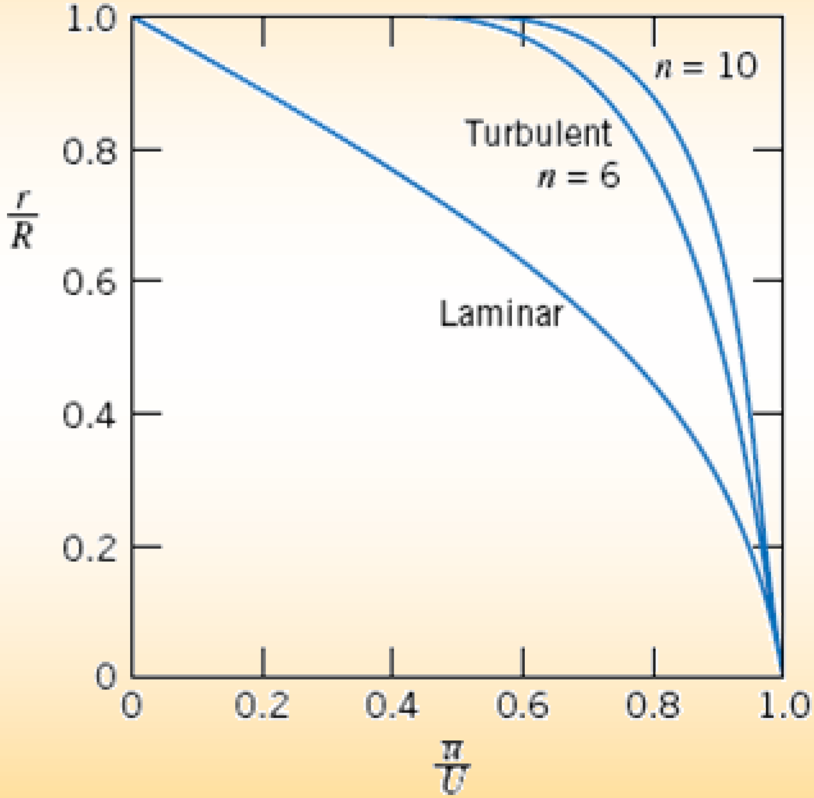
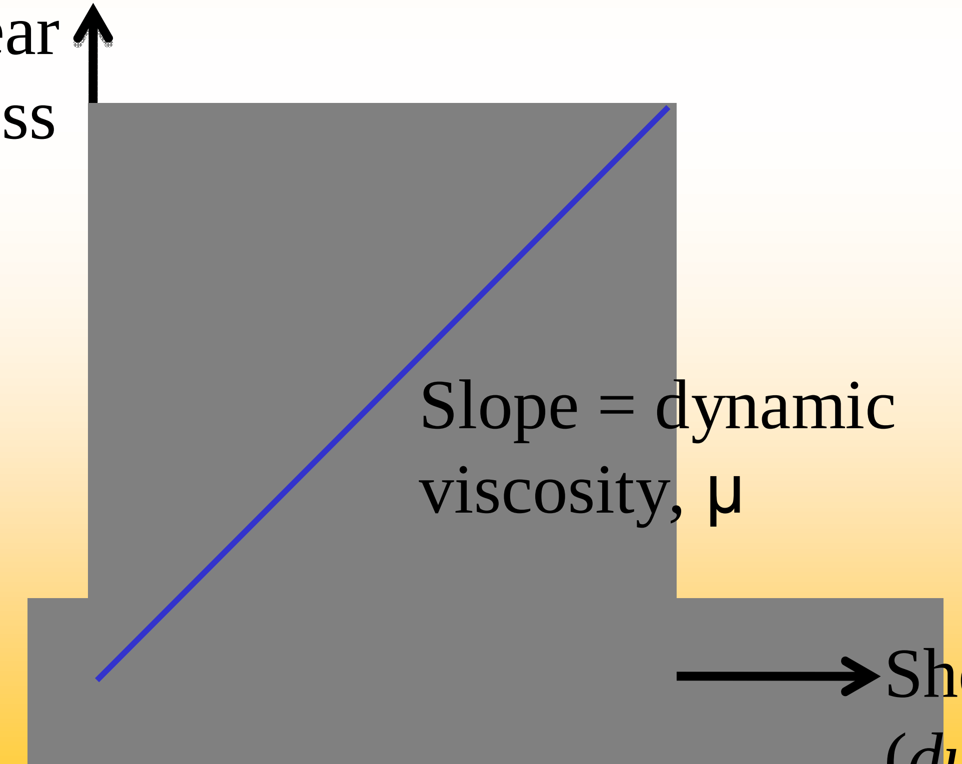


Fig. 8.11 Velocity profiles for fully developed pipe flow.

Newtonian Fluid

Fluids with the characteristic $\tau = \mu \frac{du}{dy}$

τ: Shear stress (Pa)
μ: dynamic viscosity(Pa.s)
du/dy: Shear rate (1/s)

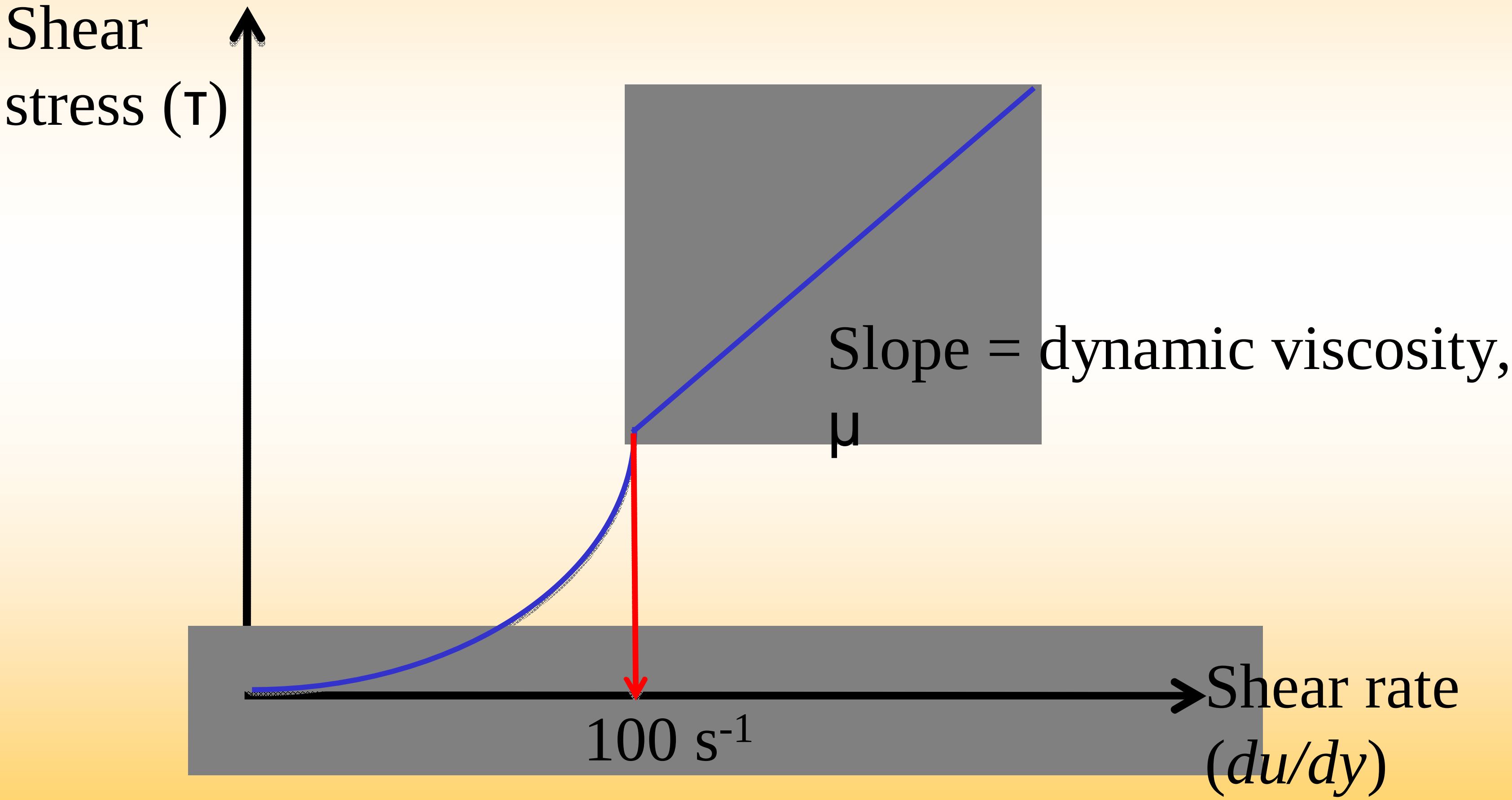


Non-Newtonian Fluids

- ✓ **Fluids that do not behave like the Newtonian fluid → viscosity, μ is dependent on shear rate, $\frac{du}{dy}$**

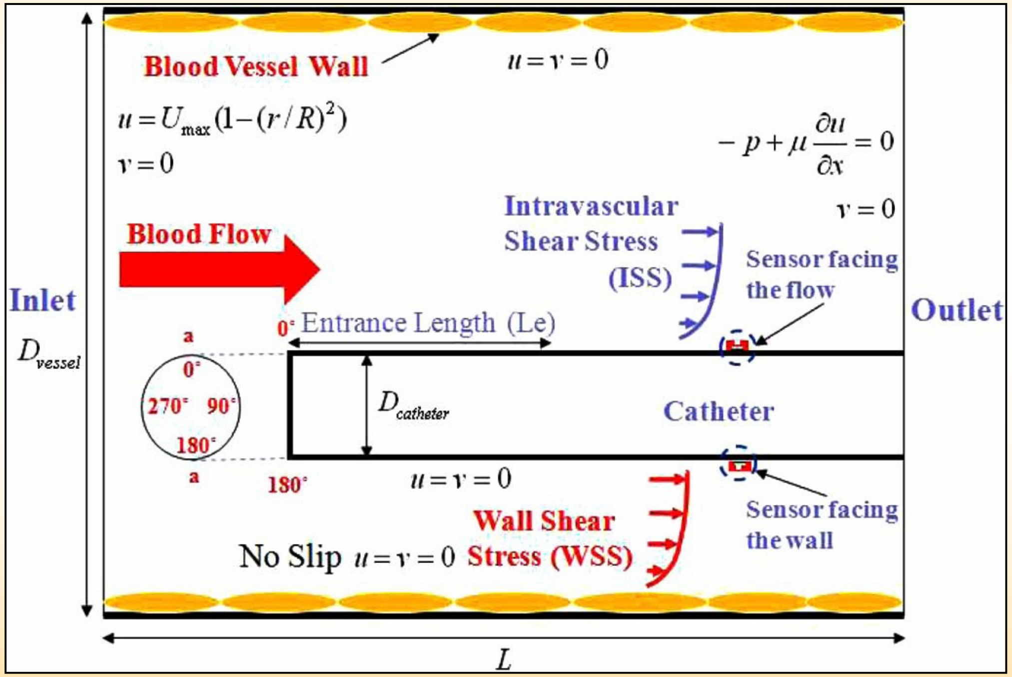
- ✓ **Blood: Non-Newtonian but can be assumed to behave as Newtonian at high shear rates (>100/s)**

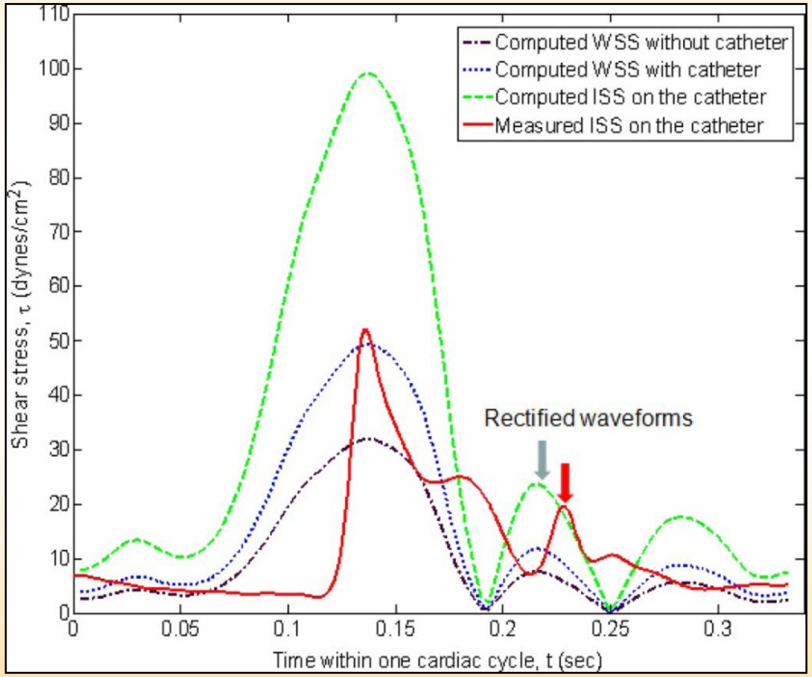
Blood Behaviour



Example Experimental

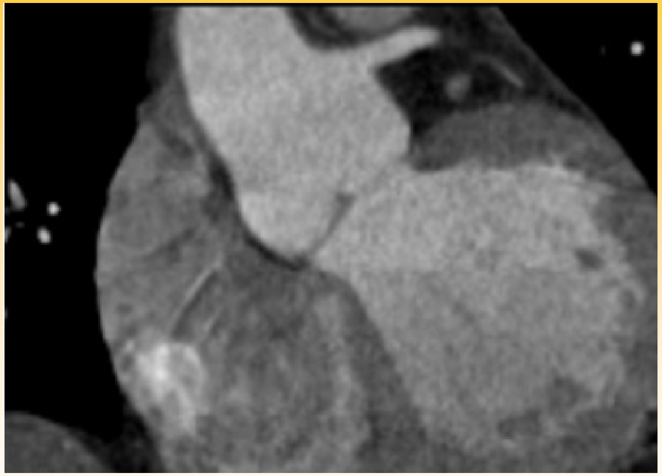
Real time intravascular shear stress in rabbit abdominal aorta



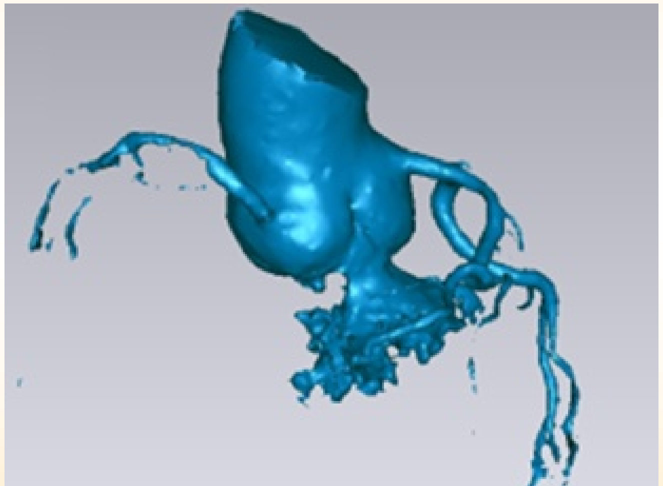


Ai et al, “Real time Intravascular Shear Stress in Rabbit Abdominal Aorta” IEEE Transactions on Biomedical Engineering, 56 (6): 1755 - 1764

