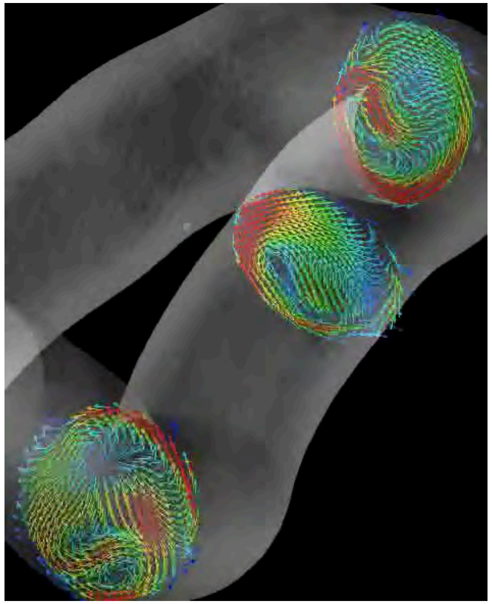
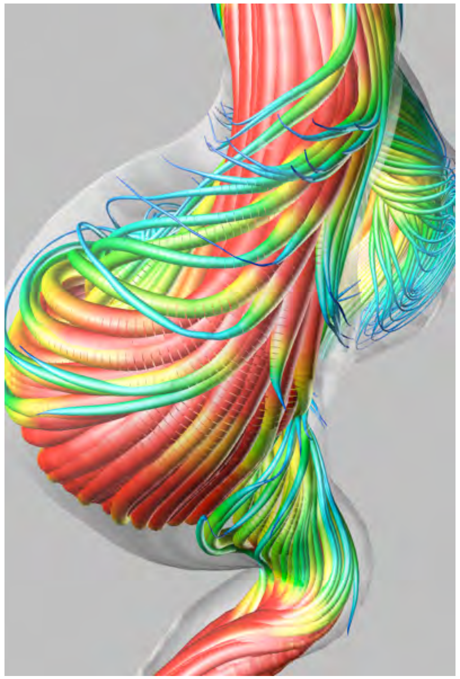
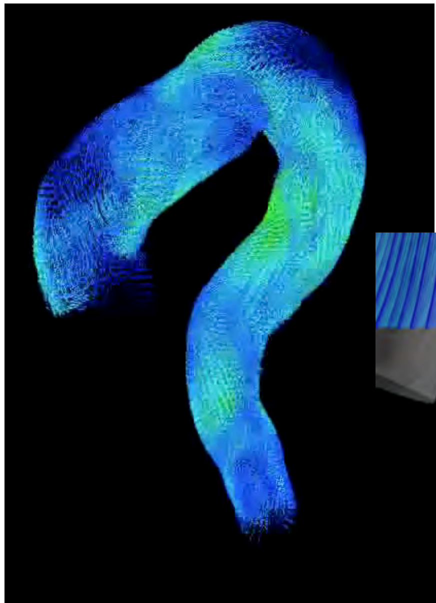
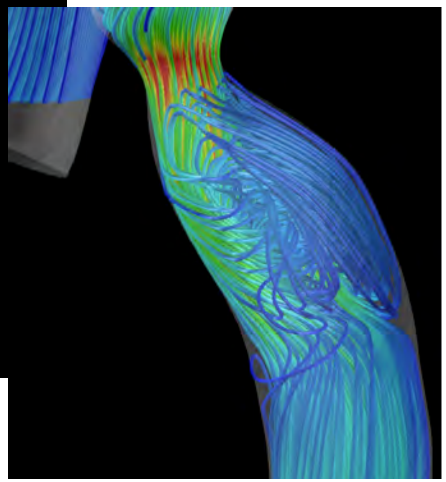


# Computational approach elucidating the mechanisms of cardiovascular diseases



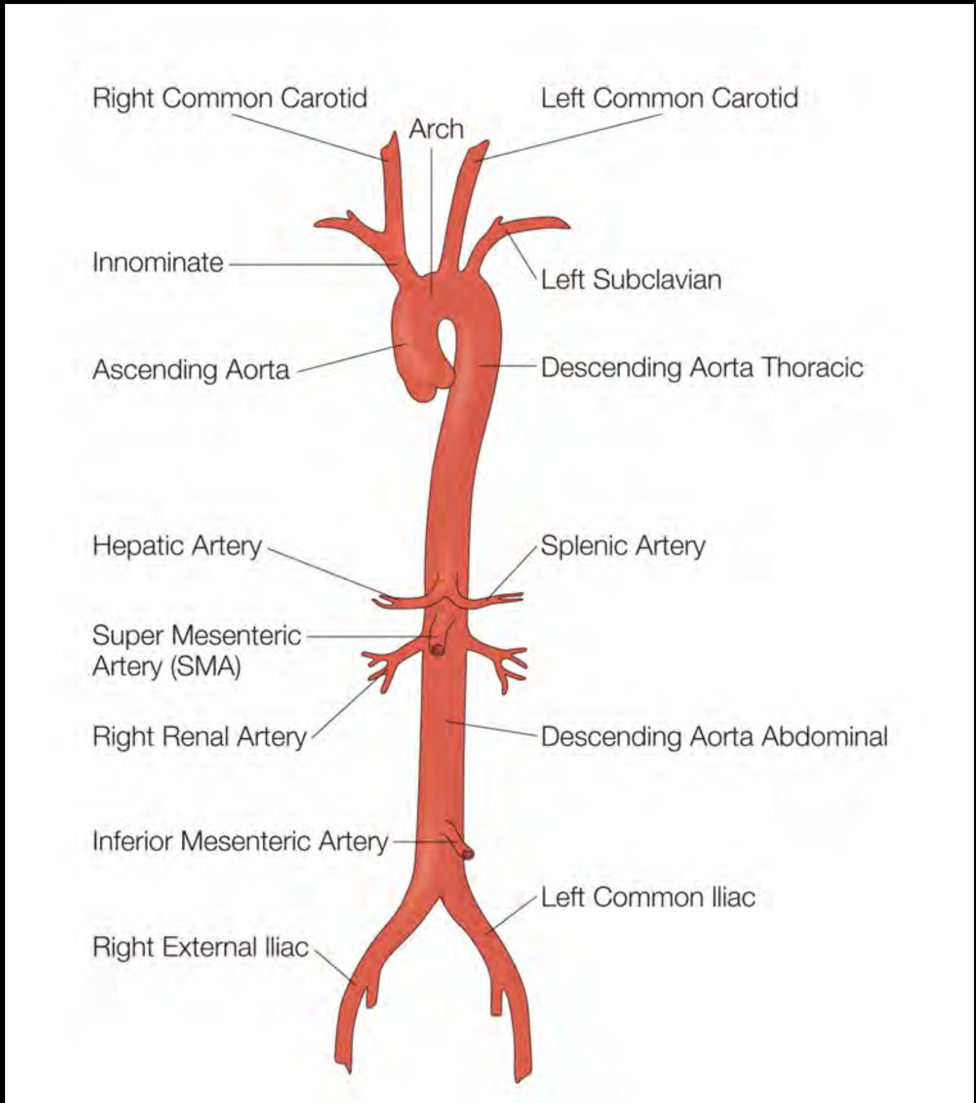





Hiroshi Suito
Kenji Takizawa
Viet Q.H. Huynh
Benjamin Morel
Takuya Ueda
Tayfun E. Tezduyar

# Contents

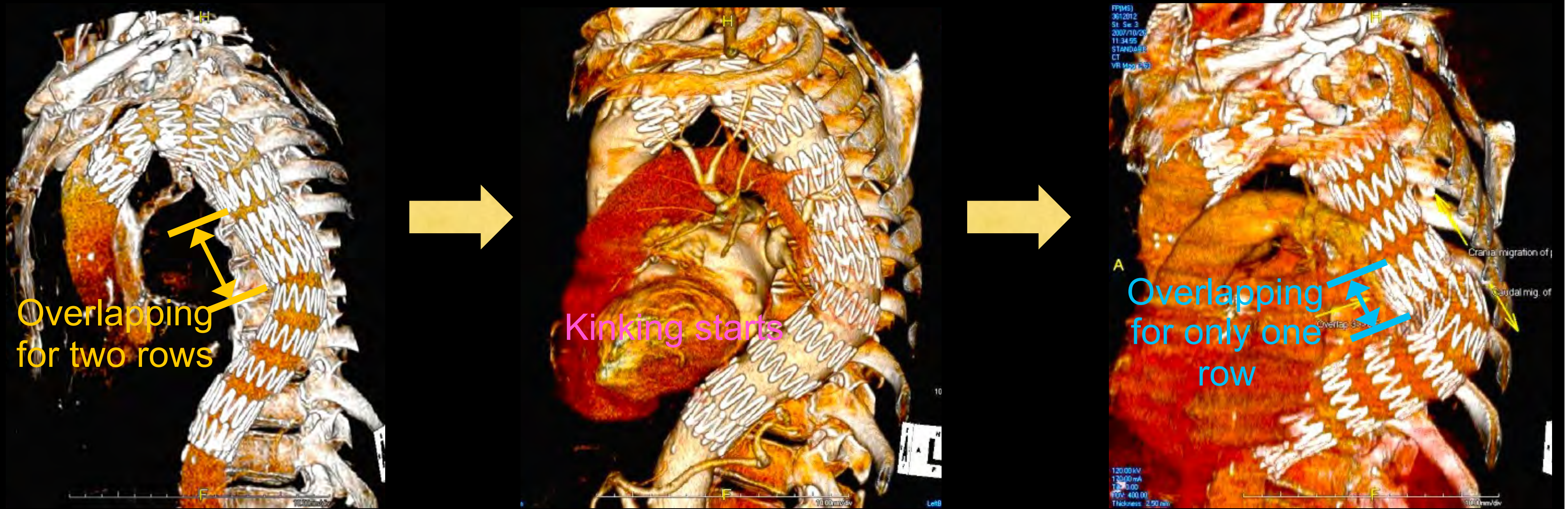
# Background




Aortic aneurysm is a life-threatening disease that slowly develops with advancing age of the patient . It presents risk of rupture. Many reports have described the risk factors, but the natural history of aneurysm development remains unclear. However, at least, stress from blood flow to the vessel wall is regarded as playing an important role in these diseases.