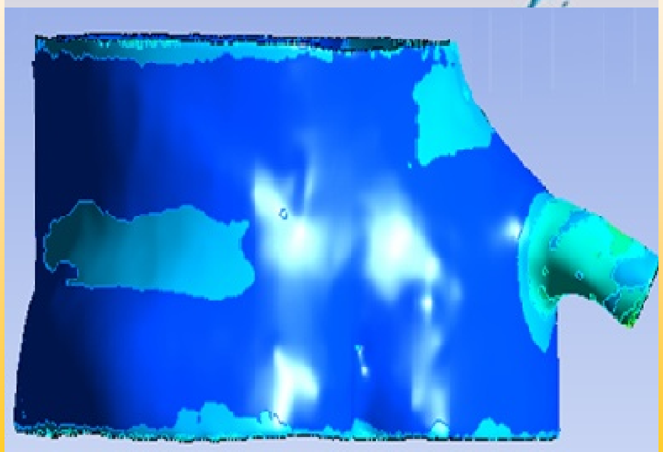
Example



CT Scan of the aorta



3D computer model



Wall shear stress distribution (CFD)

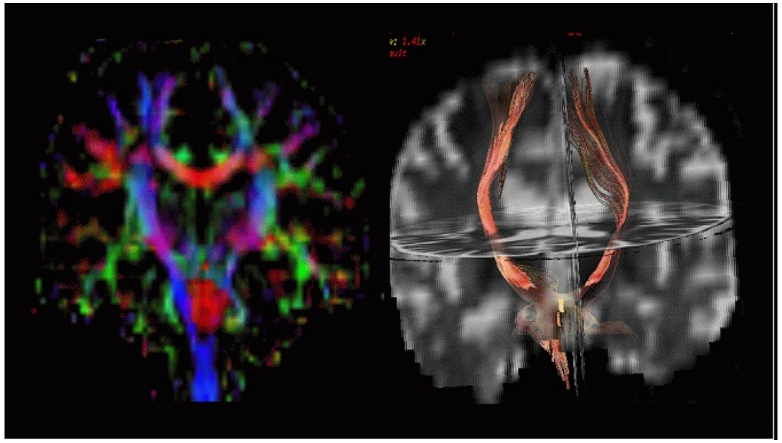
Experimental Measurement & Modelling

The difficulties of direct measurement of blood flow in-vivo

US
MRI
X-ray

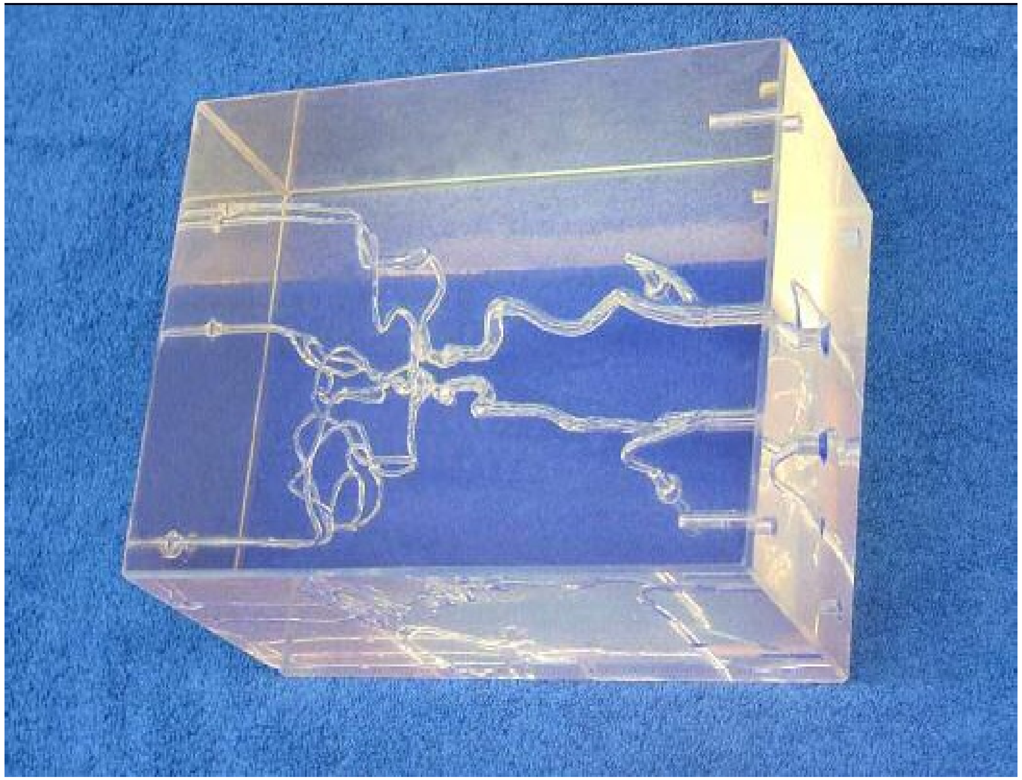
Specially, with medical device such as stent or coils

http://www.hi-ho.ne.jp/vet-yasushi/dejicon/dejiechomr.htm



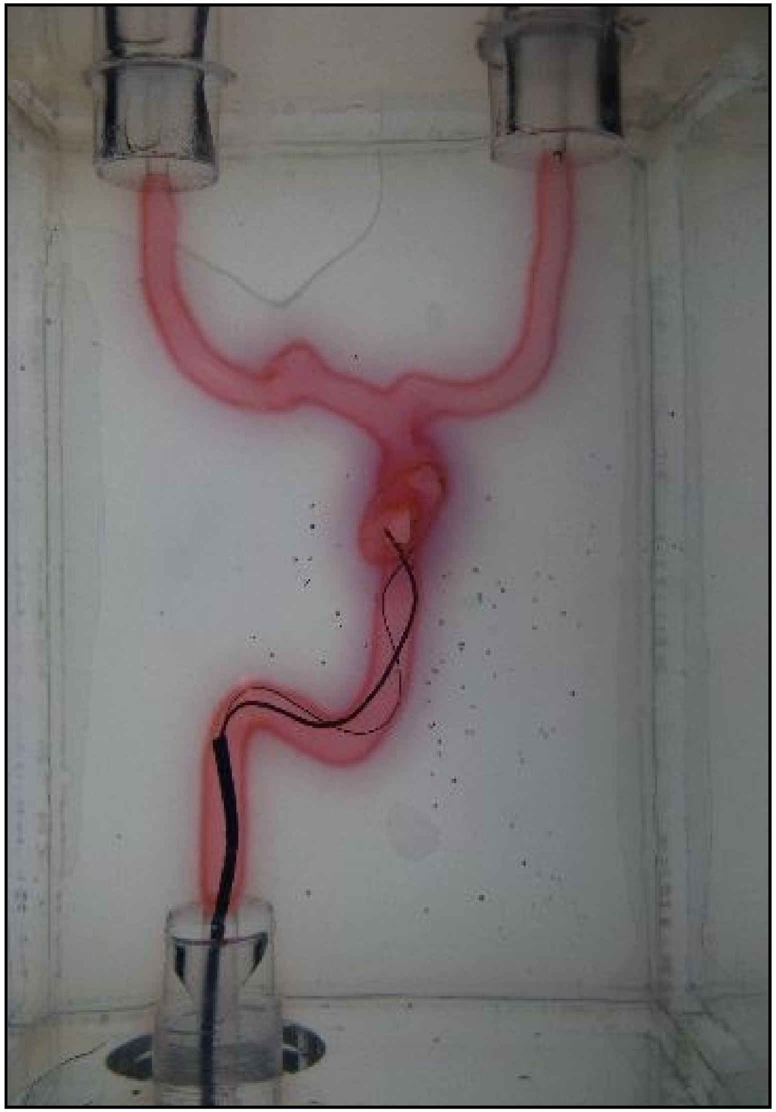
http://www.rada.or.jp/database/home4/normal/ht-docs/member/synopsis/030280.html

Conventional Biomodel

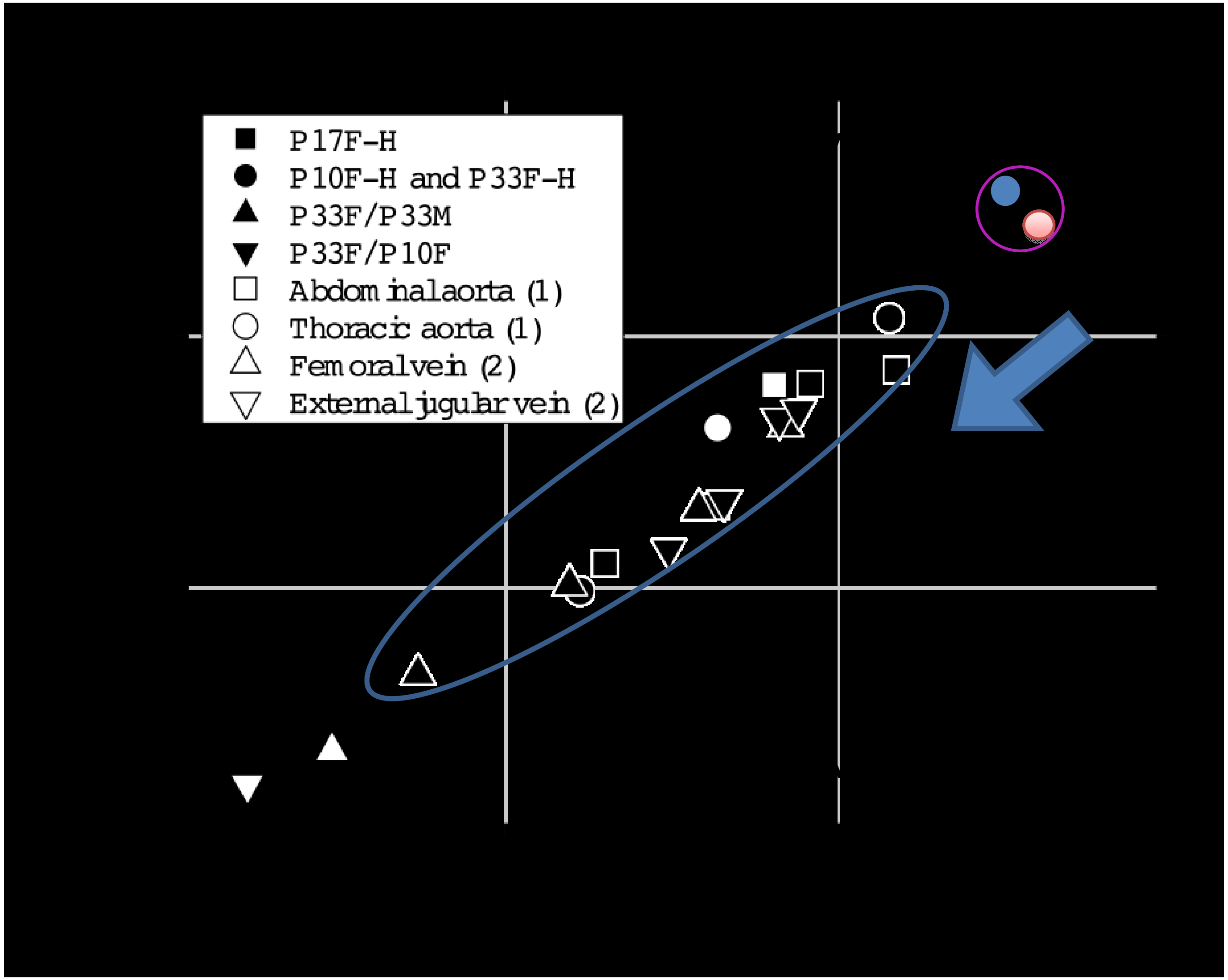


Rigid, high friction…

New type using PVA with slimy

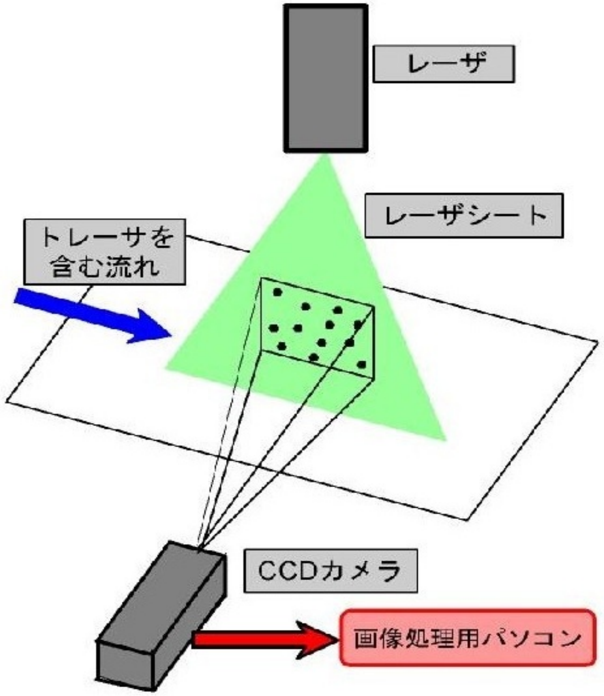


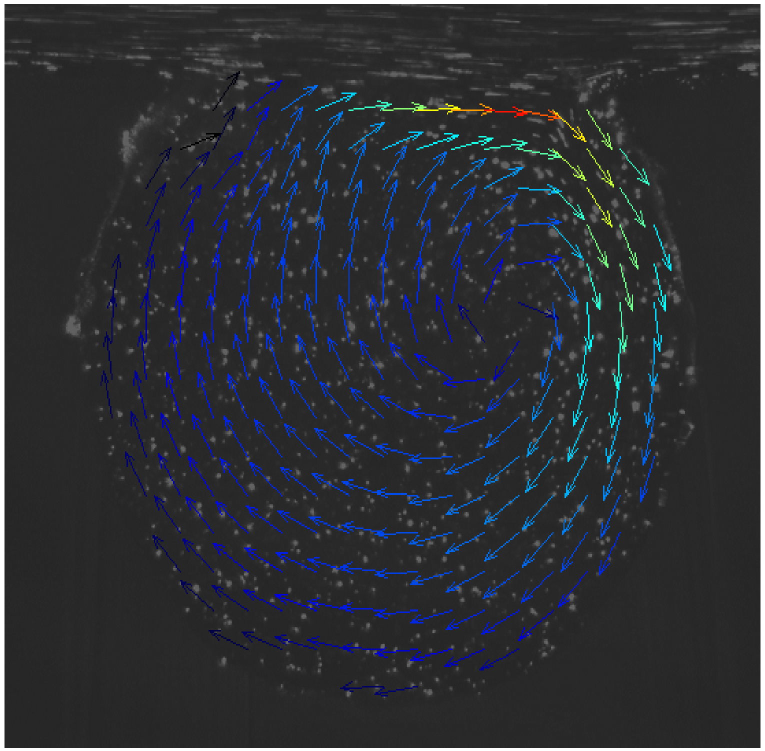
Mechanical modulus of PVA



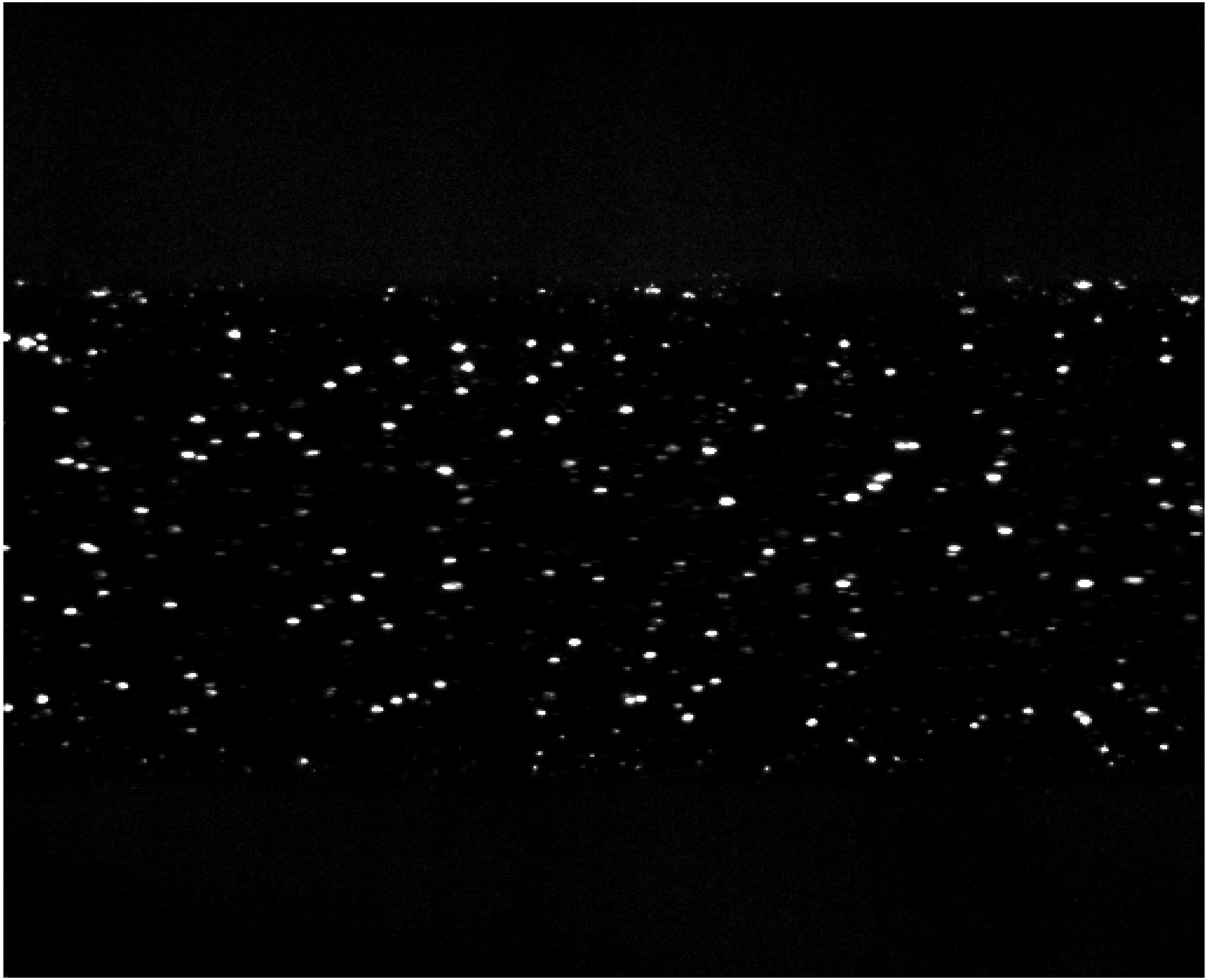
H. Kosukegawa, et al., J. Fluid Sci. Tech., 2008

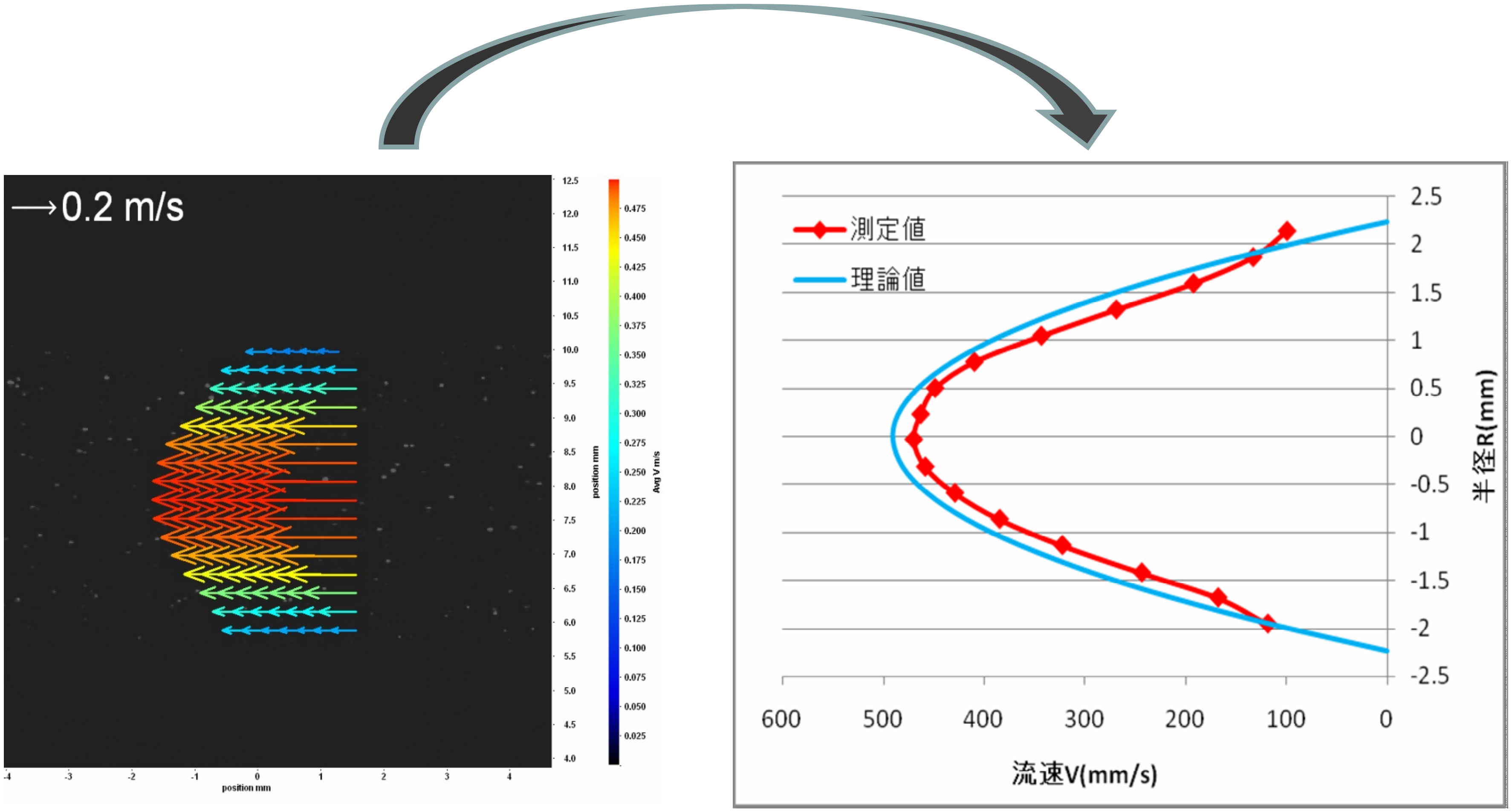
PIV(Particle Image Velocimetry)





Movie





→0.2 m/s
position mm
Avg V m/s
測定値
理論値
半径R(mm)
流速V(mm/s)
600
500
400
300
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100
0
2.5
2
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1
0.5
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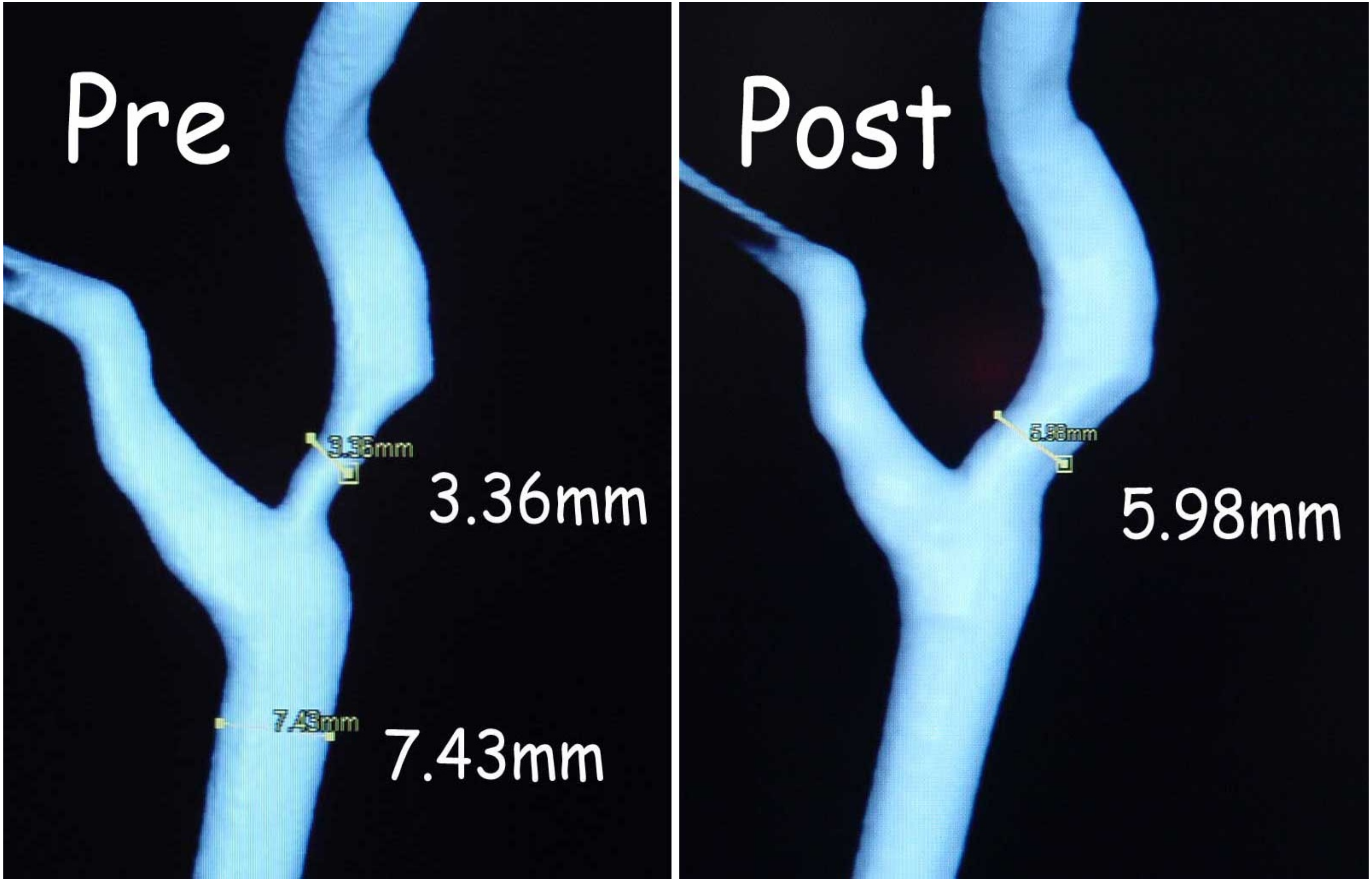
-0.5
-1
-1.5
-2
-2.5



Pre
3.36mm
3.36mm
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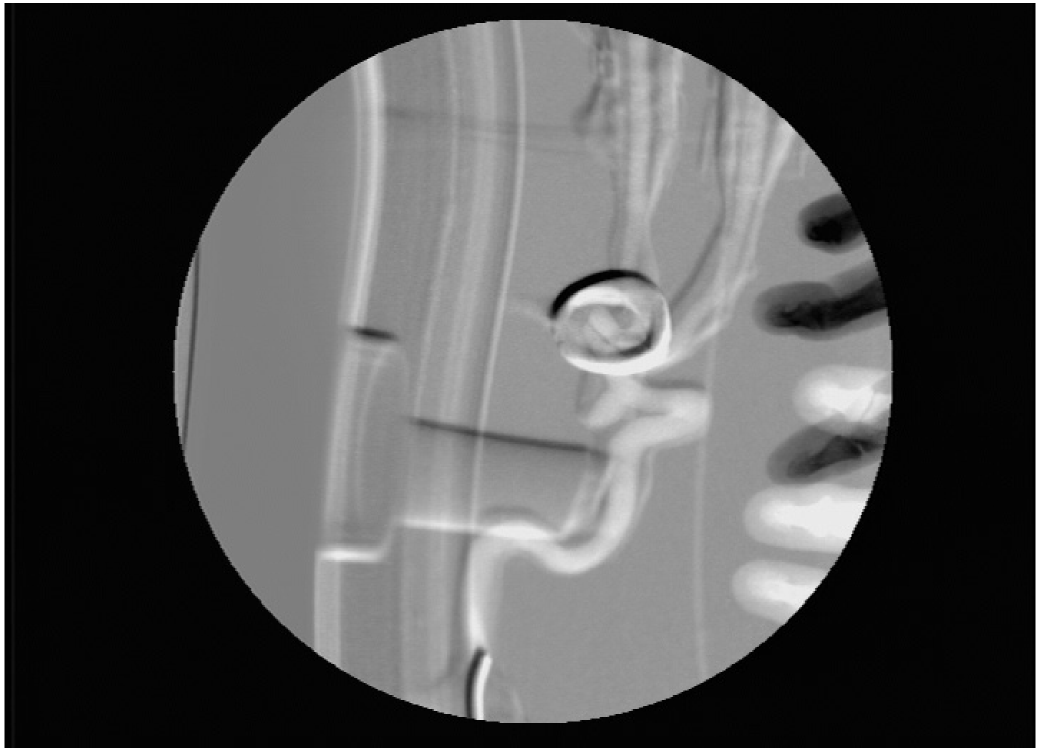
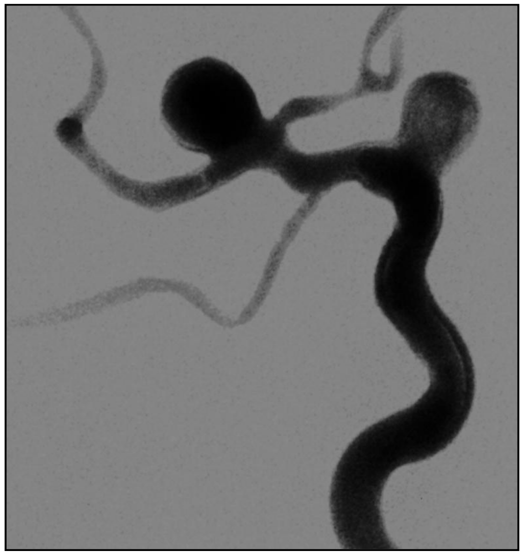
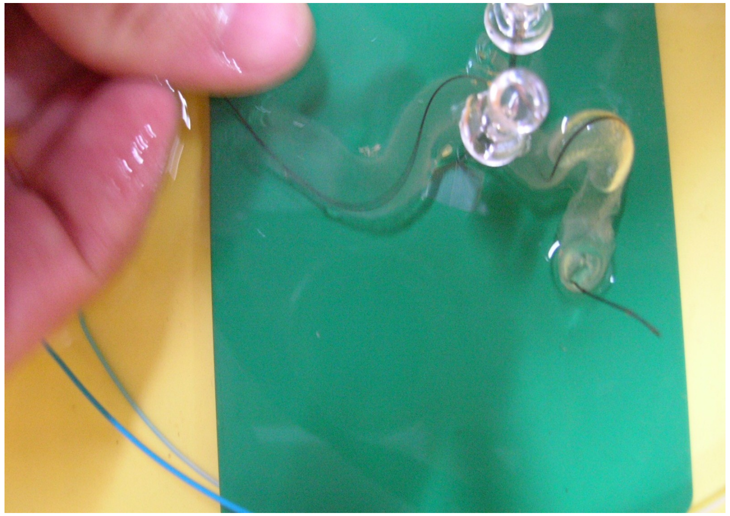
7.43mm
Post
5.98mm
5.98mm



Matching to medical image equipment



Good flexibility



Summary

1. Development of Flow system in-vitro using biomimetic polymer

2. Possibility of therapy simulation

3. Availability of engineering techniques of measurement such as PIV

Simulation & Computation of Blood Flow

K Srinivas
Contact:
Karkenahalli.srinivas@sydney.edu.au

Motion of Red Blood Cells

(Animation showed separately)

- What you have seen is the *State of Art* in Bio–Medical Computation.
- This was carried out by Dupin and Munn at Harvard Medical School.