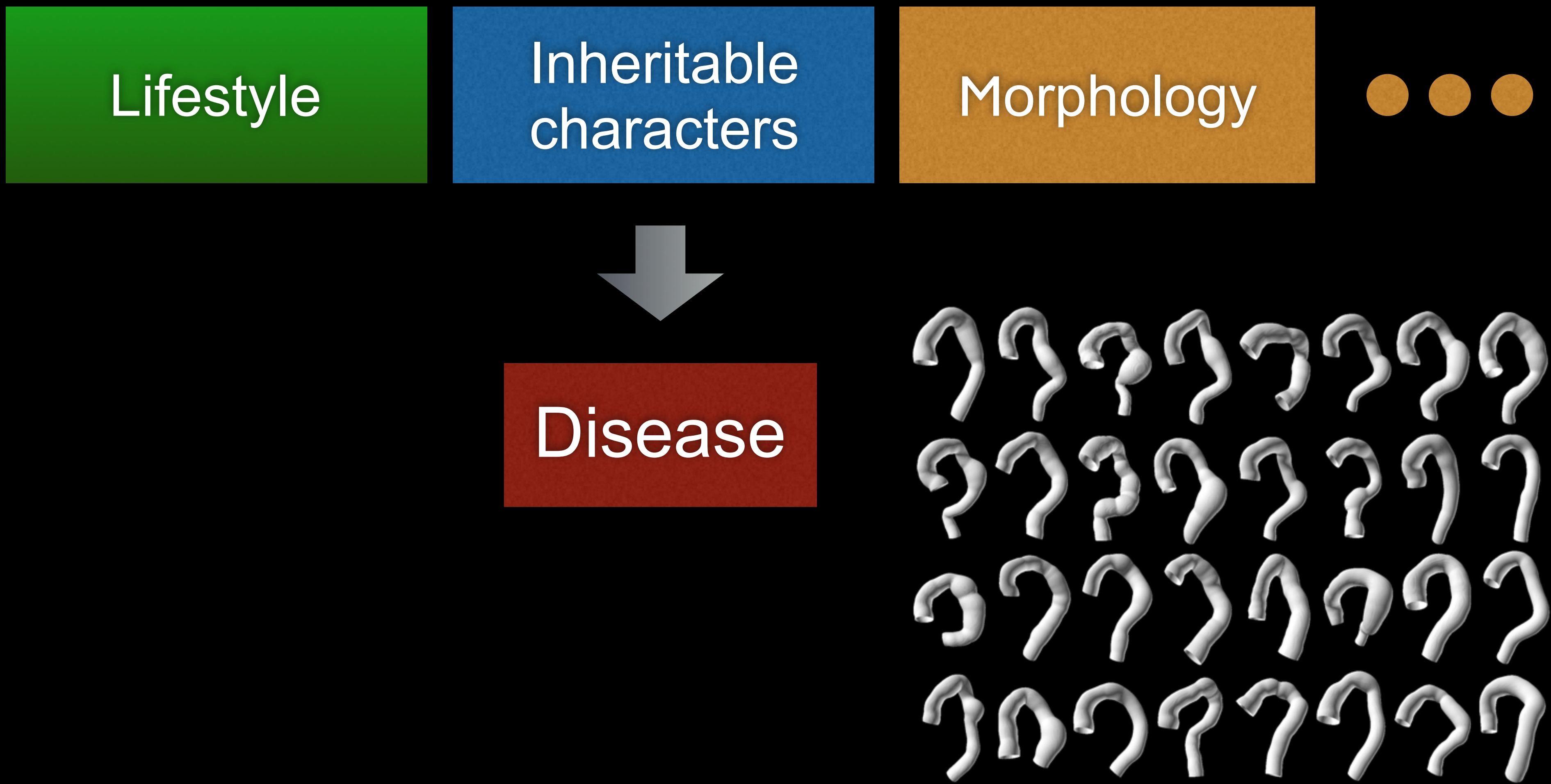
## Backgrounds

For cardiovascular diseases, several treatment options might be used such as open surgery and stent graft treatment. Even if the initial treatment technically succeeds, some patients show recurrence and progression of disease many years after treatment.




- In this patient's case, kinking slowly started and suddenly accelerated. Such long-term morphological change seems to interact synergically with hemodynamics.
- However, not all the patients show this kind of adverse event. This means that the relation between aorta shapes and blood flow seems to have positive feedback.
- The prediction whether this phenomenon will occur or not, is extremely important from the view point of clinical medicine.

# Factors influencing cardiovascular disease



Morphology

↓

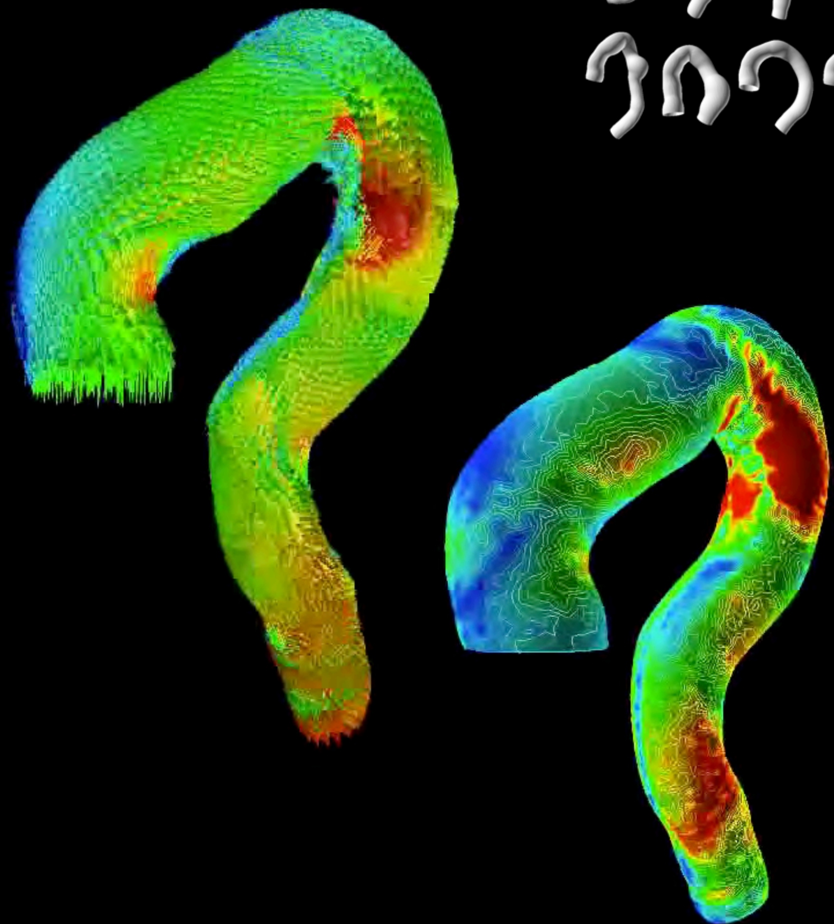
Flow characteristics

↓

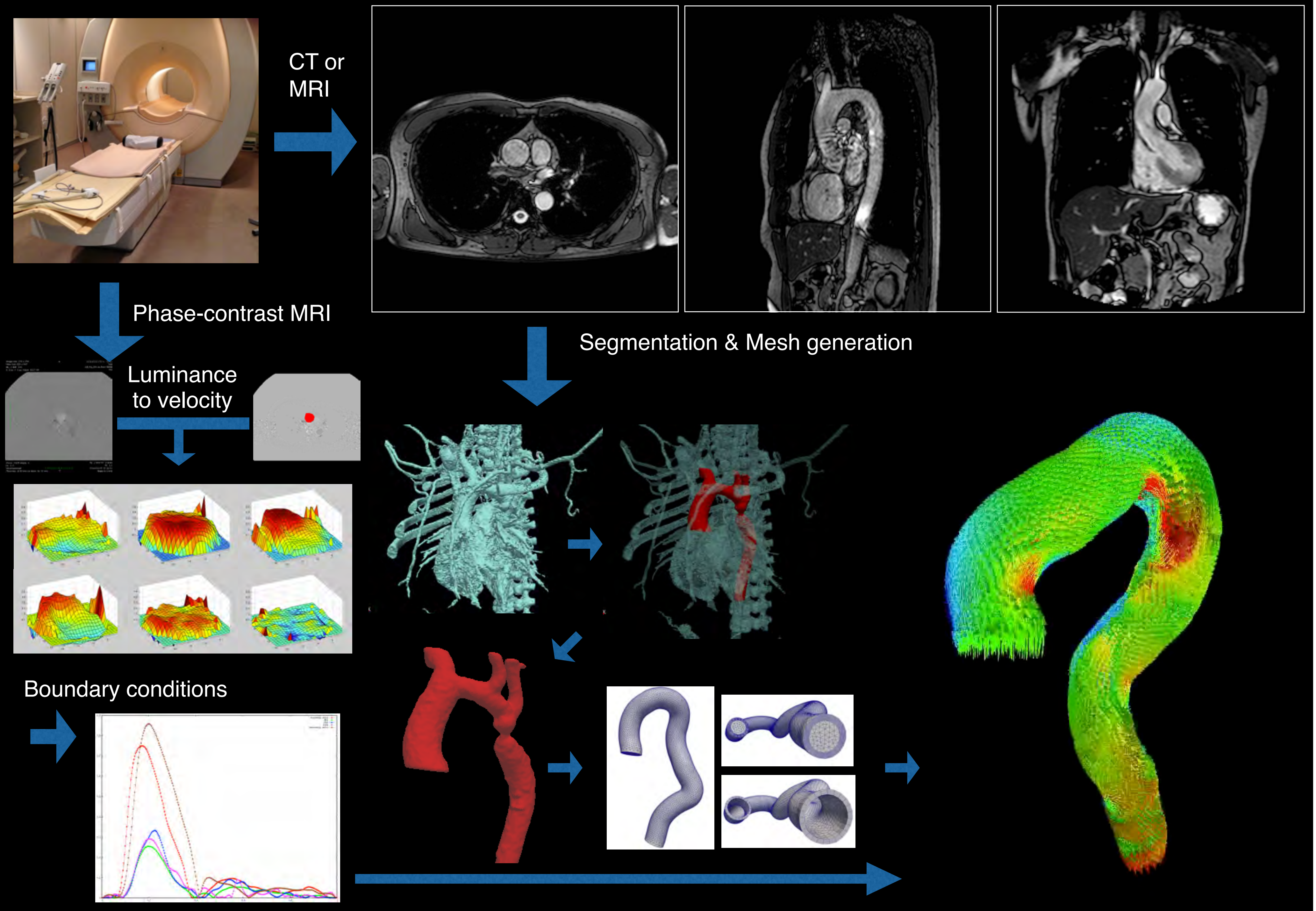
Vessel wall stresses

↓

Disease



# Simulation using medical imaging data



# Computational Method

T. Tezduyar and K. Takizawa

- Deforming-Spatial-Domain/Stabilized-Space–Time Method (DSD/SST)
- Variational Multiscale (VMS) method


[1] T.E. Tezduyar, "Stabilized finite element formulations for incompressible flow computations", Advances in Applied Mechanics, Vol. 28, pp. 1–44 (1992).

[2] K. Takizawa and T.E. Tezduyar, "Multiscale space–time fluid–structure interaction techniques", Computational Mechanics, Vol. 248, No. 3, pp. 247–267 (2011).

[3] T.E. Tezduyar, K. Takizawa, C. Moorman, S. Wright and J. Christopher, "Multiscale Sequentially-Coupled Arterial FSI Technique", Computational Mechanics, Vol. 46  17–29 (2010).

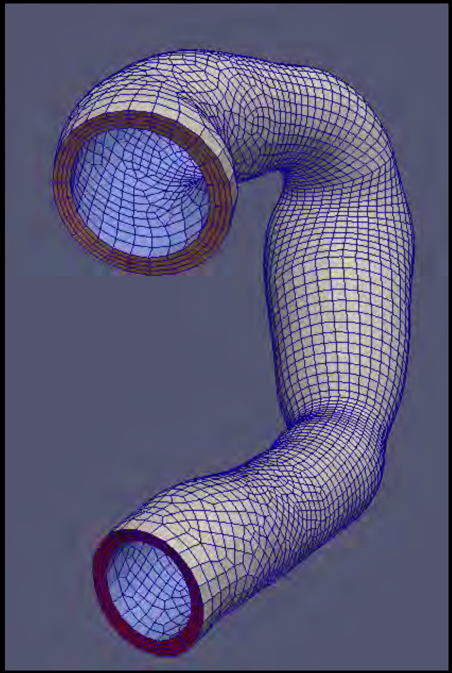
# FSI (Fluid-structure Interaction) procedure

## Sequentially-Coupled Arterial FSI (SCAFSI) Technique

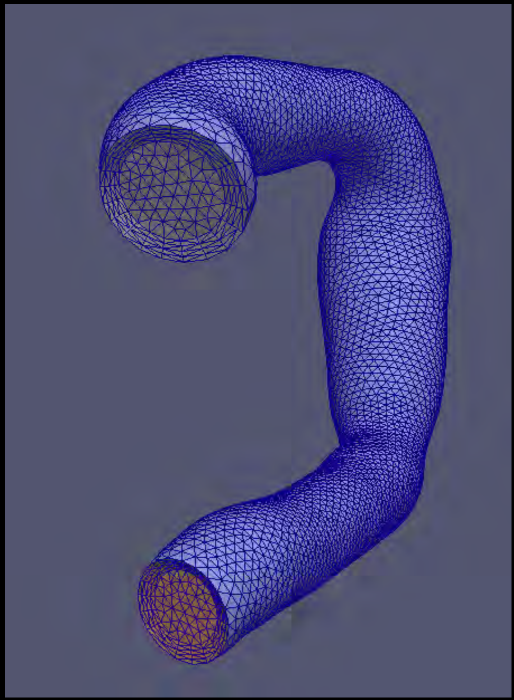
1. Compute the vessel wall motion for one heart period using the equation for structure. Measured pressure history data are given as an external force.