Computations

- These results were obtained through computations meaning
- By solving Equations of Motion for Blood.

Merits of Computations

- One can carry out computations for conditions which we cannot obtain in a laboratory.
  - Size Limitations
  - Flow velocity limitations
  - And others.

Governing Equations

- ## Navier–Stokes Equations

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

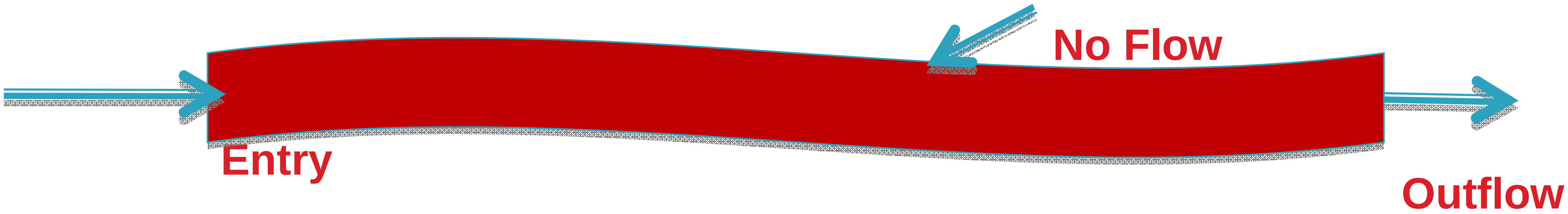
$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)$$

Where u,v are velocity components, p is pressure,
ρ is density and μ is viscosity.

Boundary Conditions

- Equations are valid for any flow
- To make them give solution for blood flow in a system we supply Boundary Conditions.
- One of the important conditions is that there is no flow through any solid surface.



Difficulty

- Equations cannot be solved easily.
- We solve them over a grid generated in the region of interest.
- Grid for a simple geometry may have a few thousand points or cells.
- For a human system we may need a few million grid points.
- CPU time also increases – a few hours.

Specialty of Blood Flow

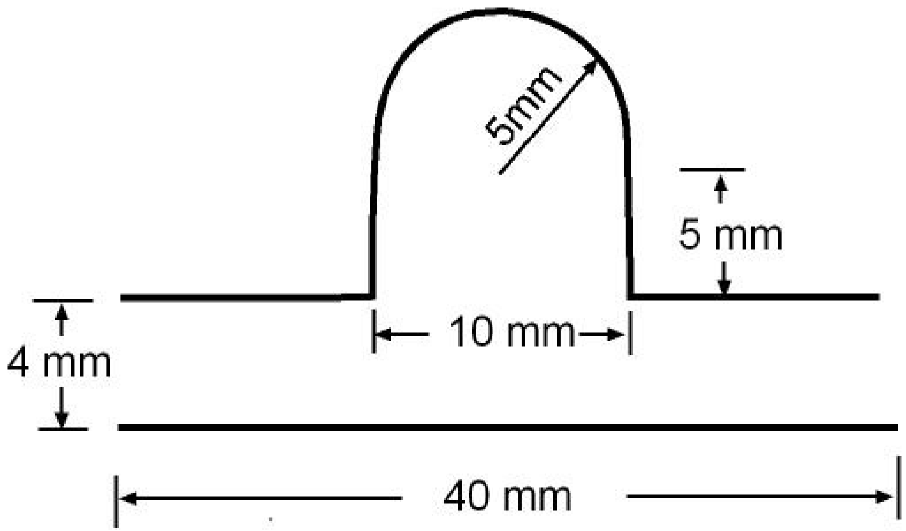
- In general a complex flow
- Highly irregular geometry
- Three dimensional, pulsating
- Blood is Non-Newtonian

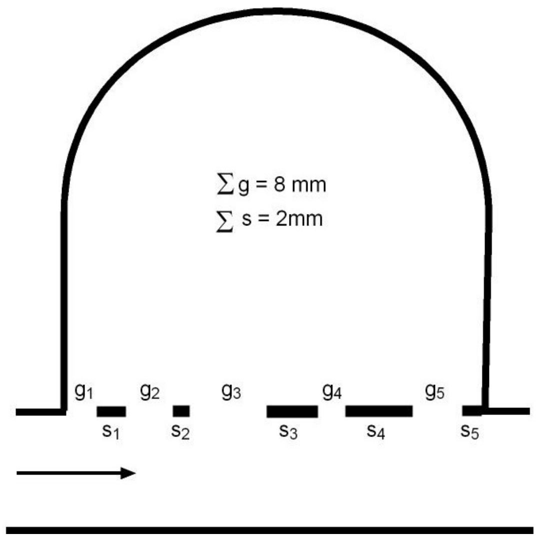
Simplifying Approximations

- Flow is Newtonian
  - Good approximations is shear rates are not too low.
- Flow is steady
  - Depends on the flow to be computed.

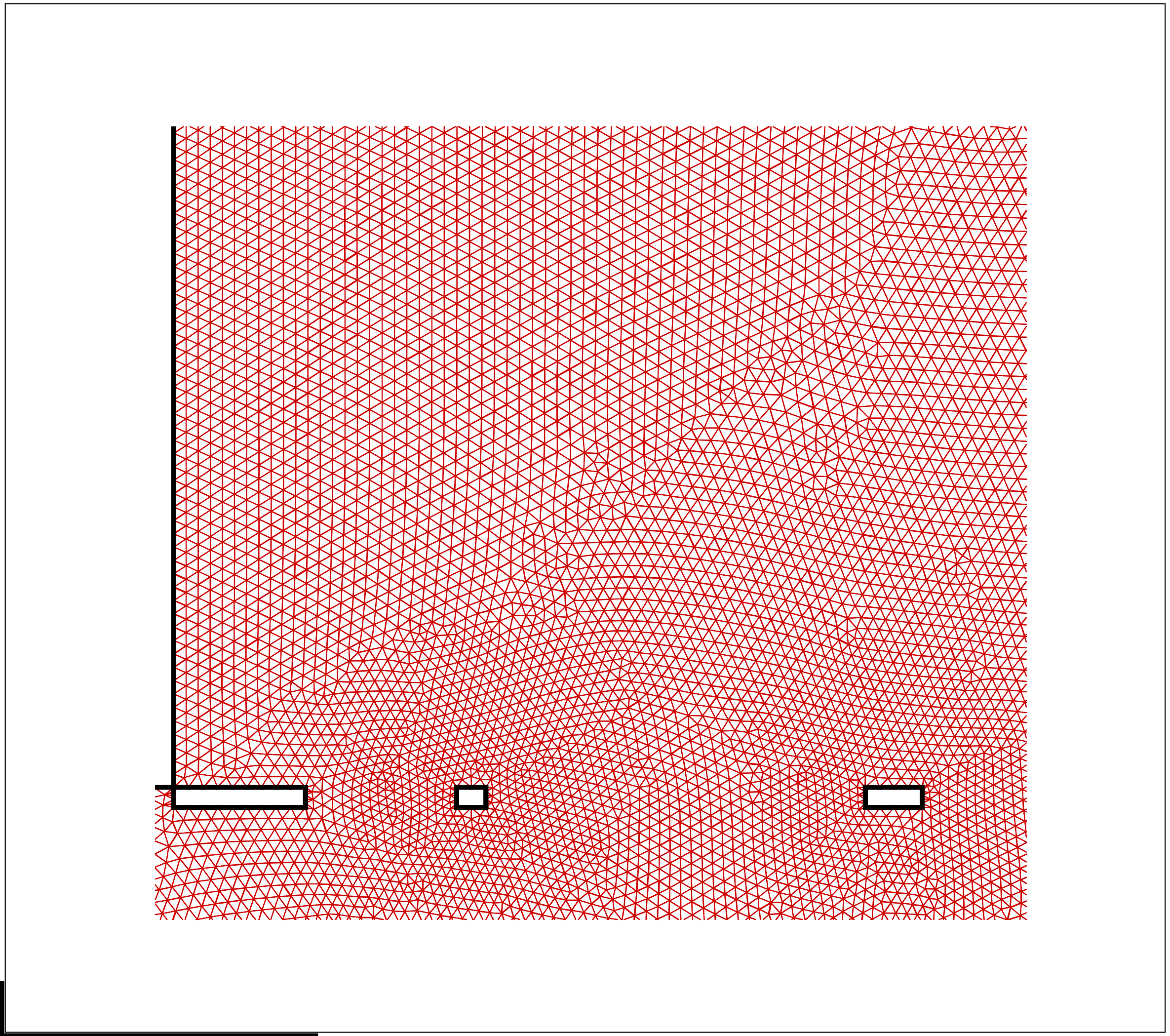
Grid Generation

- An important task
- May take weeks or months.
- Easily generated for regular geometries.





Enlarged Grid

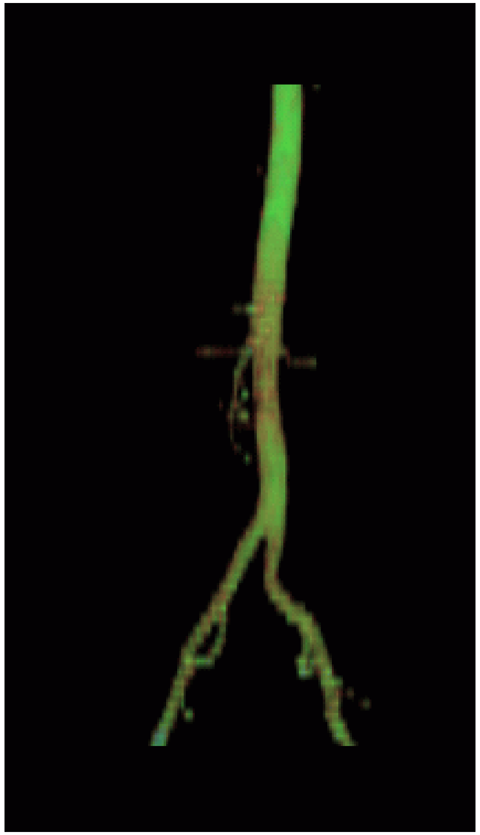


Grid for Bio-Medical Flows

- One desires to perform computations for a real patient geometry.
- How do you make measurements?
- Thanks to image reconstruction methods.

Image Reconstruction

- It is possible to reconstruct the patient geometry using Cat Scan or MRI images.
- Many softwares and programs exist.
- Some of them, US Government software, for example are available.

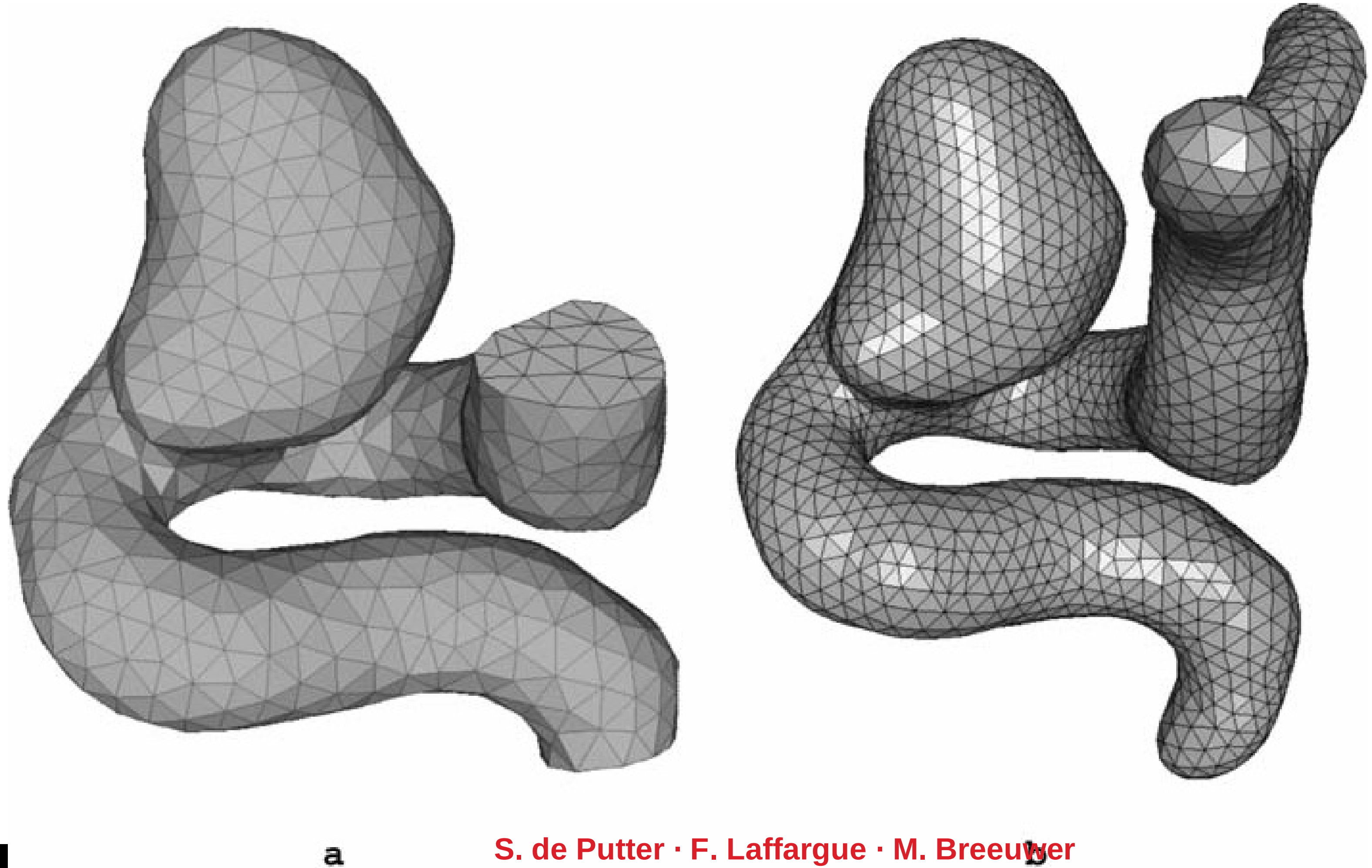


Alfredo Tirado-Ramos, Derek Groen, Peter Sloot
Faculty of Sciences, Section Computational Science
University of Amsterdam
Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

Actual Grid Generation

- There are many packages available.
- Rampant (attached to Fluent or Ansys), Solid Works, etc, etc.
- Usual to choose tetrahedrons to cover the computational space.
- Accuracy of computation depends upon the size of these tetrahedrons. More the better.
- Usually a few million cells required.