2. Compute the mesh motion for the fluid region by imposing the surface mesh displacement as a Dirichlet condition.

3. Compute the flow field on the prescribed moving mesh calculated in the previous step.



Hexahedral mesh for structure



Tetrahedral mesh for fluid

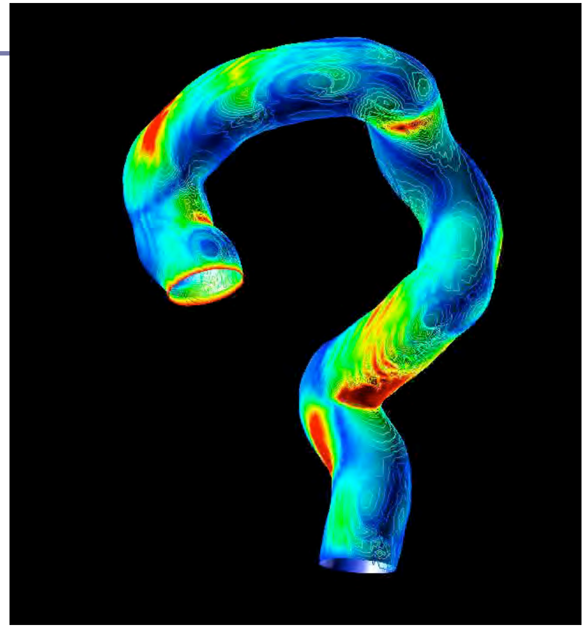
[3] T.E. Tezduyar, K. Takizawa, C. Moorman, S. Wright and J. Christopher, "Multiscale Sequentially-Coupled Arterial FSI Technique", *Computational Mechanics*, Vol. 46 17–29 (2010).

# Geometrical representation of the aorta

## Frenet–Serret formula

$$\frac{d}{ds}\begin{pmatrix} \boldsymbol{\tau} \\ \boldsymbol{n} \\ \boldsymbol{b} \end{pmatrix} = \begin{pmatrix} 0 & Cv & 0 \\ -Cv & 0 & To \\ 0 & -To & 0 \end{pmatrix} \begin{pmatrix} \boldsymbol{\tau} \\ \boldsymbol{n} \\ \boldsymbol{b} \end{pmatrix}$$

- **Radius**: Almost linearly decreasing for healthy aorta. Not considered here.
- **Curvature**: Human aorta goes upward from heart and then turns downward. Therefore, differences among individuals are small. Curvature effect is characterized by **Dean's number**.
- **Torsion**: Human aorta goes through several organs and borns. Therefore, torsion differences among individuals are large.



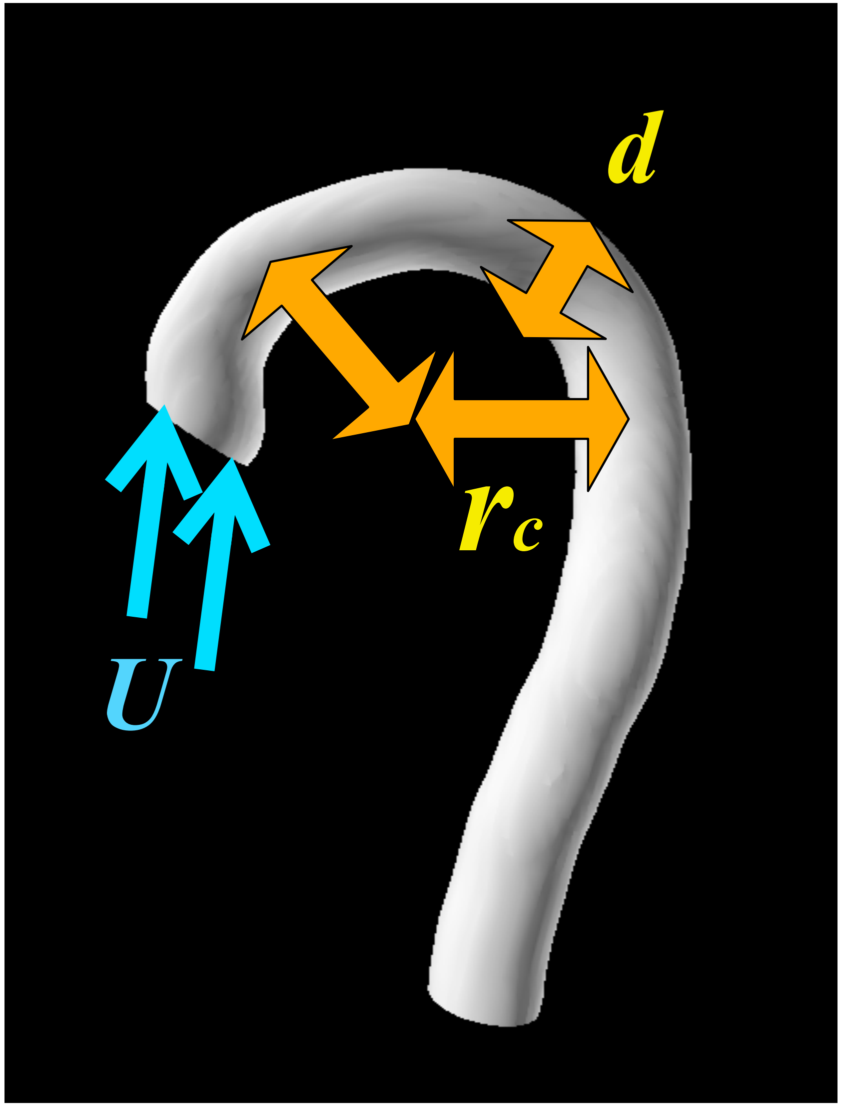
# Non-dimensional parameters

- Reynolds number

$$Re = \frac{Ud}{\nu}$$

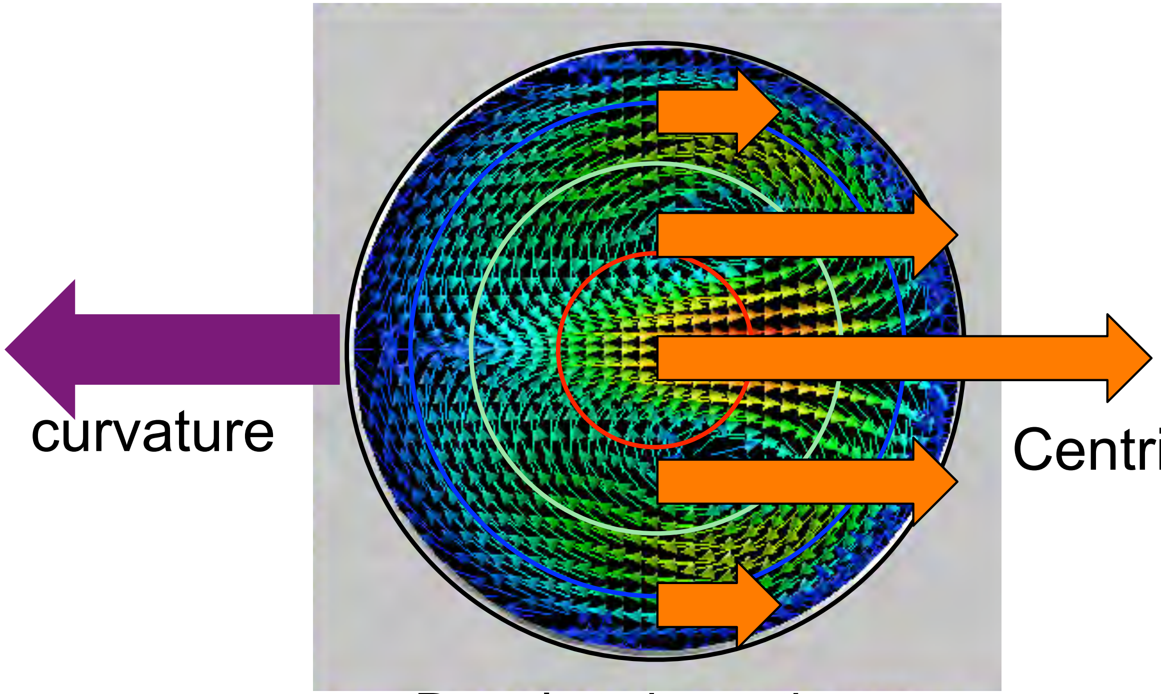
- Dean number

$$De = 4\sqrt{\frac{d}{r_c}}$$



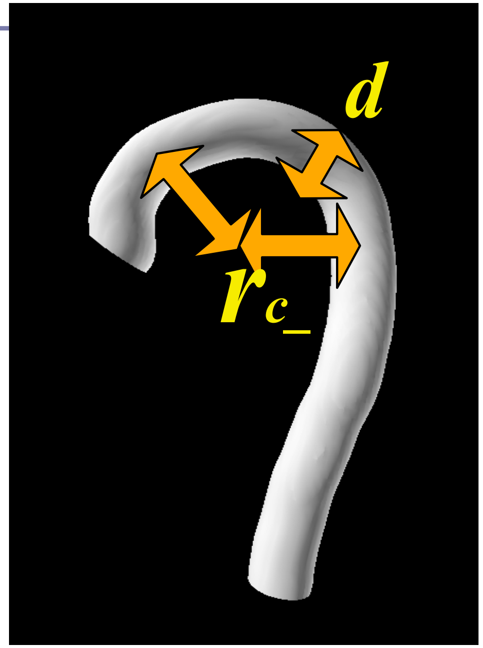
# Dean’s vortices

Characteristic secondary flows are observed in curved tubes.