Example of a Grid



S. de Putter · F. Laffargue · M. Breeuwer
F.N. van de Vosse · F.A. Gerritsen

Flow Solver

- Today a number of methods are available to solve the Governing Equations.
- Some researchers write their own codes for the purpose.
- Use of commercial codes is also wide spread –Fluent (ANSYS), Star CD, CFX etc.

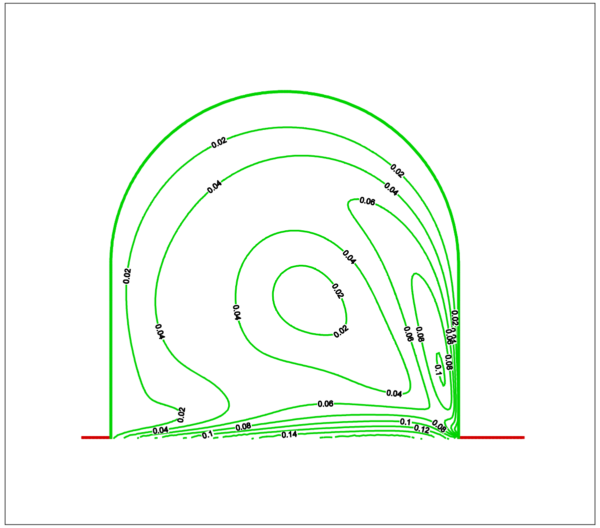
Post Processing

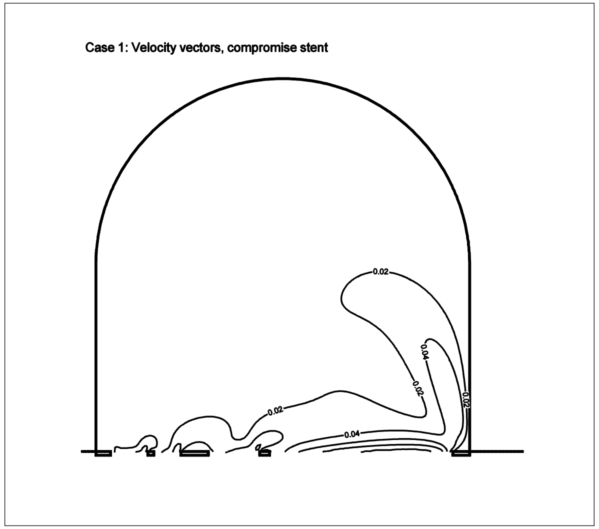
- The Flow Solver yields several MB or GB of data depending upon the flow.
- The data has to be analyzed and rendered as Graphs, Charts, Tables, Vectors and contours.
- The Flow Solvers usually have the post processors incorporated.
- Separate processors – TECPLOT etc. are available.

Post Processing (Continued)

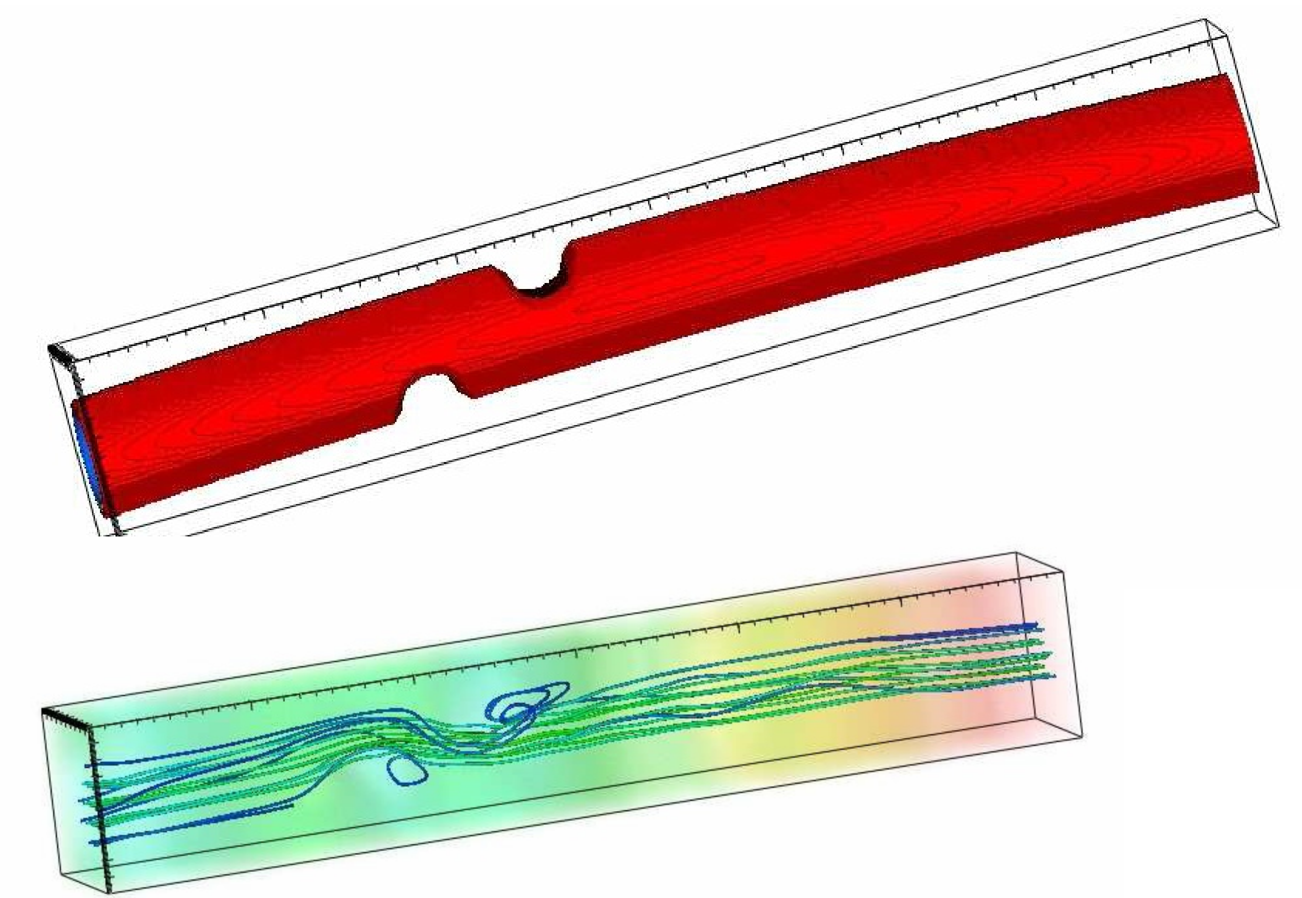
- Analyzing data itself may take weeks.

Two-Dimensional Example





Bilel Hadri
University of Houston



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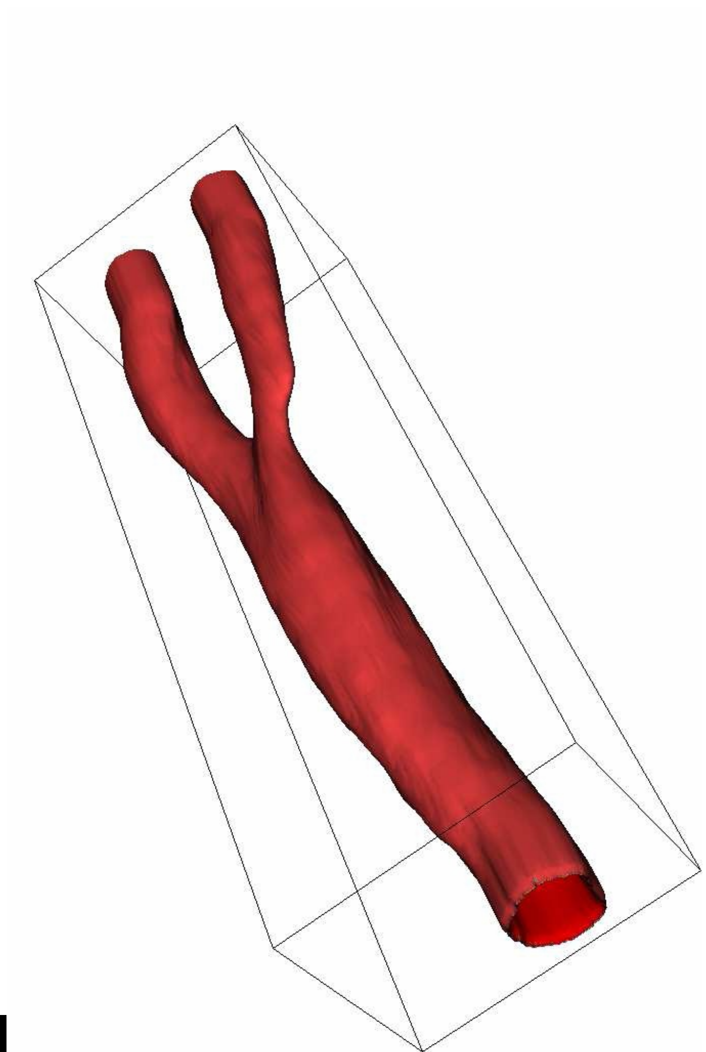

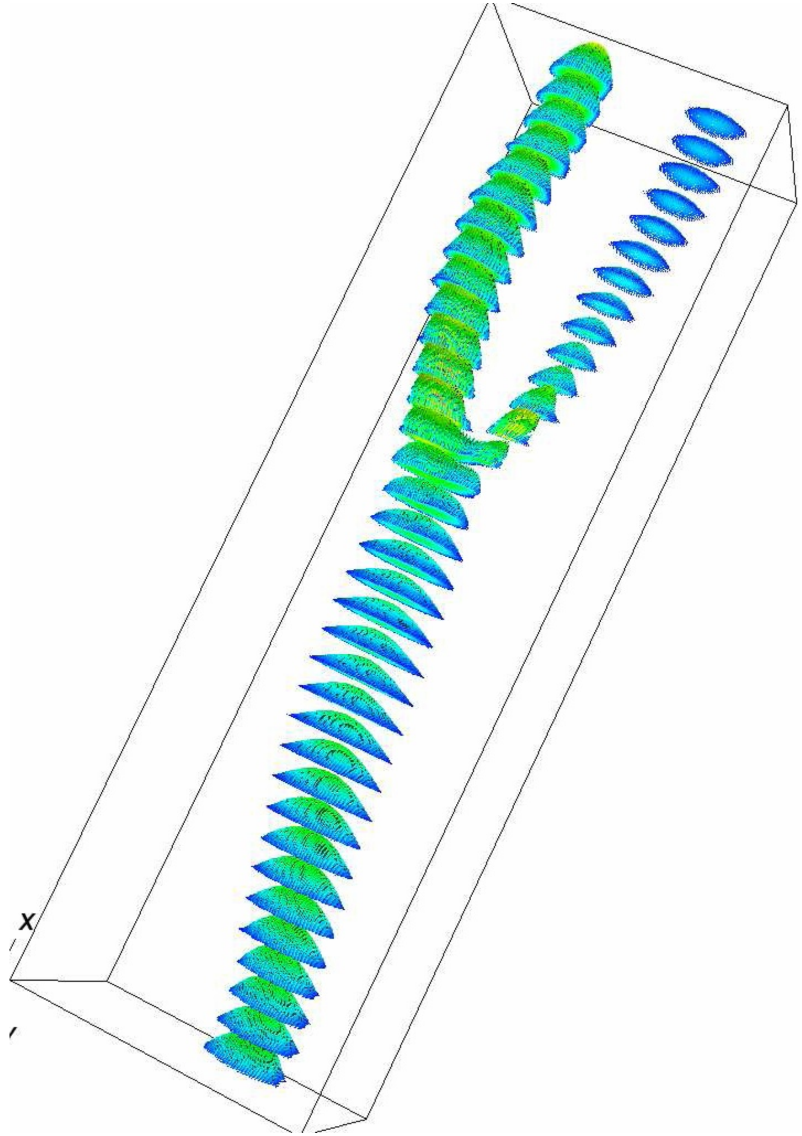

Ken-ichi Tsubota[*1], Shigeo Wada[1], Hiroki Kamada[1], Yoshitaka Kitagawa[1],
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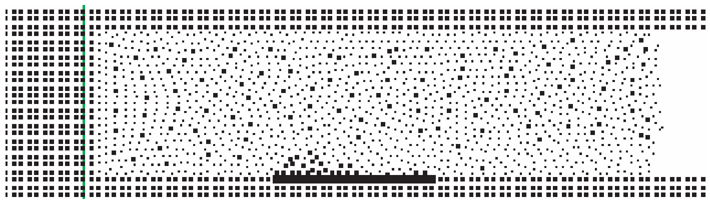
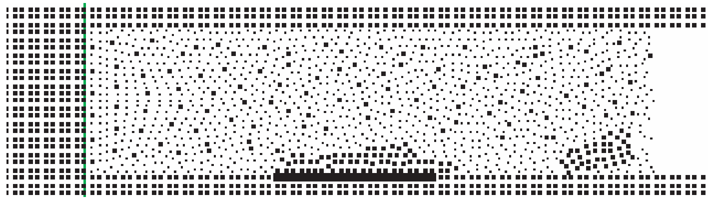
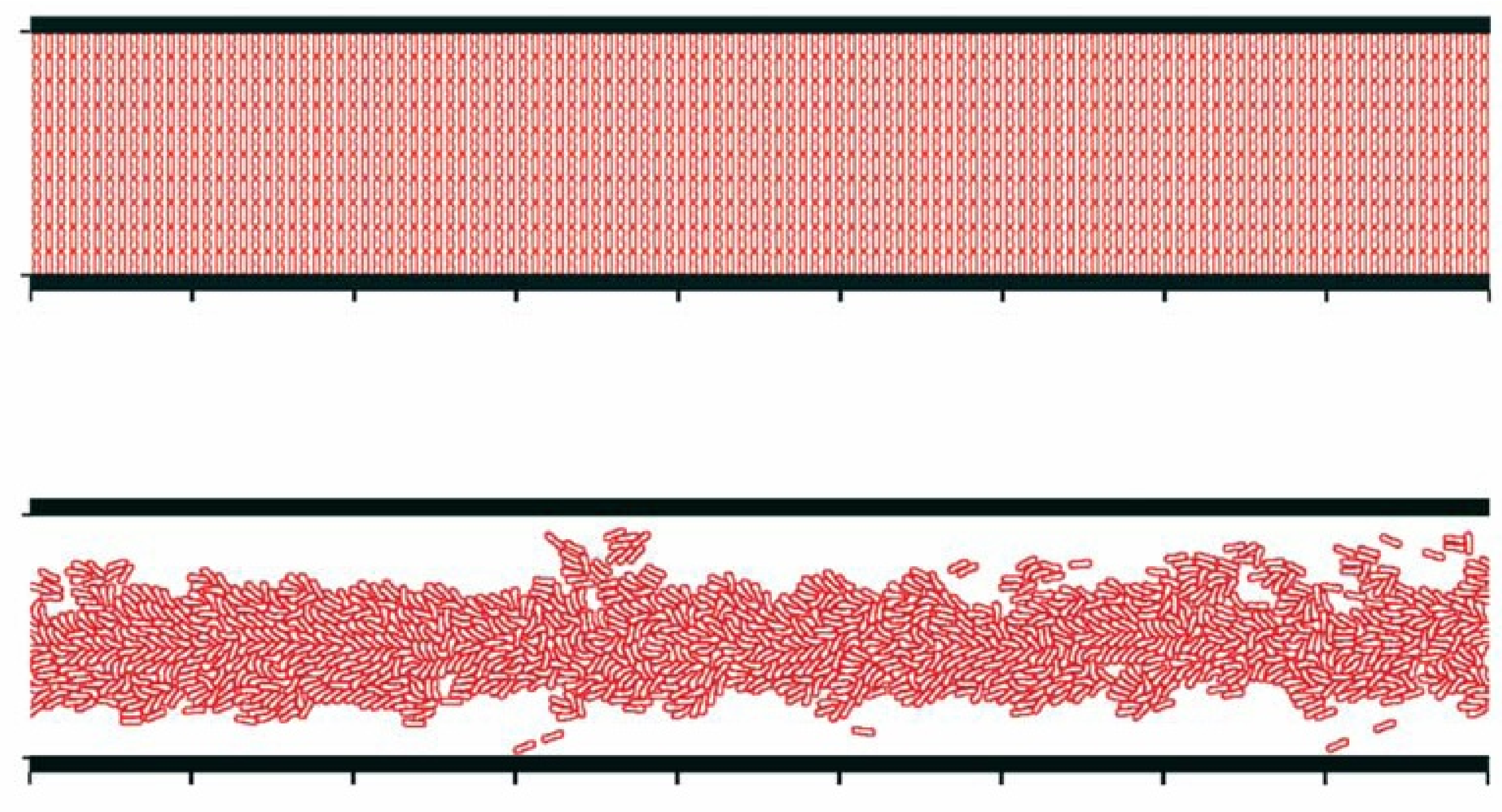


Ken-ichi Tsubota[*1], Shigeo Wada[1], Hiroki Kamada[1], Yoshitaka Kitagawa[1], Rui Lima[1] and Takami Yamaguchi[1]

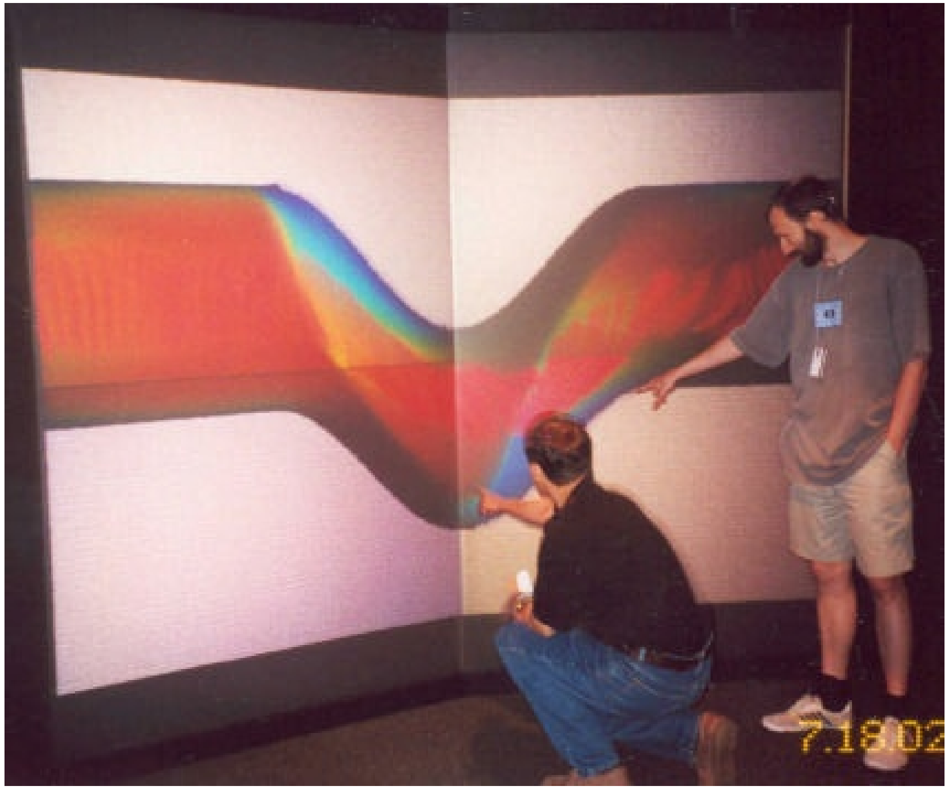
- Motion of Red Blood Cells



Ken-ichi Tsubota*1, Shigeo Wada1, Hiroki Kamada1, Yoshitaka Kitagawa1,
Rui Lima1 and Takami Yamaguchi1



Krzysztof Boryczko[1,2], Witold Dzwinel[1], David A.Yuen[2],
[1]Institute of Computer Science, AGH University of Technology, Mickiewicza 30, 30-059 Kraków, Poland,
[2]Minnesota Supercomputing Institute, University of Minnesota



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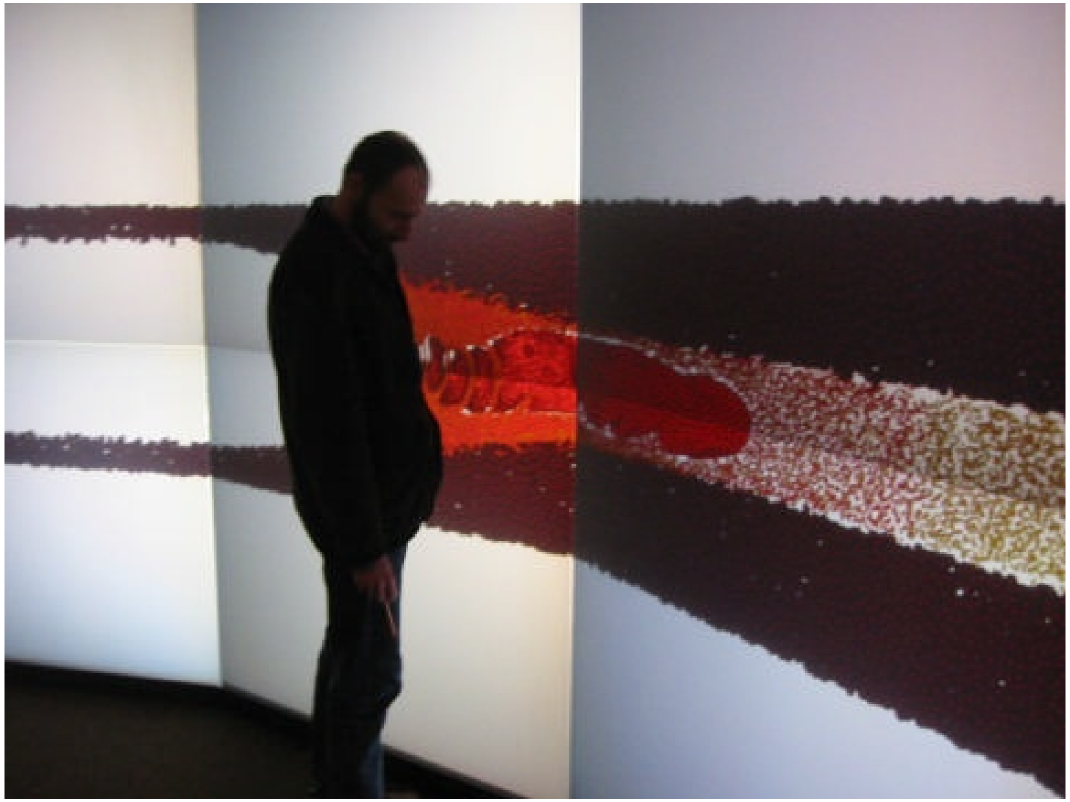
1Institute of Computer Science, AGH University of Technology, Mickiewicza 30, 30-059 Kraków, Poland,
2Minnesota Supercomputing Institute, University of Minnesota



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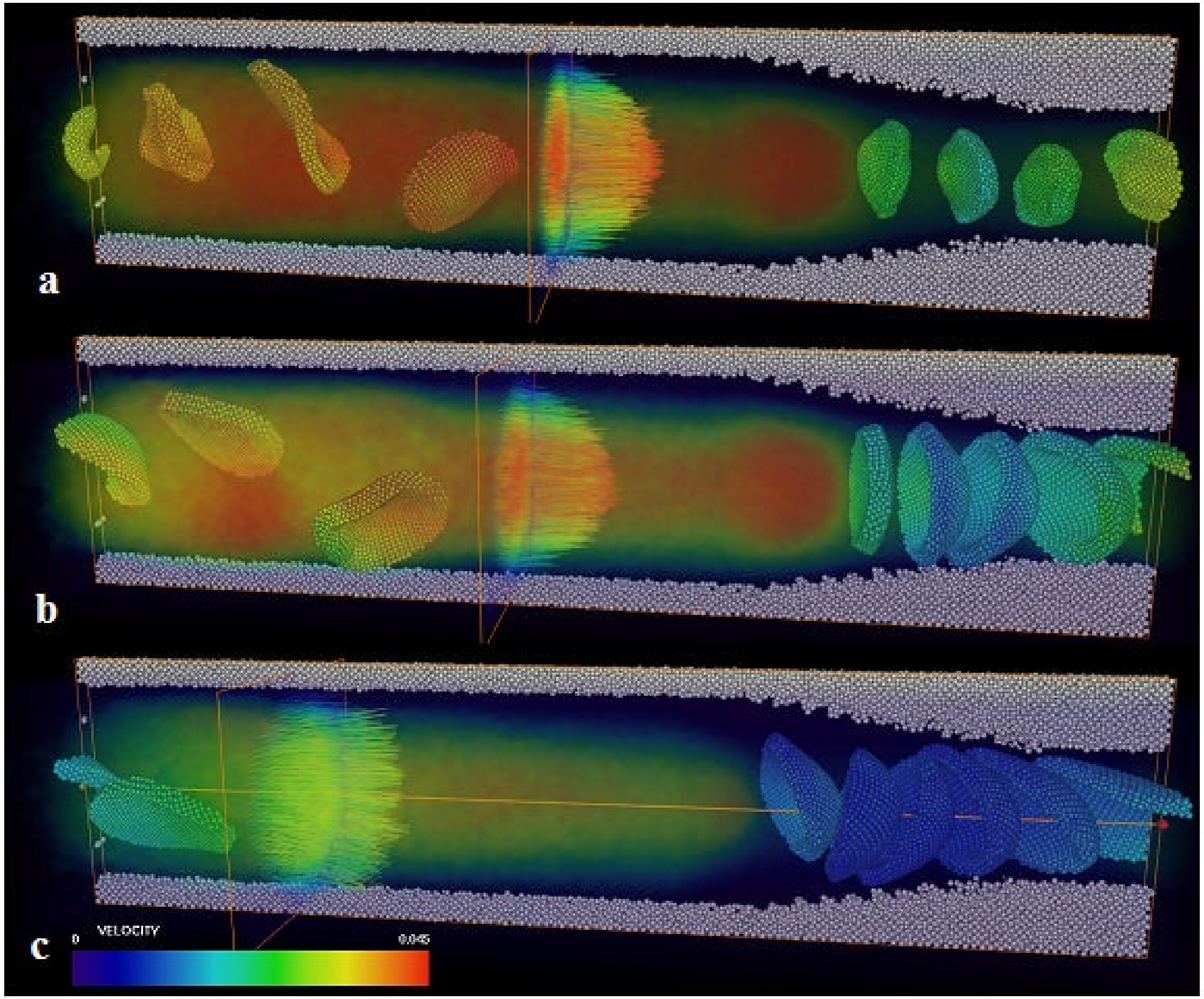
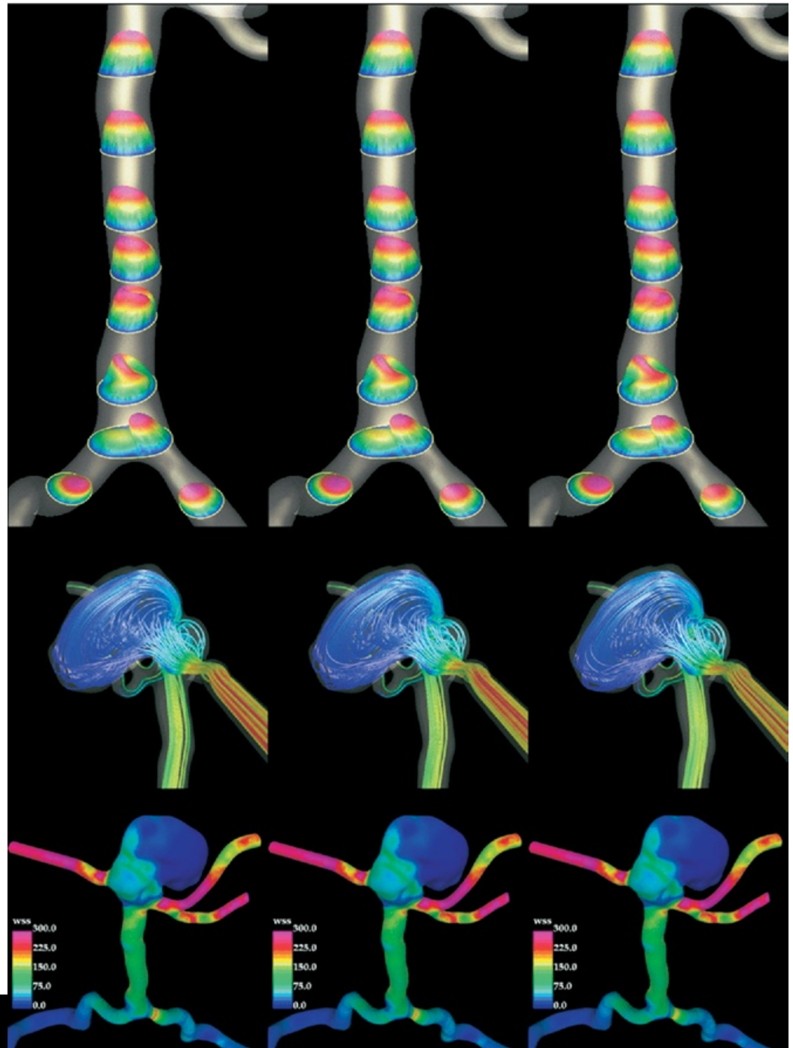
1Institute of Computer Science, AGH University of Technology, Mickiewicza 30, 30-059 Kraków, Poland, 2Minnesota Supercomputing Institute, University of Minnesota



New Possibilities

- Prediction of risk associated with rupture of an aneurysm.
- Prediction of the effectiveness of stents in cardiac and coronary applications.