Hagen-Poiseuille flow profile

Dean’s twin vortices

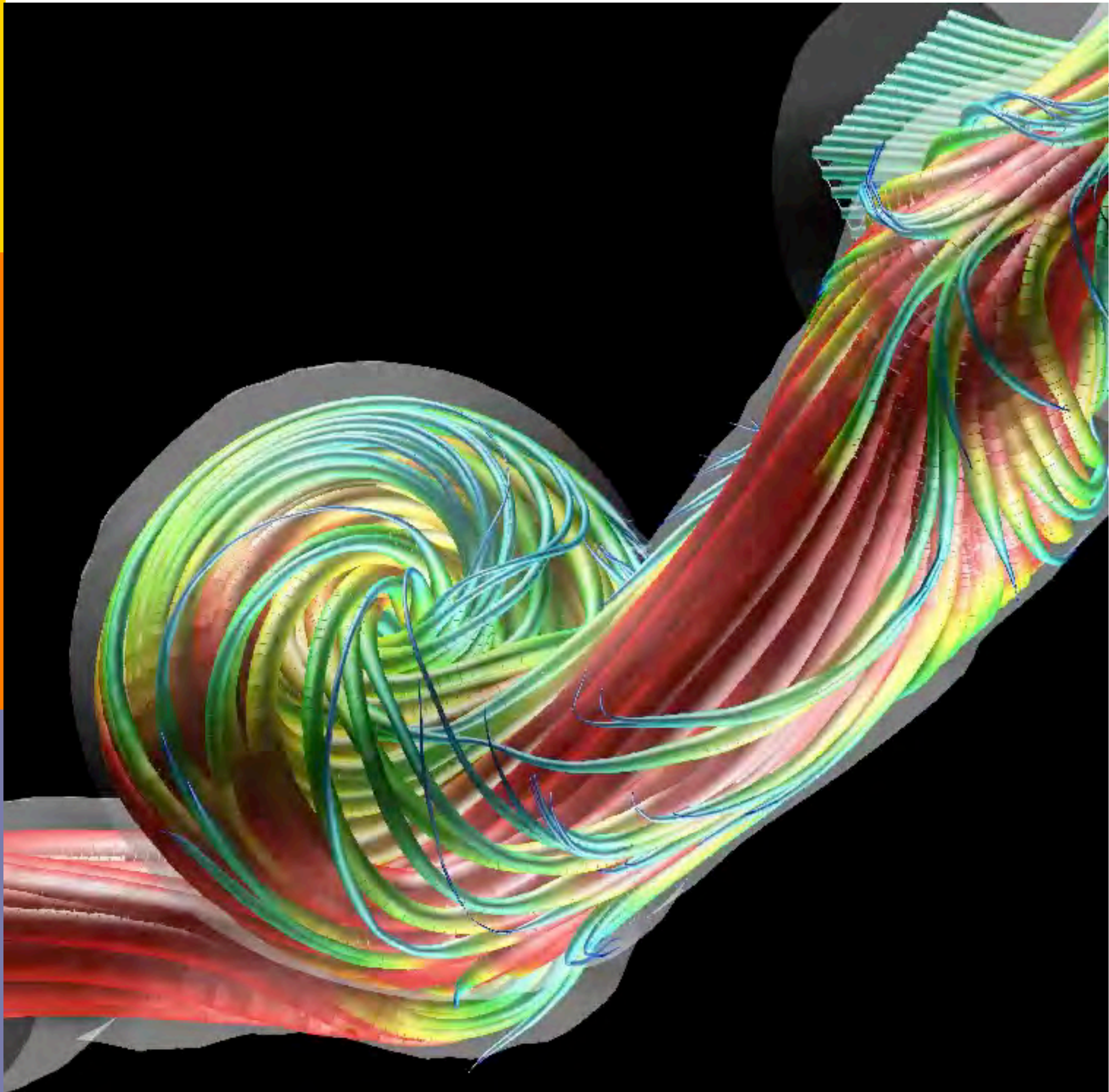


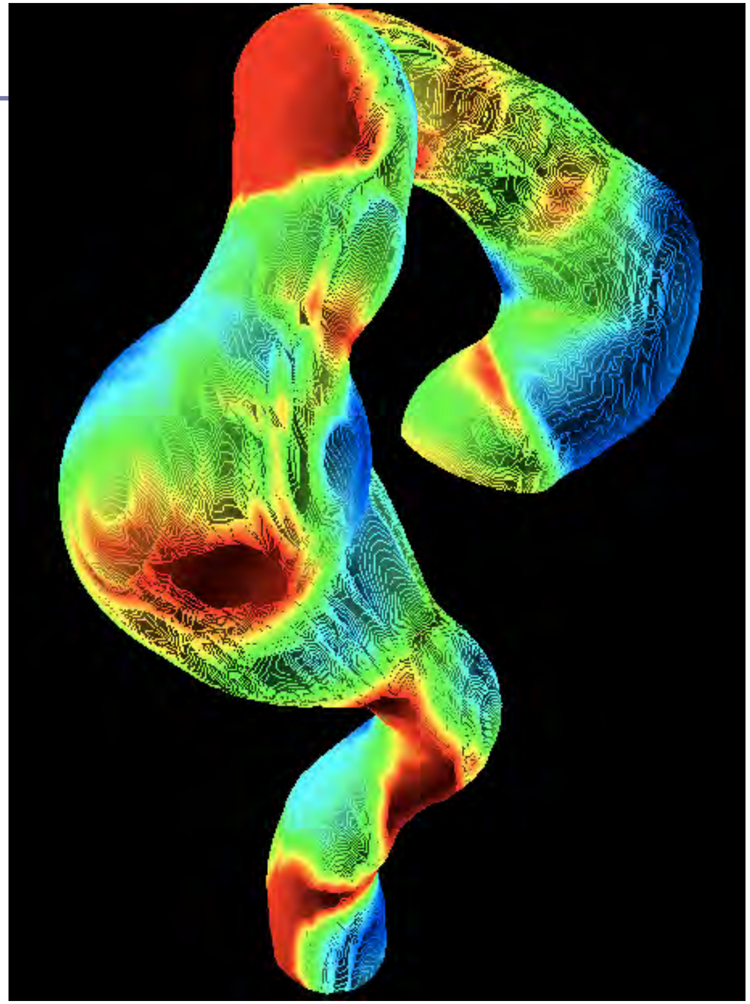

Dean number

$$De = 4\sqrt{\frac{d}{r_c}} \approx 5$$

(1) In the straight circular tube, Hagen-Poiseuille flow profile is achieved.
(2) If the tube has curvature, then the centrifugal force acts in the opposite direction of the curvature.
(3) The centrifugal force is proportional to the velocity in the axis direction.
(4) A set of opposite-sign vortices is generated as a secondary flow.

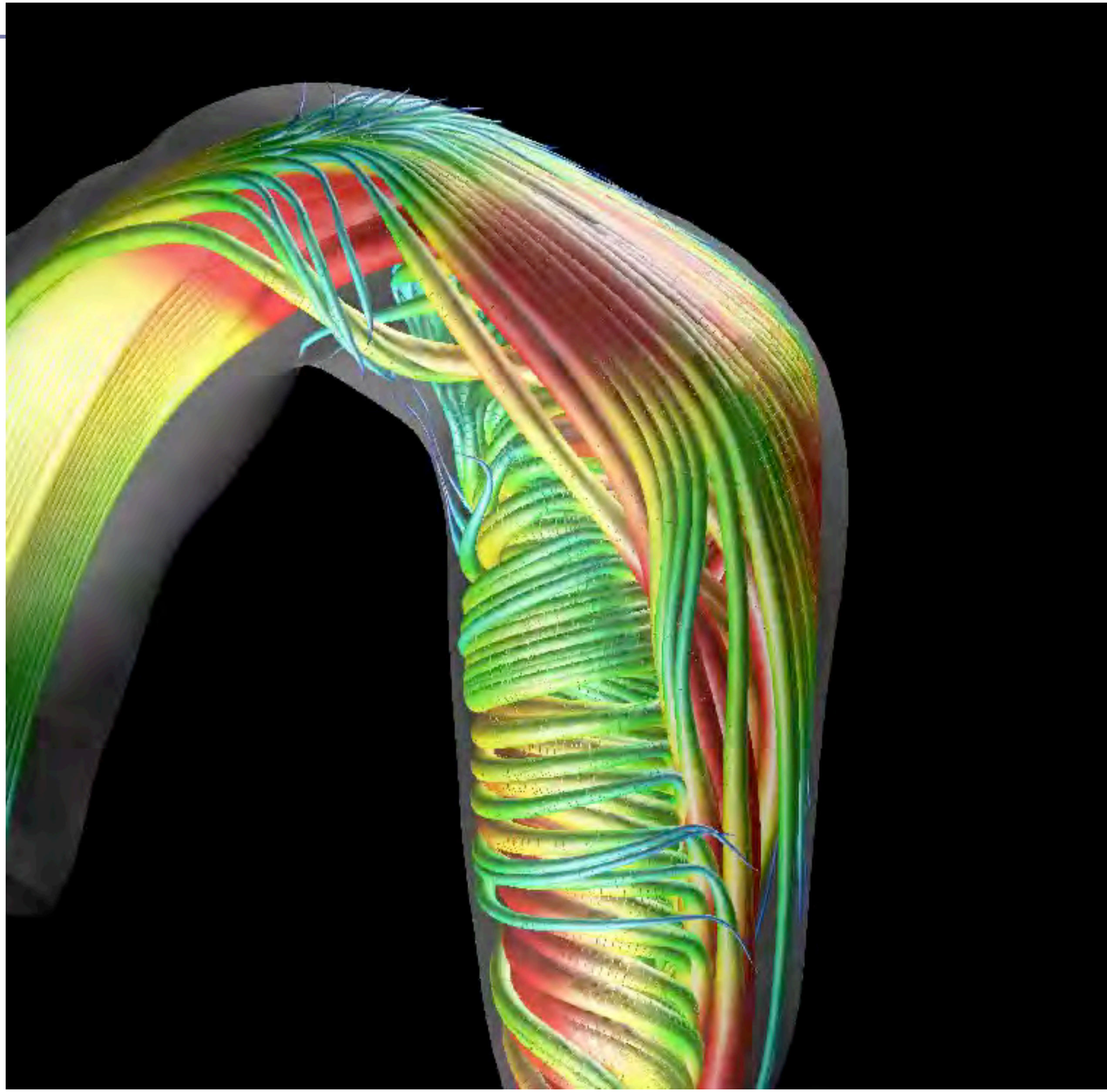
## Blood flow visualized by instantaneous streamlines

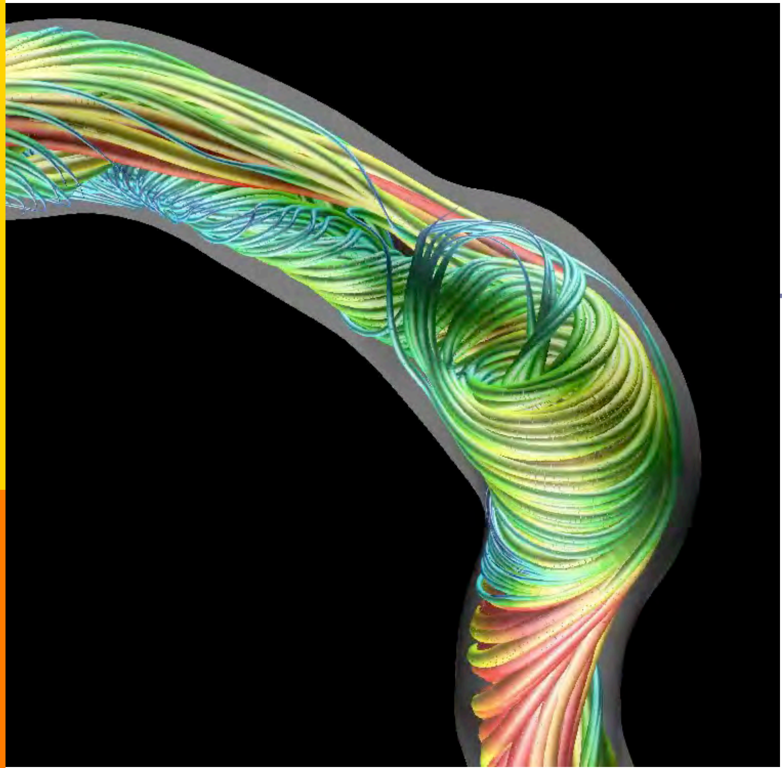




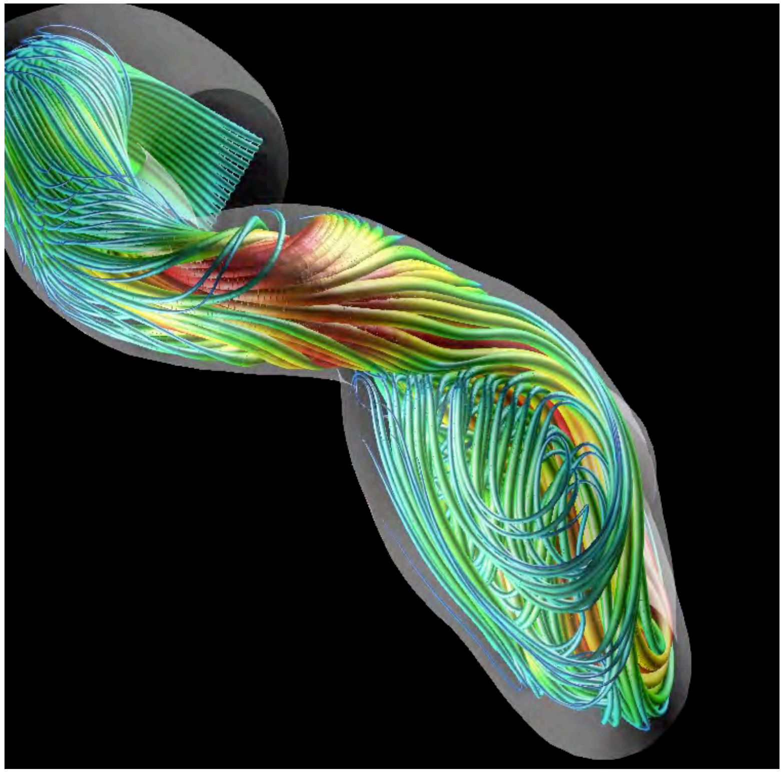
Distribution of time-averaged wall shear stress