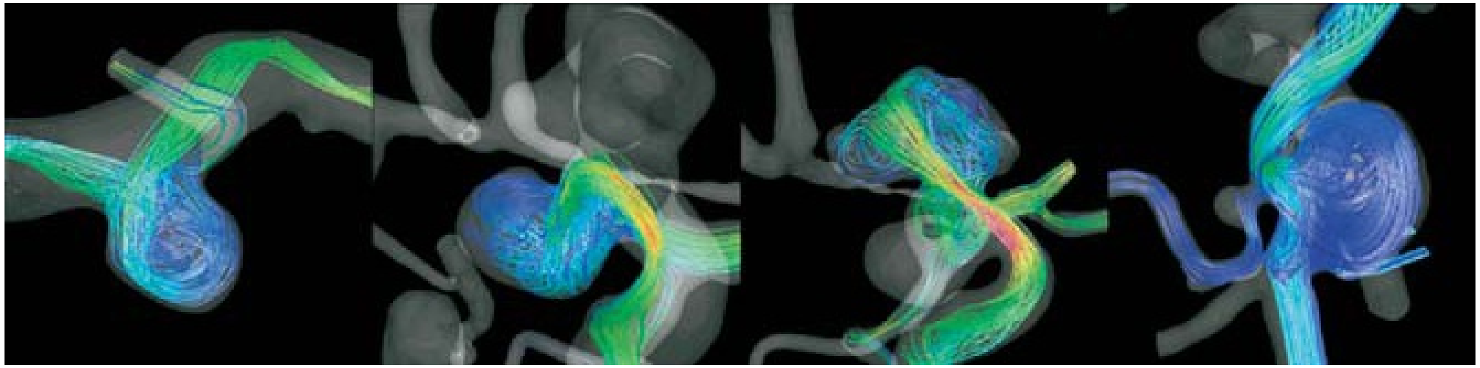
Flow in Aneurysms



Castro, Putman and cebral

Stream Lines in Aneurysms

Castro, Putman and cebral



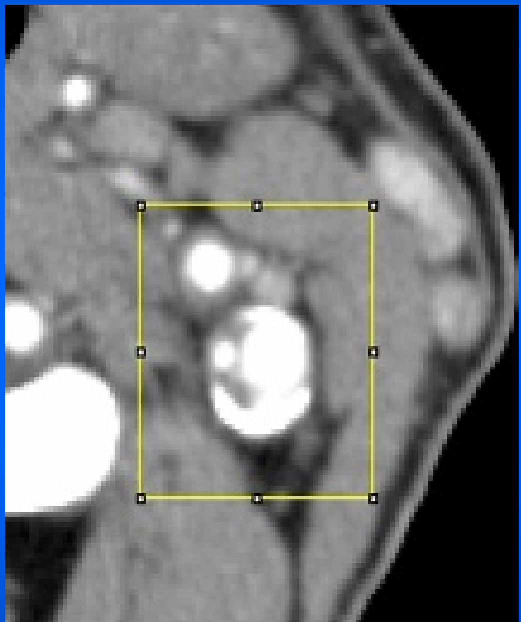
Conclusions

- Computations can be of considerable help in
  - Diagnosis
  - Prediction of risk
  - Prediction of effectiveness of devices such as stents.

Sample CFD Results

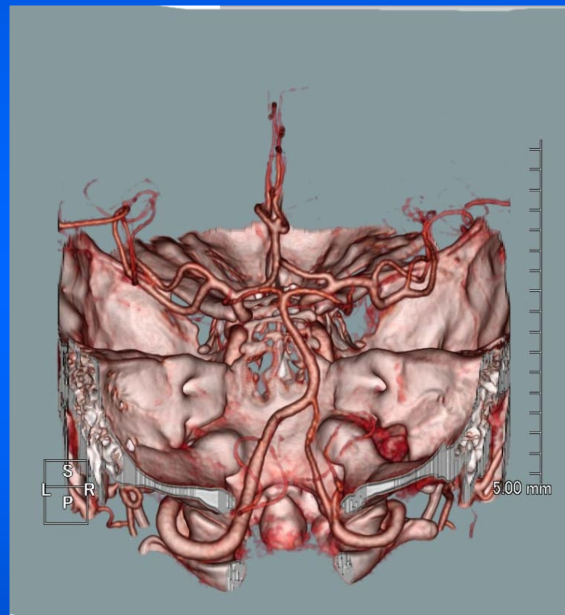
Medical Images

- Examples: Images in Medical Field



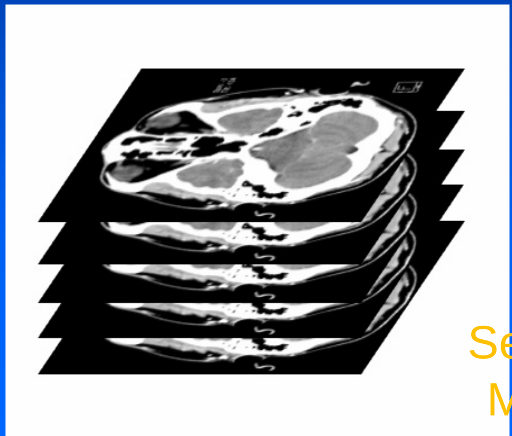
MRI & CT image

Angio Image



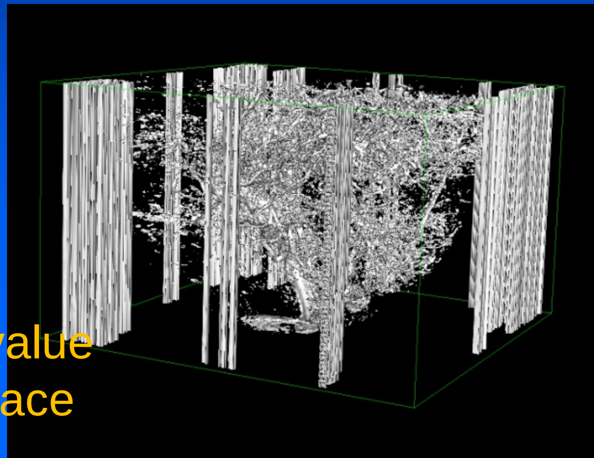
3D image on Workstation

Reconstruction of 3D shape

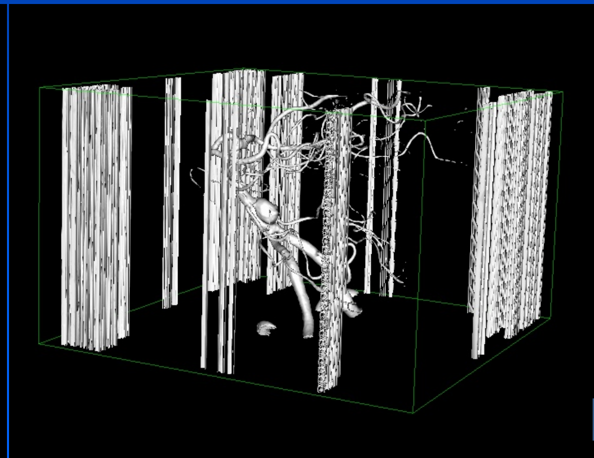


Stack images

Select step value
Making surface

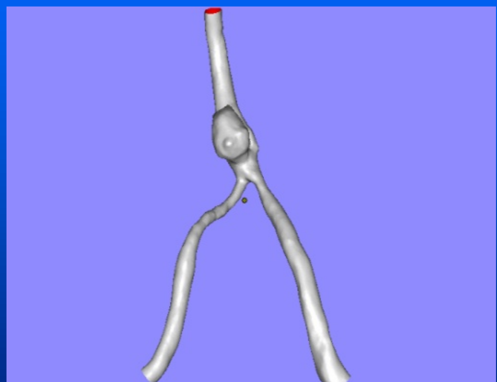


3D shape (Not good case)



3D Shape (Good case)

Delete branch vessel,
Tissue and noise.
Surface cleaning

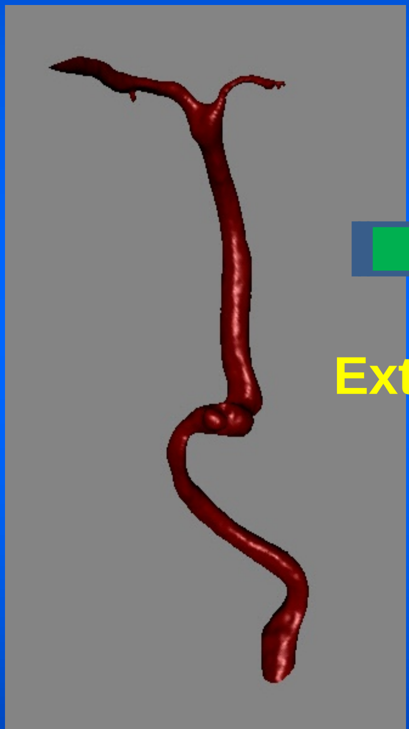


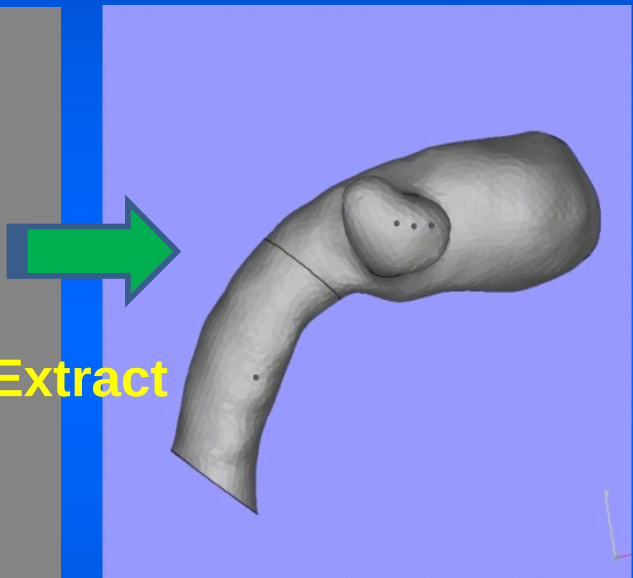
Completed 3D shape

If you have an interest in 3D reconstruction,
OsiriX (Machintosh software) is recommended!! Very easy!
Let's Try It!

Example of reconstructed 3D shape

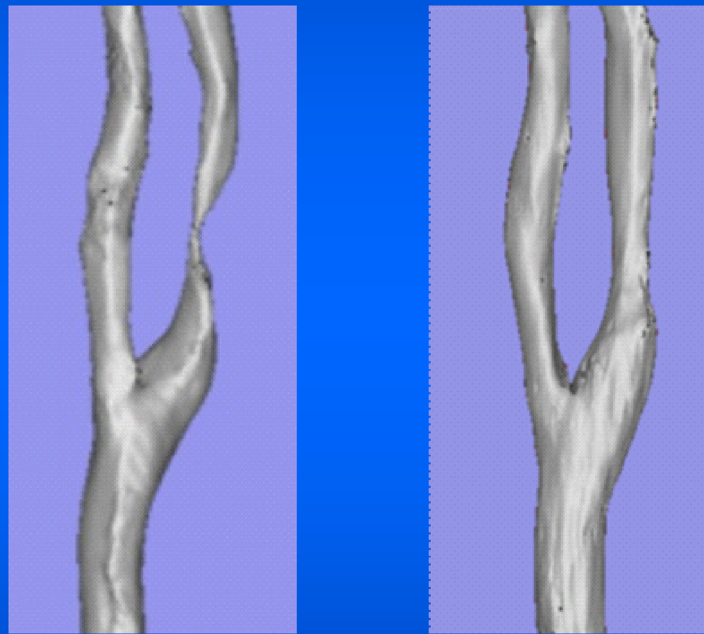
- Cerebral Aneurysm





1. CFD calculating time depends on the analysis region.
2. Extracted only attentions region.
3. CFD calculating speed up!

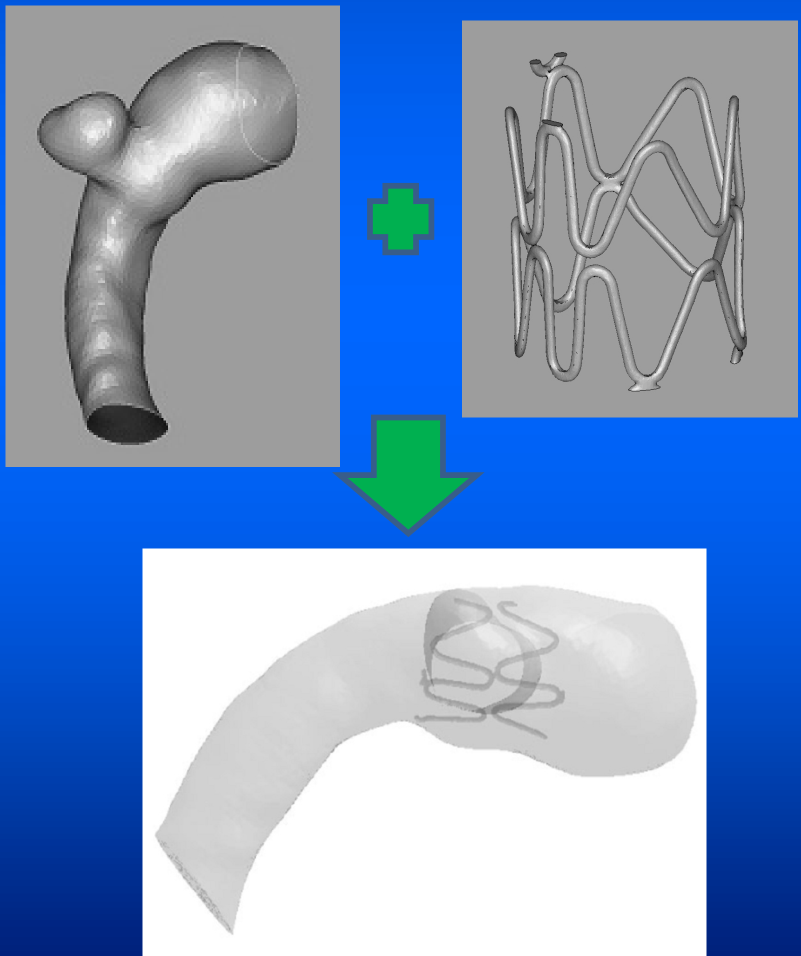
- Carotid artery



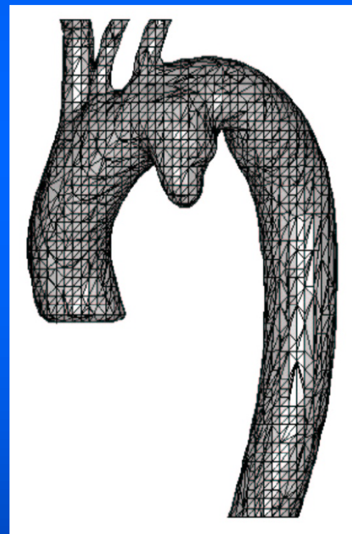
Pre CAS   Post CAS

Example of reconstructed 3D shape

- Stenting in Aneurysm



- Aorta Aneurysm
  - Same process at Cerebral Aneurysm case



●This research by Prof. Matsuzawa

Japan Advanced Institute of Science and Technology (JAIST)