# Swirling flow visualized by instantaneous streamlines (A001)

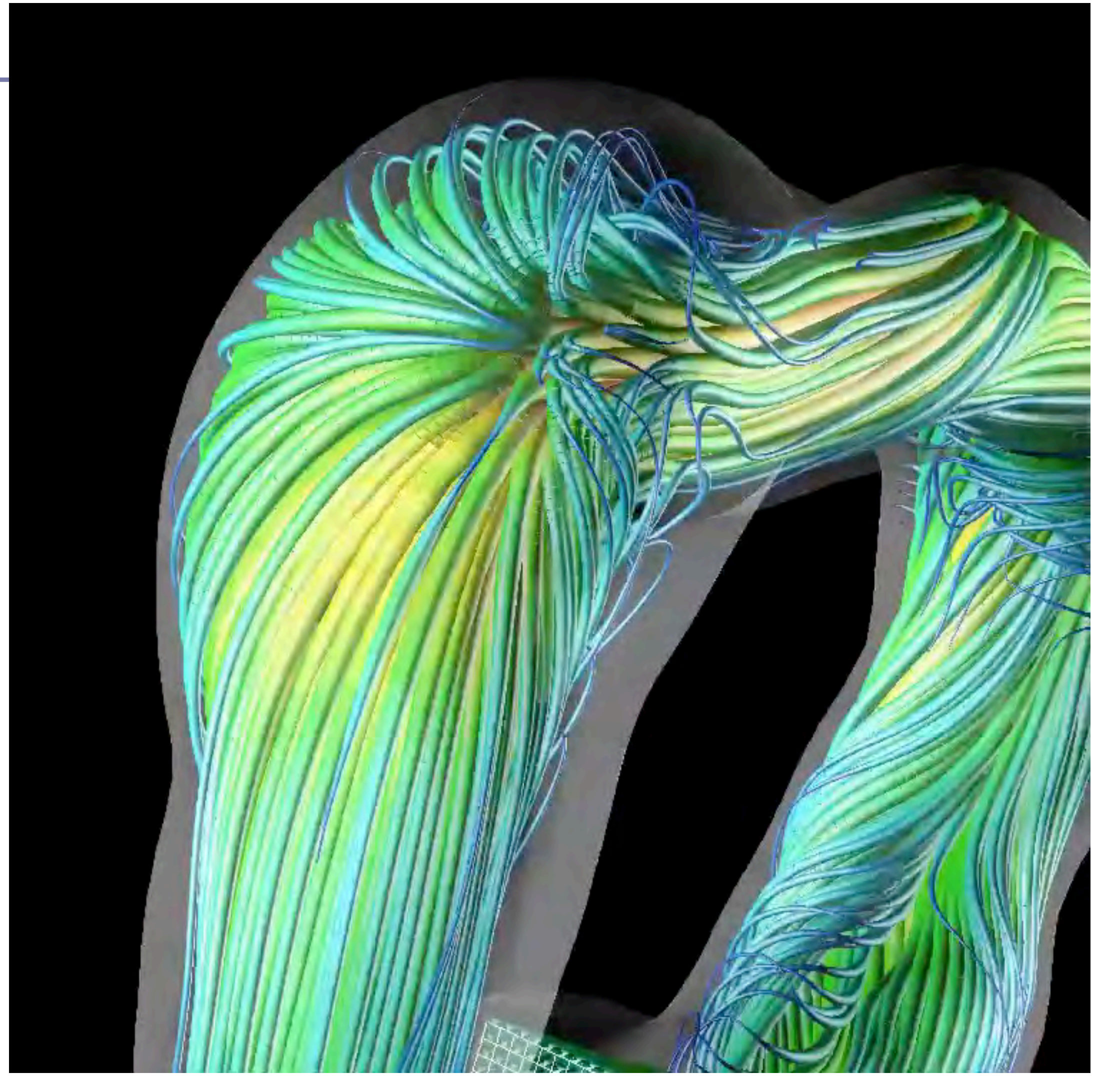




A006



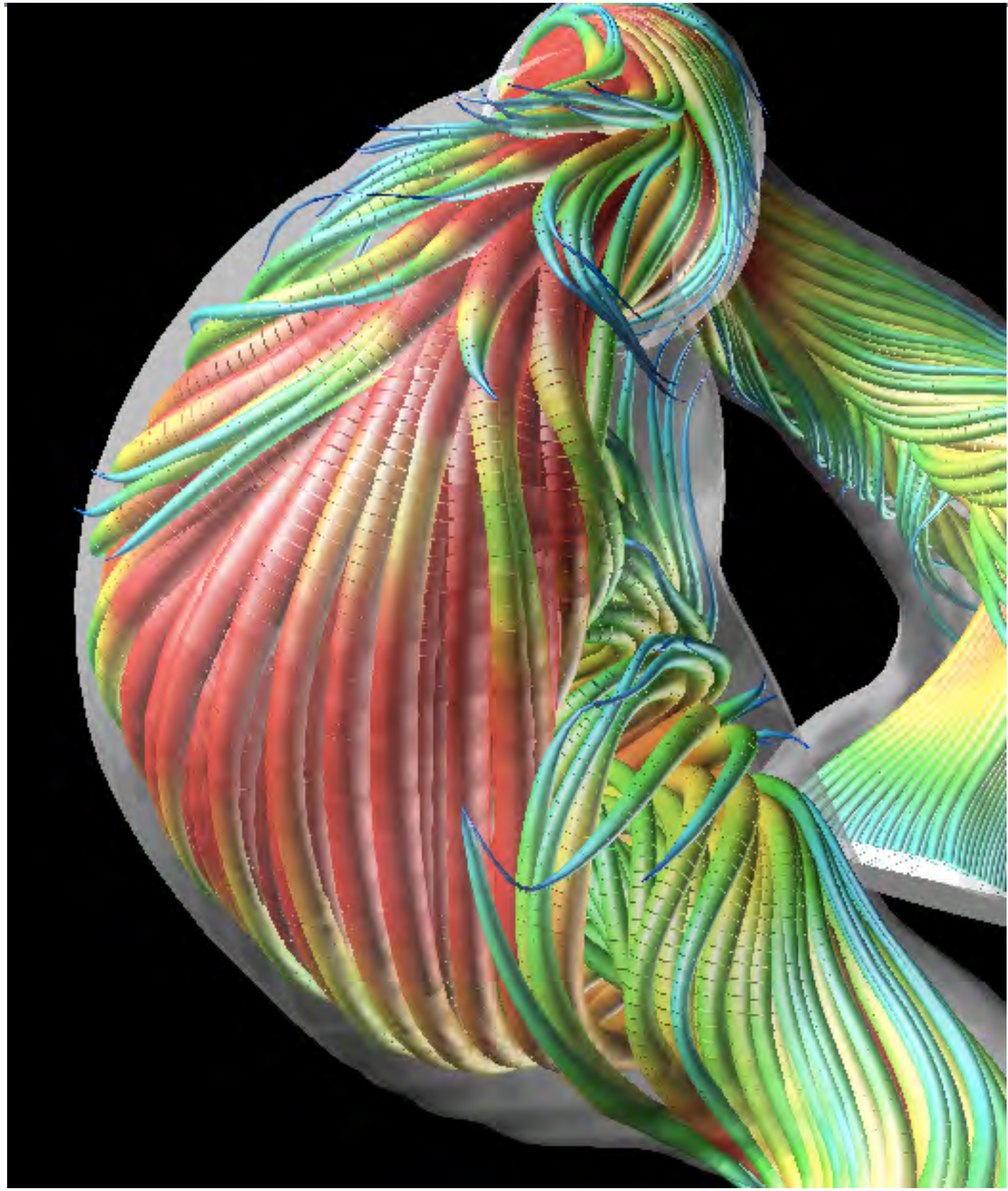
A004



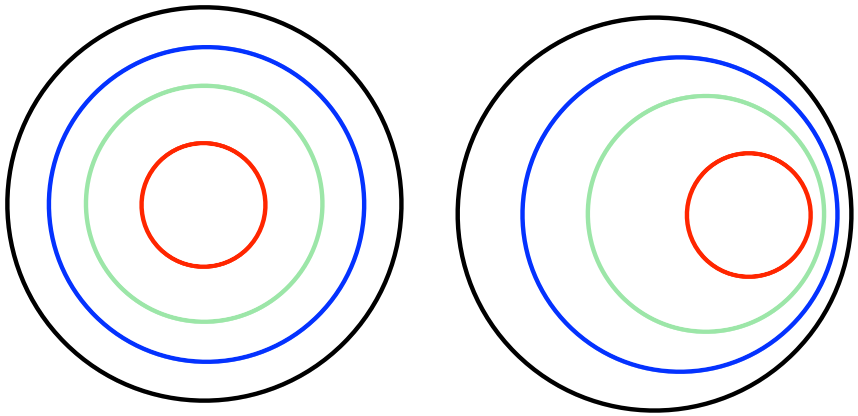


A010  with stagnation point

# Naked flow

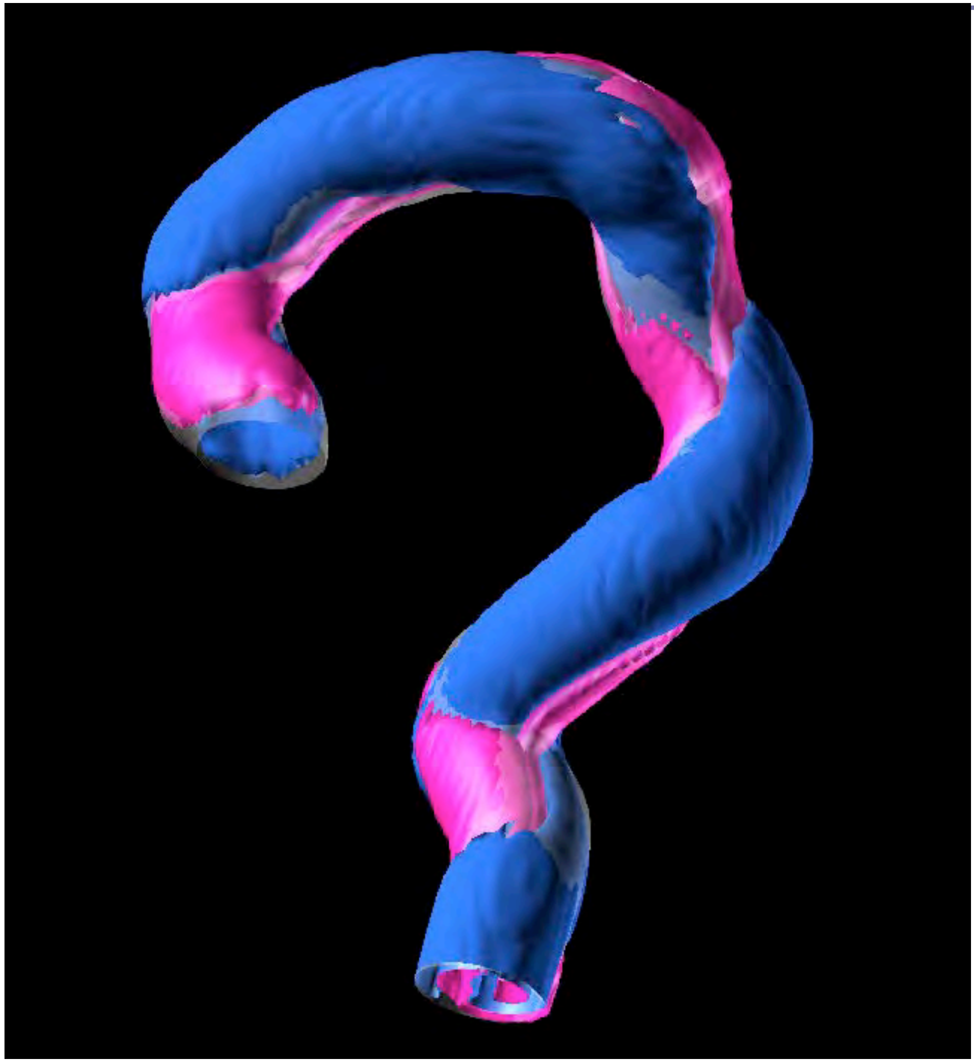


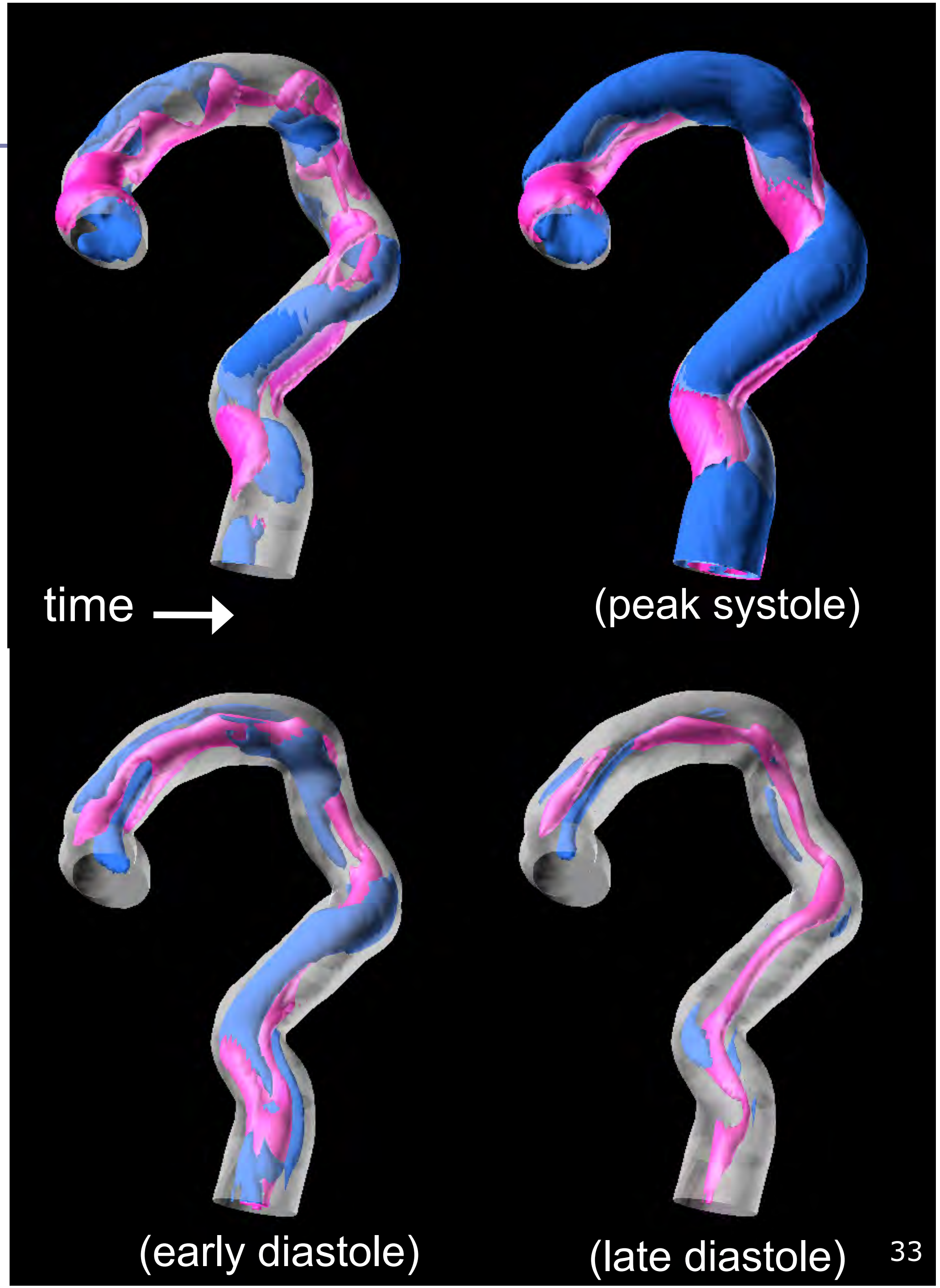
- If the vessel is straight, Poiseuille-like flow profile is achieved. The strong velocity is confined to the center region of the vessel.
- In the case with curvature and torsion, this strong velocity is conducted to the near-wall region, which causes strong wall shear stress.



# Streamwise vorticity contours

red, clockwise
blue, counter-clockwise

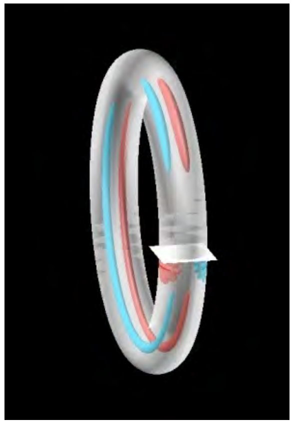




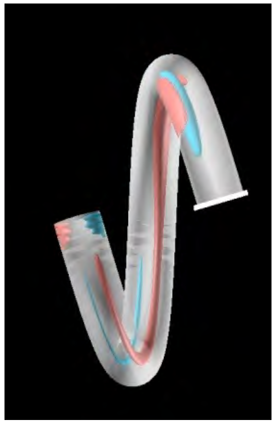
# Simple spiral tubes

- The aorta has numerous shape factors, such as the radius, shape of cross-sections, and shape of centerlines.
- We are going to examine the fundamental flow characteristics using simplified spiral geometries.

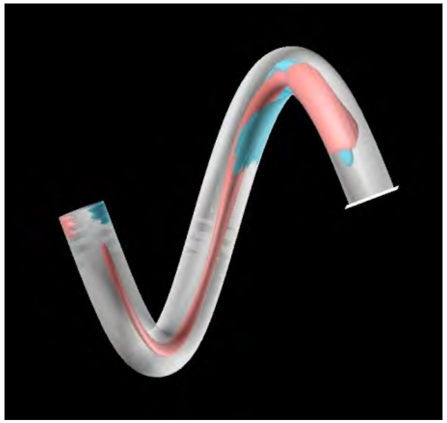
$$\begin{cases} x = a\cos u \\ y = a\sin u \\ z = hu \end{cases} \qquad \mathrm{Cv} = \frac{a}{a^2+h^2} \qquad \mathrm{To} = \frac{h}{a^2+h^2}$$



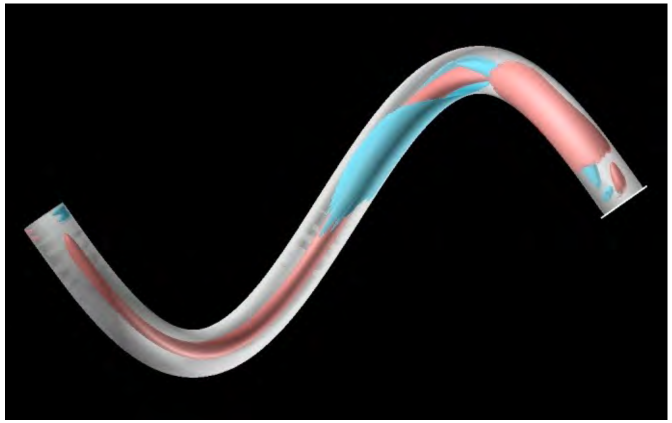
$\chi = 16.7$
$\tau = 0.0$



$\chi = 16.2$
$\tau = 2.7$



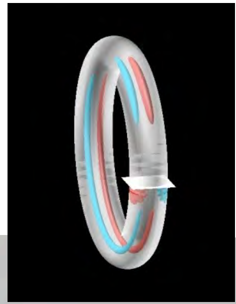
$\chi = 15.0$
$\tau = 5.0$

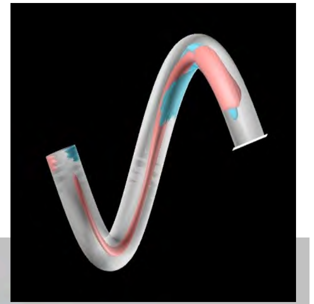


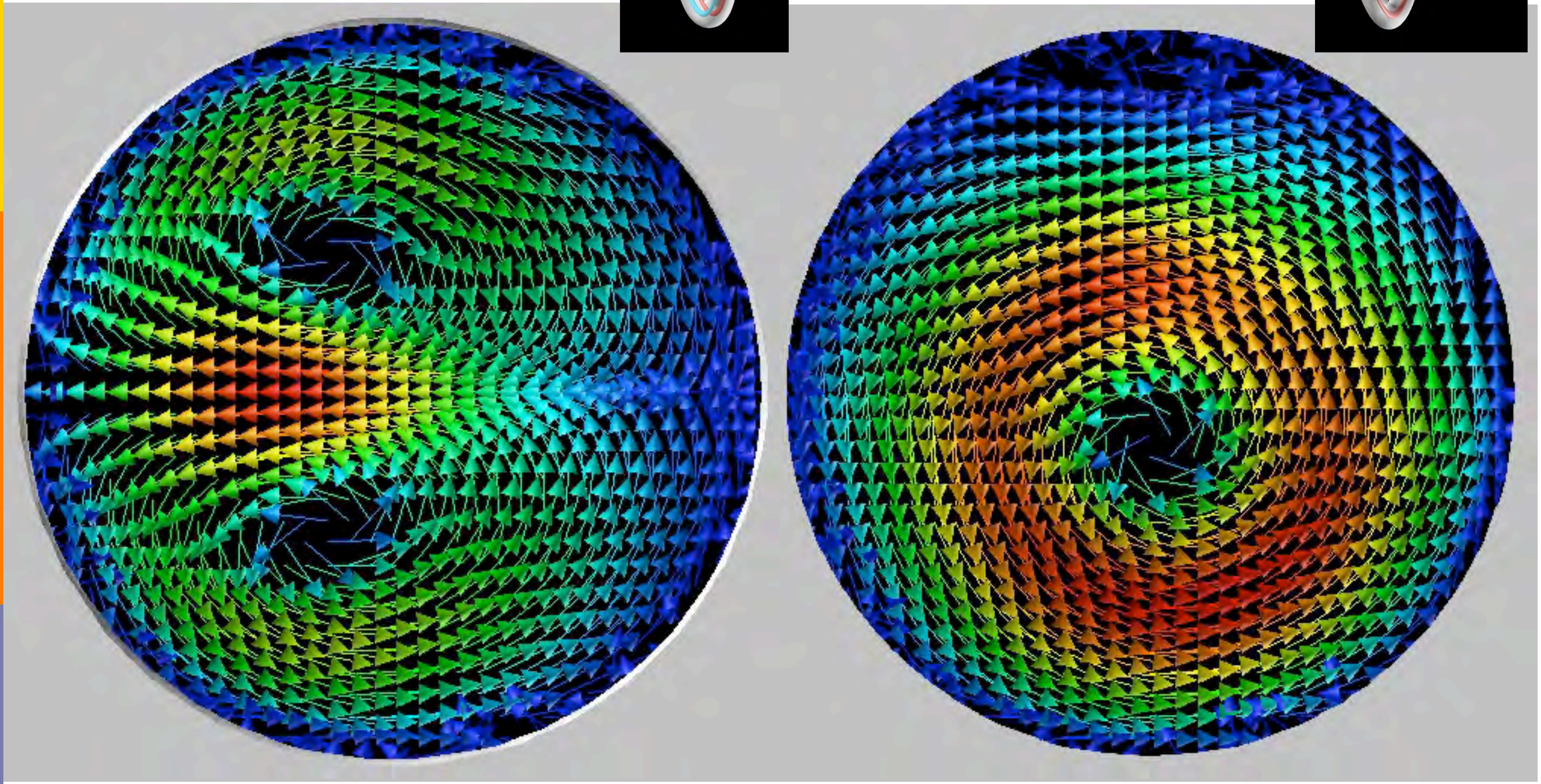
$\chi = 11.5$
$\tau = 7.7$

Consider these simple spiral tubes to investigate the dependence of the flows on several parameters. The pulsate velocity profile is given in the in-flow boundary.