Example of reconstructed 3D shape

- Nasal Cavity
  - Same process at Aneurysm case

Numerical Simulation

- Basic Equation
  - Equation of Continuity
  - Navier-Stokes Equations

- Solver
  - Finite Volume Method
  - Fluent Co. Fluent version 6.1.22

Numerical Simulation

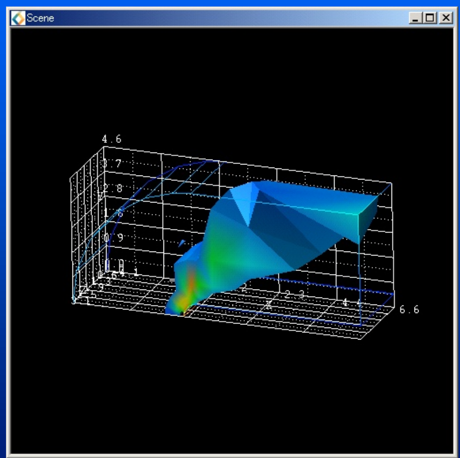
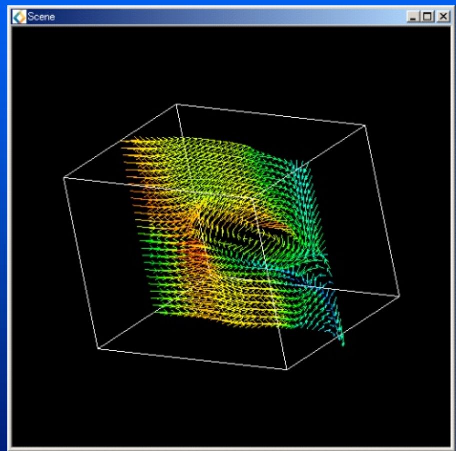
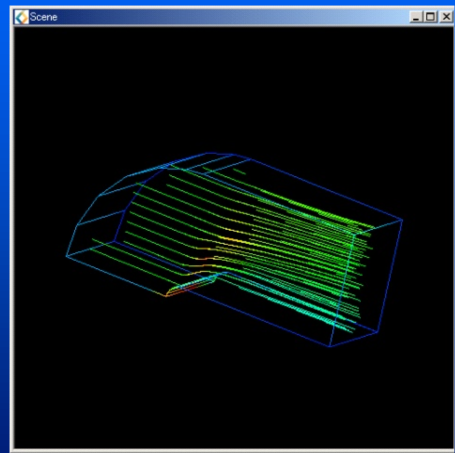
- The condition of simulation
  - Steady simulation
  - Inlet Condition: 0.162 [m/s] (Uniform flow)
    - Reynolds Number: 200 (Inlet)
  - Outlet Condition□Pressure 0 [Pa]
  - Wall & Stent: No-slip
  - Volume Meshes: about 2,000,000 (All case)
    - Mesh Type: Tetrahedron mesh

Results

CFD Visualization

- What is CFD results?
  - Velocity, Pressure, Wall Shear Stress, Vortex…

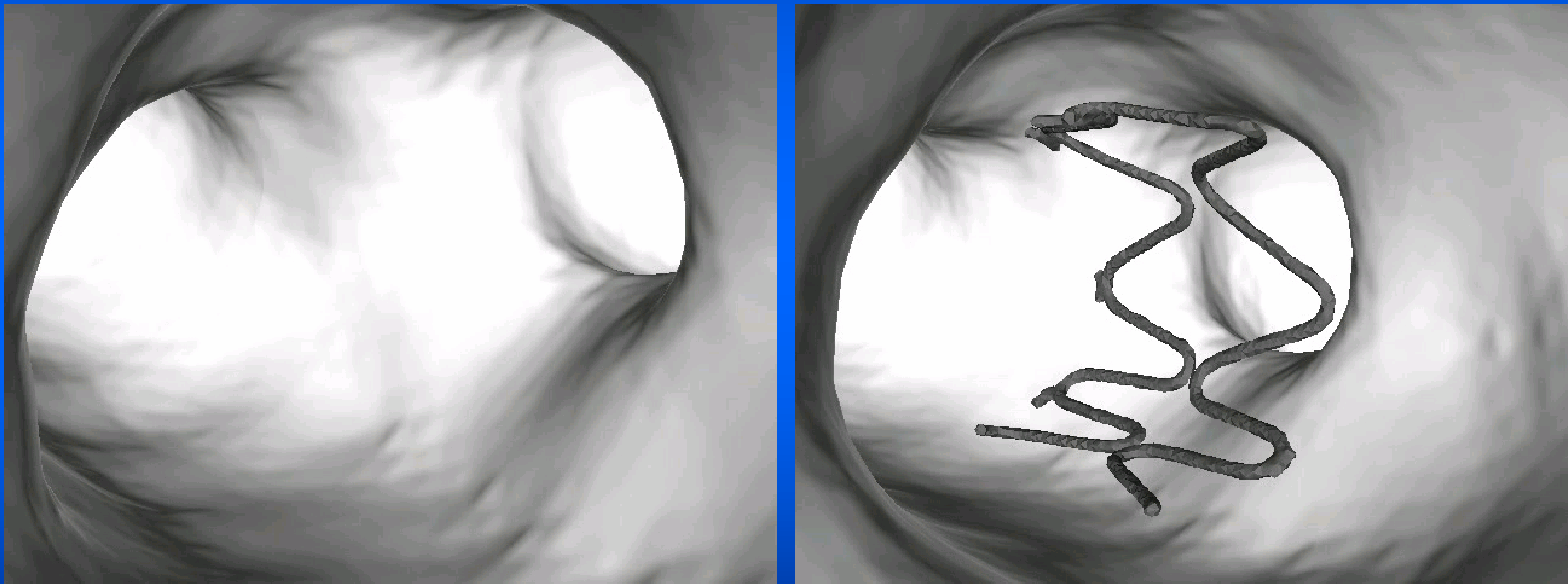
- What is visualization method?
  - Movie, Figure, Contour, Vector, Steam line…

Results

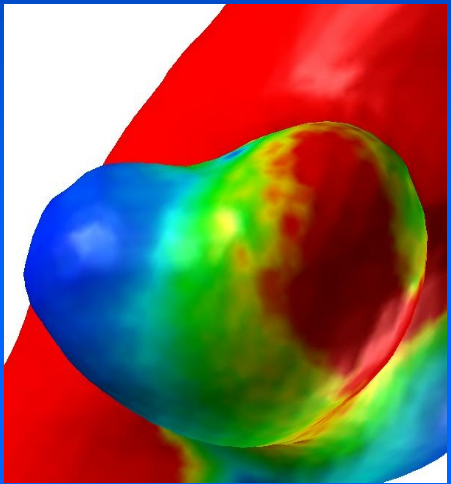
Stenting in cerebral aneurysm

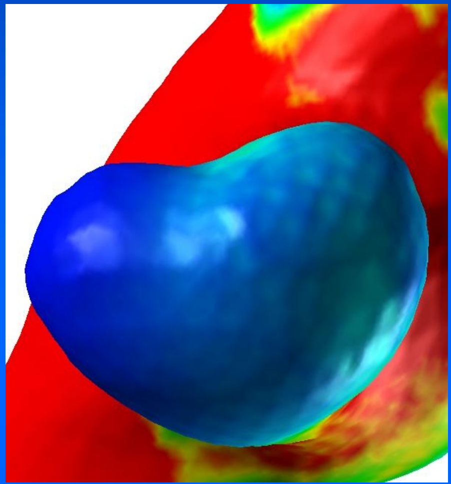
-



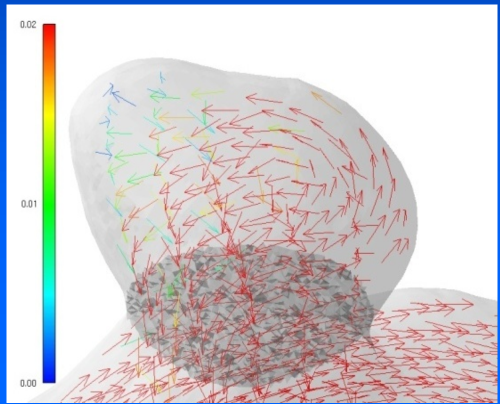
Results
Stenting in cerebral aneurysm

Wall Shear Stress

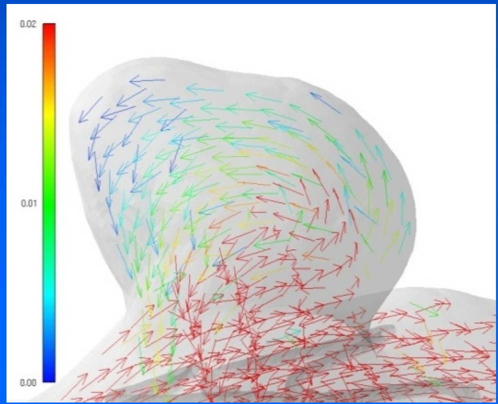

Without Stent


Stenting case

Velocity Vector

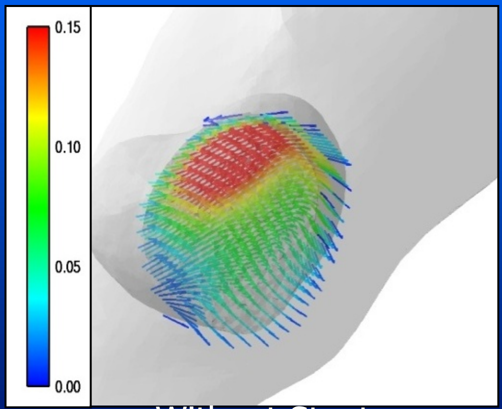


Without Stent

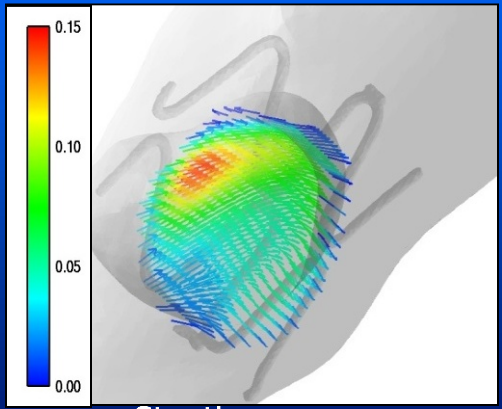


Stenting case

Velocity Vector



Without Stent

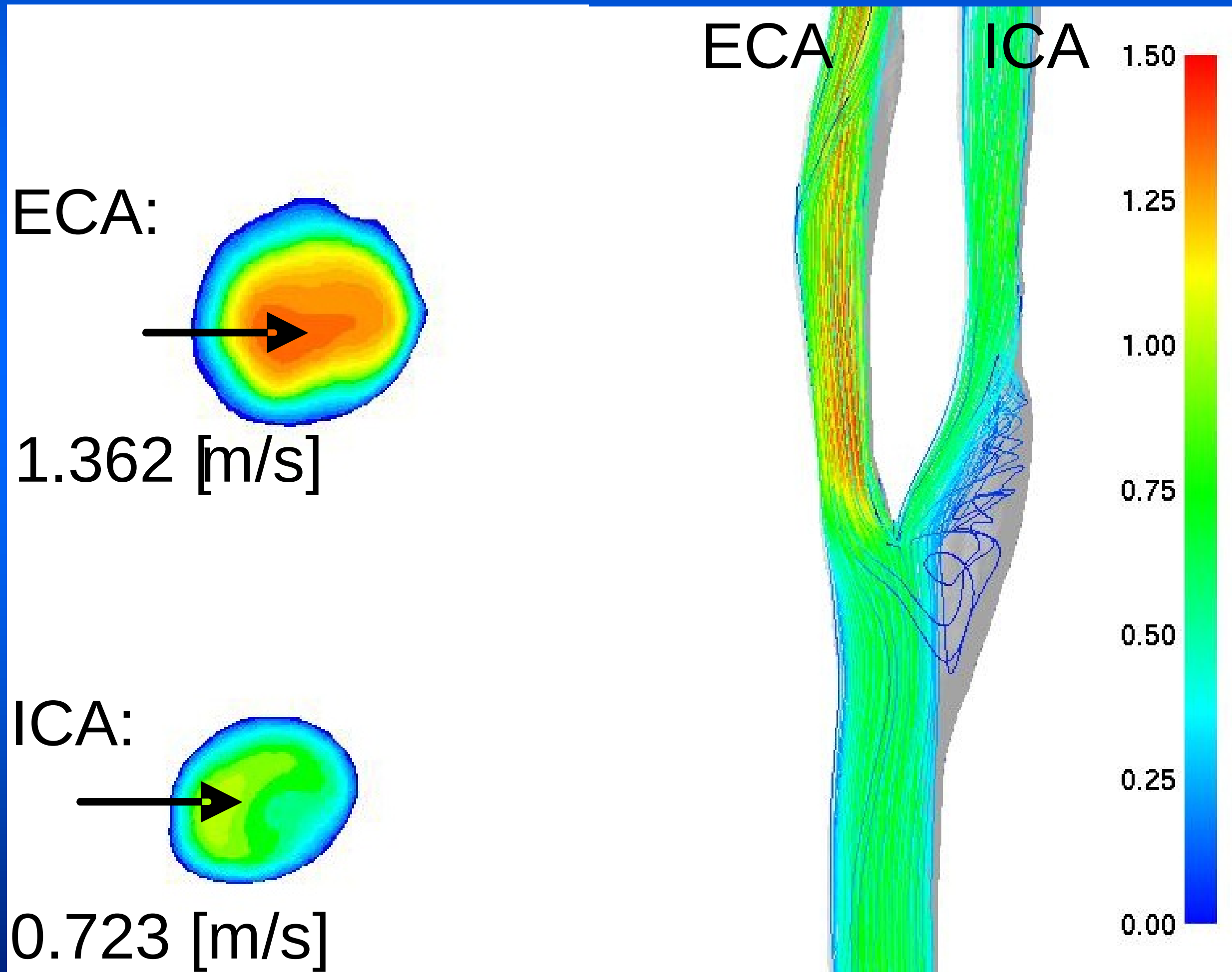


Stenting case

Results

Carotid Artery

-



Results
3D Visualization System

- Virtual Reality System

Virtual Reality System
(H. Anzai, IFS, Tohoku University)

Right: Liquid crystal Shutter glasses
Left: Image Controller

Conclusion

- Realistic shape CFD can be useful for medical doctors to understand the patient condition, or discuss treatment policy.
  - The effect of stent in blood vessel
  - The blood flow pattern at stenosis
  - The blood flow pattern in anuerysm
  - The pressure and stress to blood vessel wall
  - Evaluation of New device