# Secondary flows



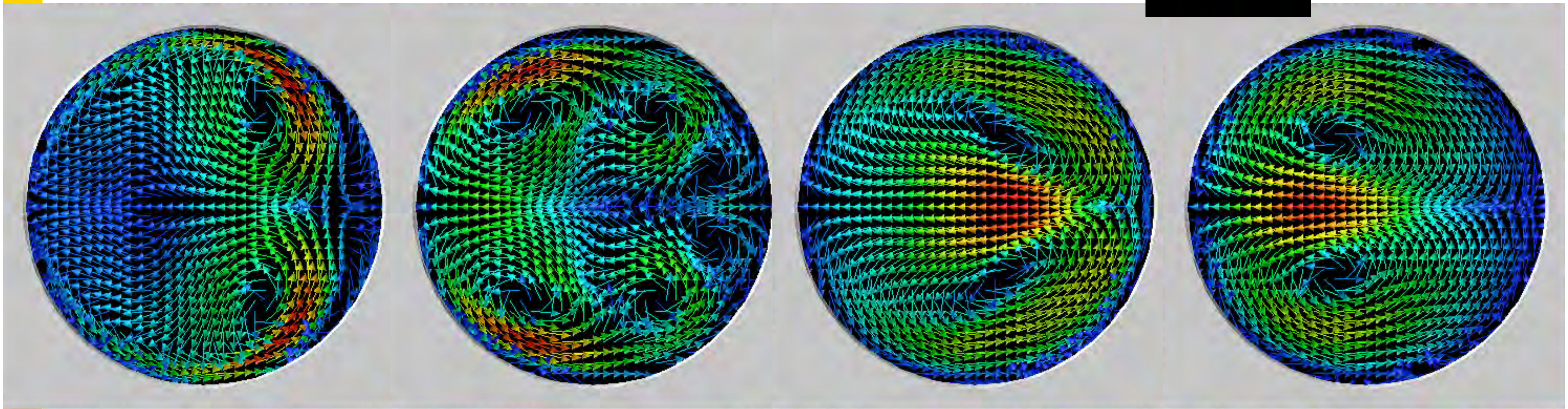




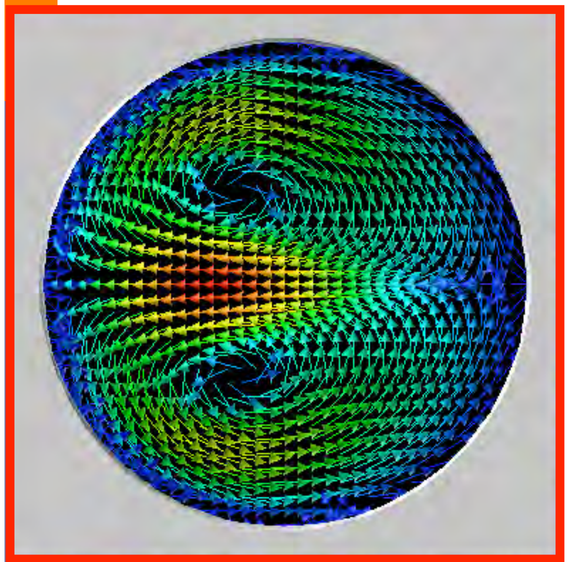
Torsion = 0.0 Torsion = 5.0

In the right hand side movie, merging and growing history of the one vortex can be seen.

# Secondary flow in a simple spiral tube (zero torsion case)



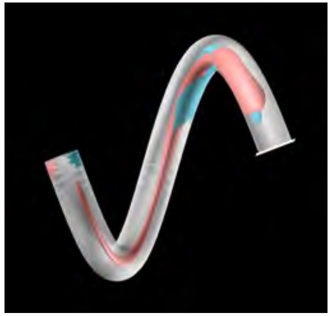
(peak systole) (late systole) (early diastole) (late diastole)

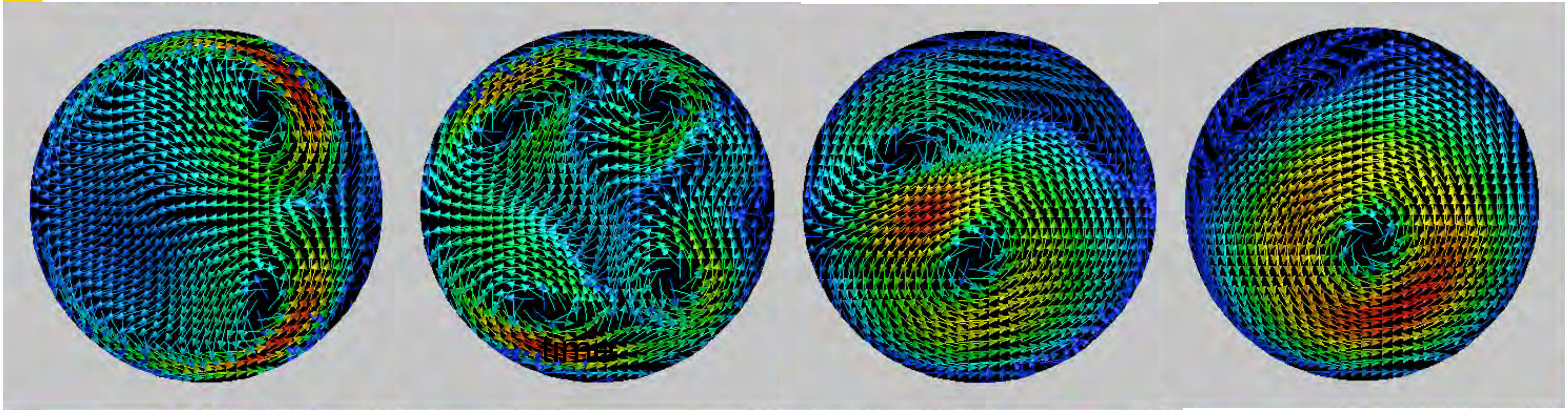


steady case

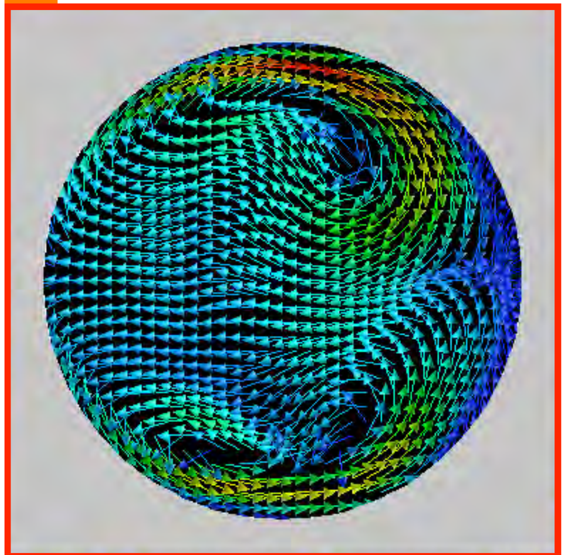
In the zero-torsion case, two Dean's vortices are apparent throughout the whole cardiac cycle. Furthermore, these characteristics are the same for the steady case.

# Secondary flow in a simple spiral tube (non-zero torsion case)






(peak systole) (late systole) (early diastole) (late diastole)

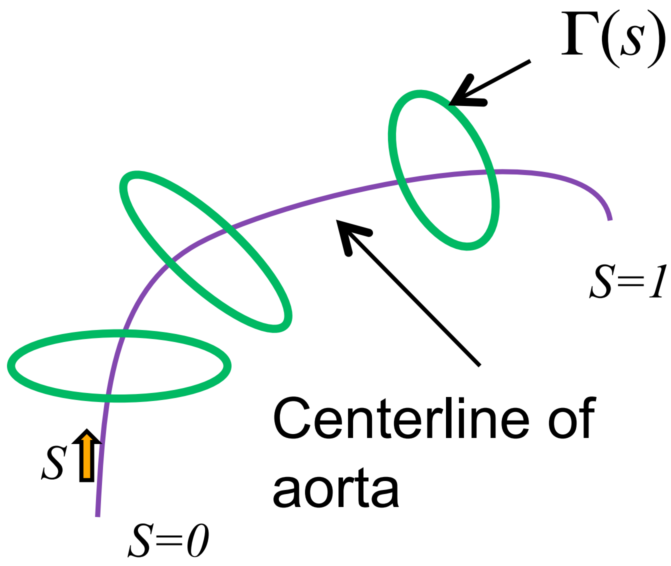


steady case

In the peak systole phase, symmetric Dean's vortices are generated just as in the zero-torsion case. However, in the diastole phase, they merge; one of them dominates the other. Actually, the lower right small vortex in the second figure persists and expands.

This phenomenon differs completely from that of the steady flow case for equivalent geometry. In the steady case, nearly symmetric Dean's vortices exist.

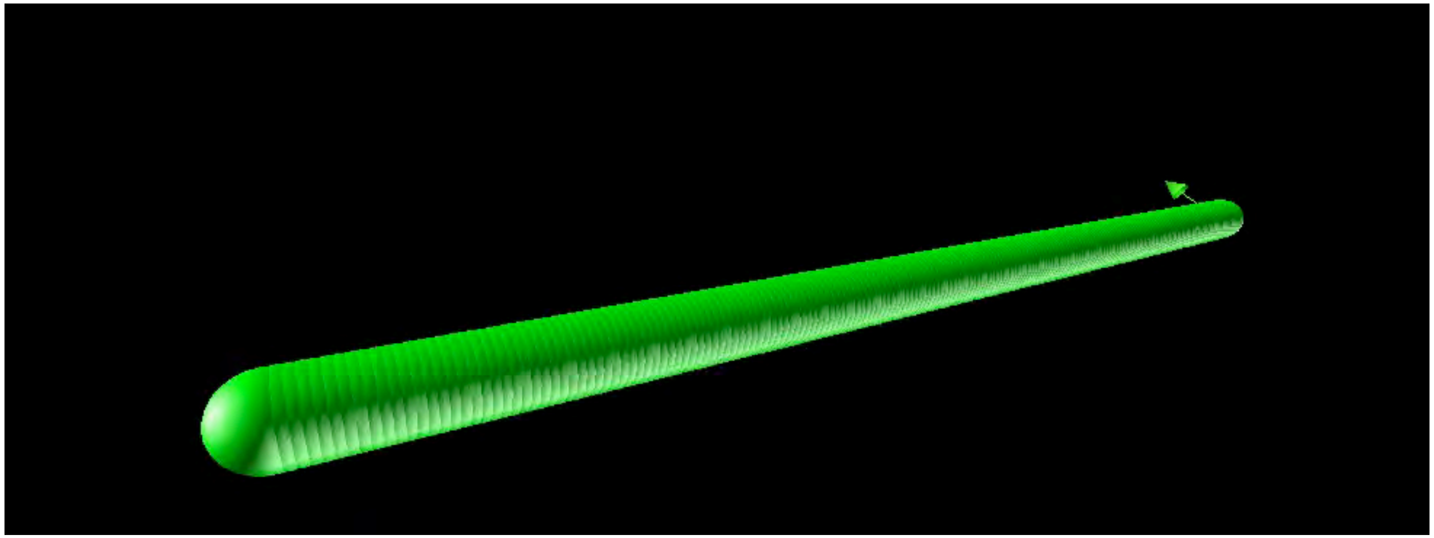
# Torque on the aortic wall




To evaluate the swirling flow effect,
we compute the torque as

$$T(s) = \int_{\Gamma(s)} (\boldsymbol{r} \times \boldsymbol{\sigma}) \cdot \boldsymbol{\tau} d\Gamma$$

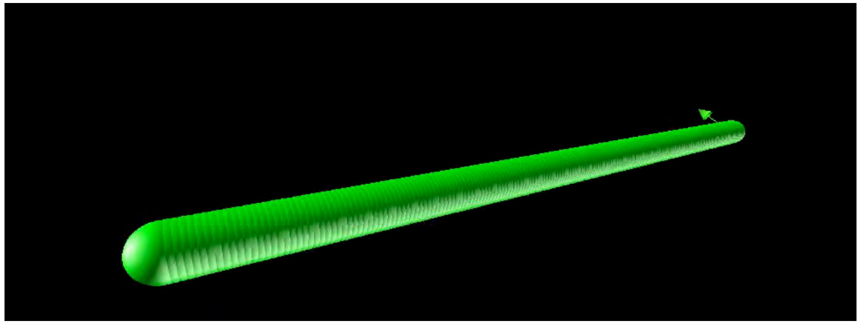
1D elastic rod (Kirchhoff rod)

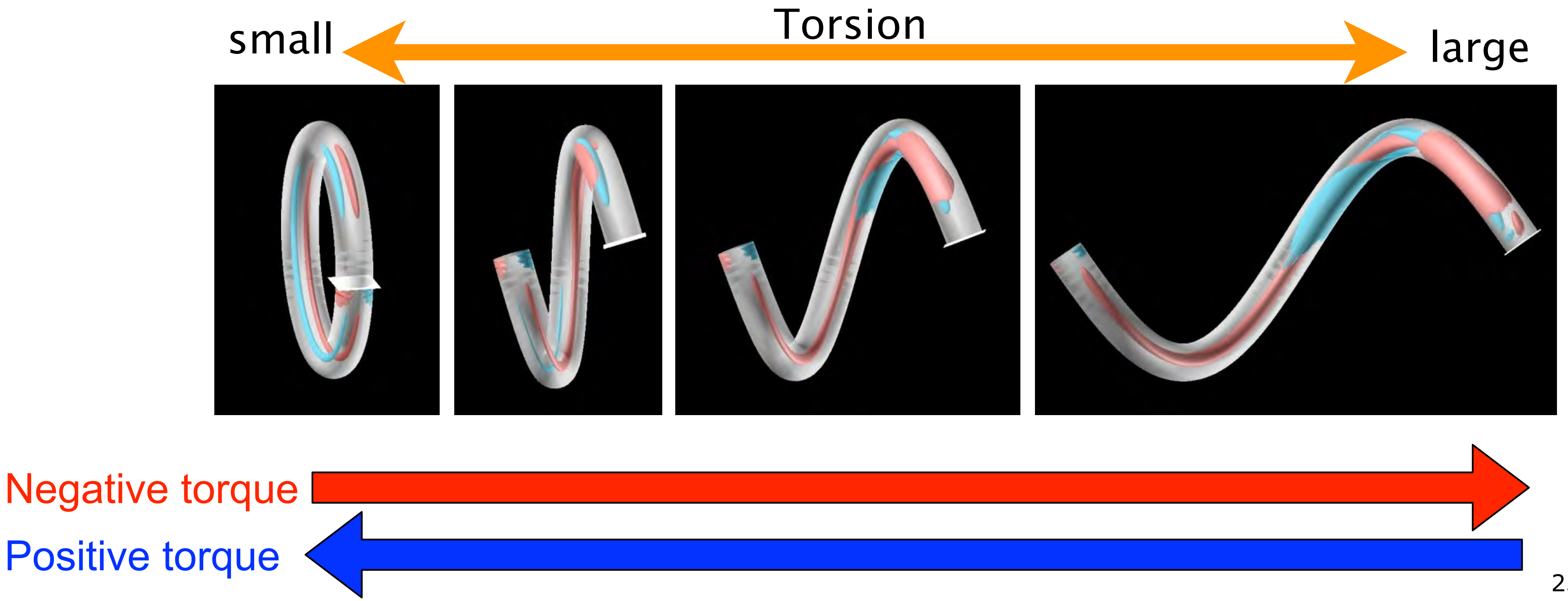


It is apparent that the rod forms a spiral if the positive torque is applied at the end.

# Relation between torque and torsion

As for the relation between torque and torsion  in a one-dimensional elastic rod, negative torque intensifies torsion, whereas the positive torque works to reduce torsion.

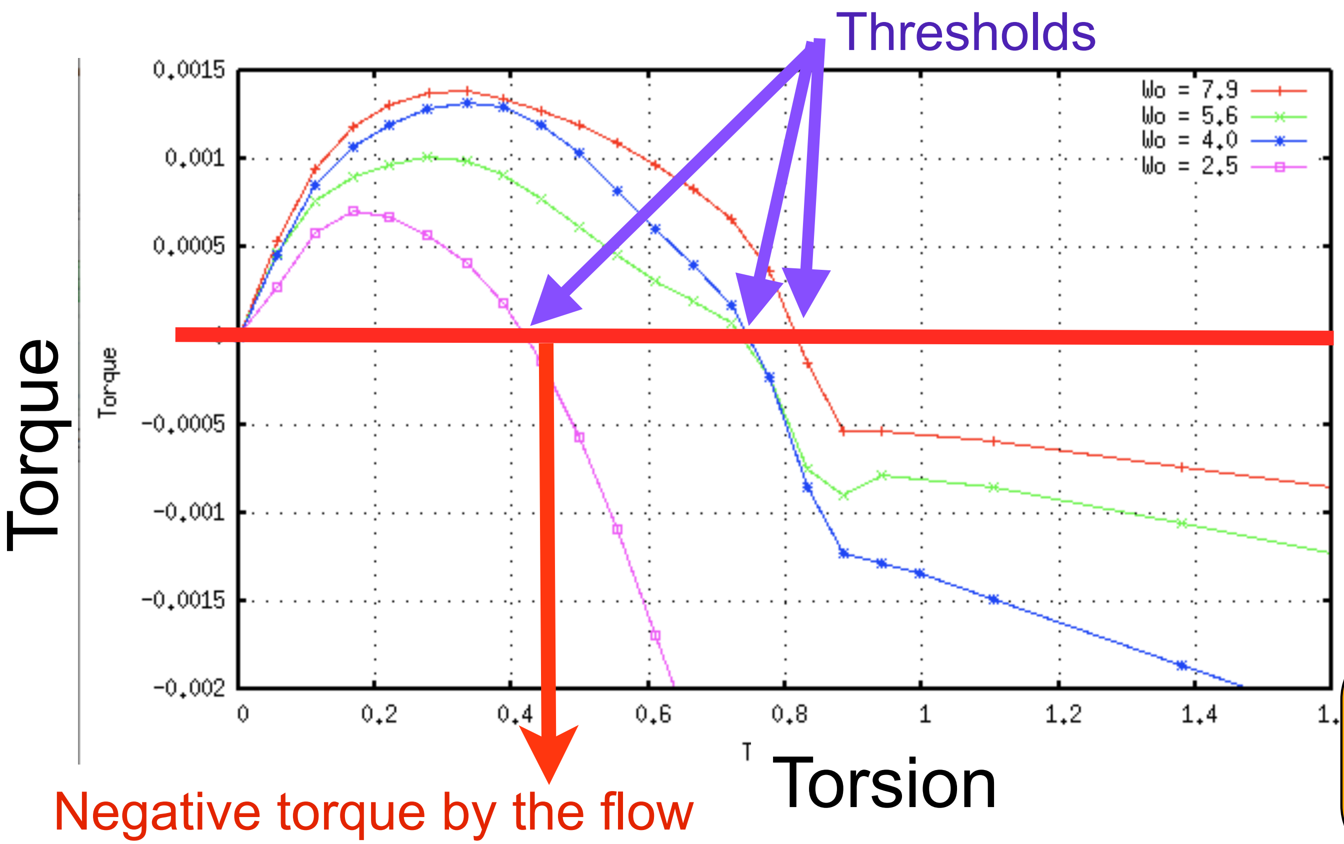




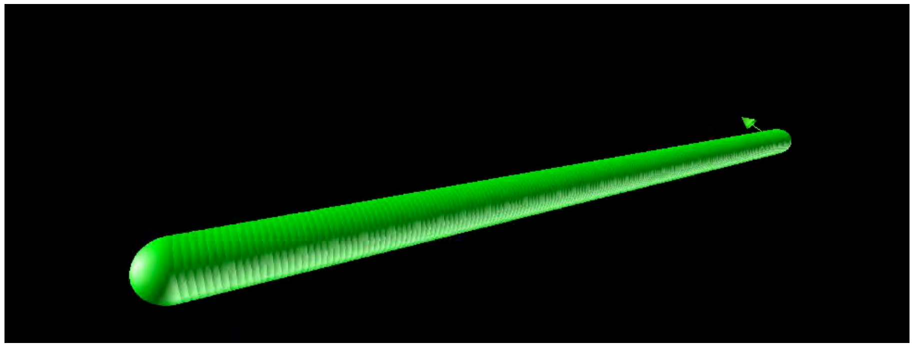
# Diagram

$$Wo = \frac{d}{2}\sqrt{\frac{2\pi}{\nu T_p}}$$

- If the torsion = 0, the torque is of course 0.
- An important characteristic of this diagram is that there exists a threshold at which the sign of the torque becomes negative.




Positive feedback between aorta morphology and flow structure



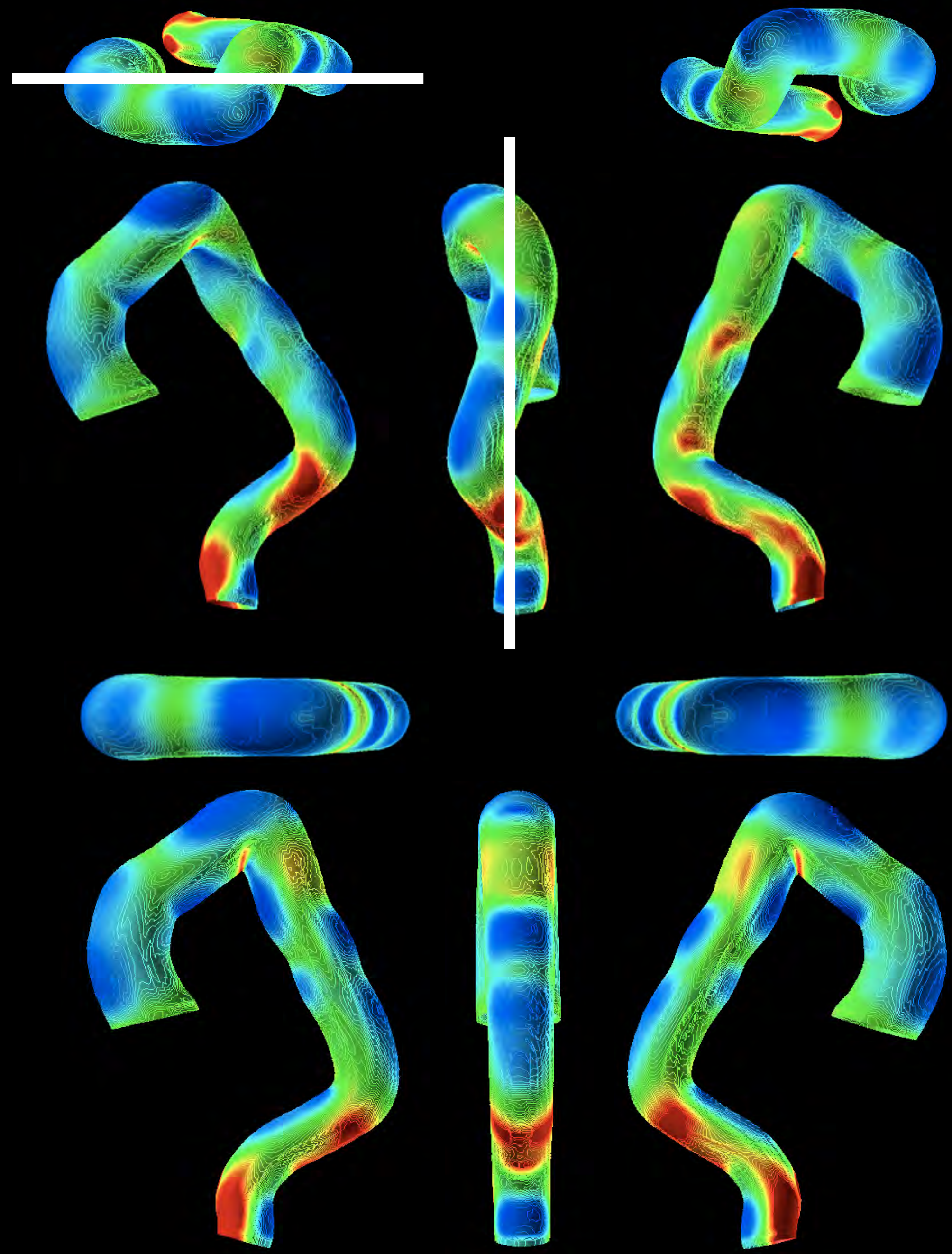
If the torsion of the tube is smaller than the threshold, the flow works to reduce the torsion. However, if the torsion is larger than the threshold, the flow-induced torque intensifies the torsion.

## Examine the effects of torsion from a different perspective

**Original shape**

**Projection onto a plane of curvature**

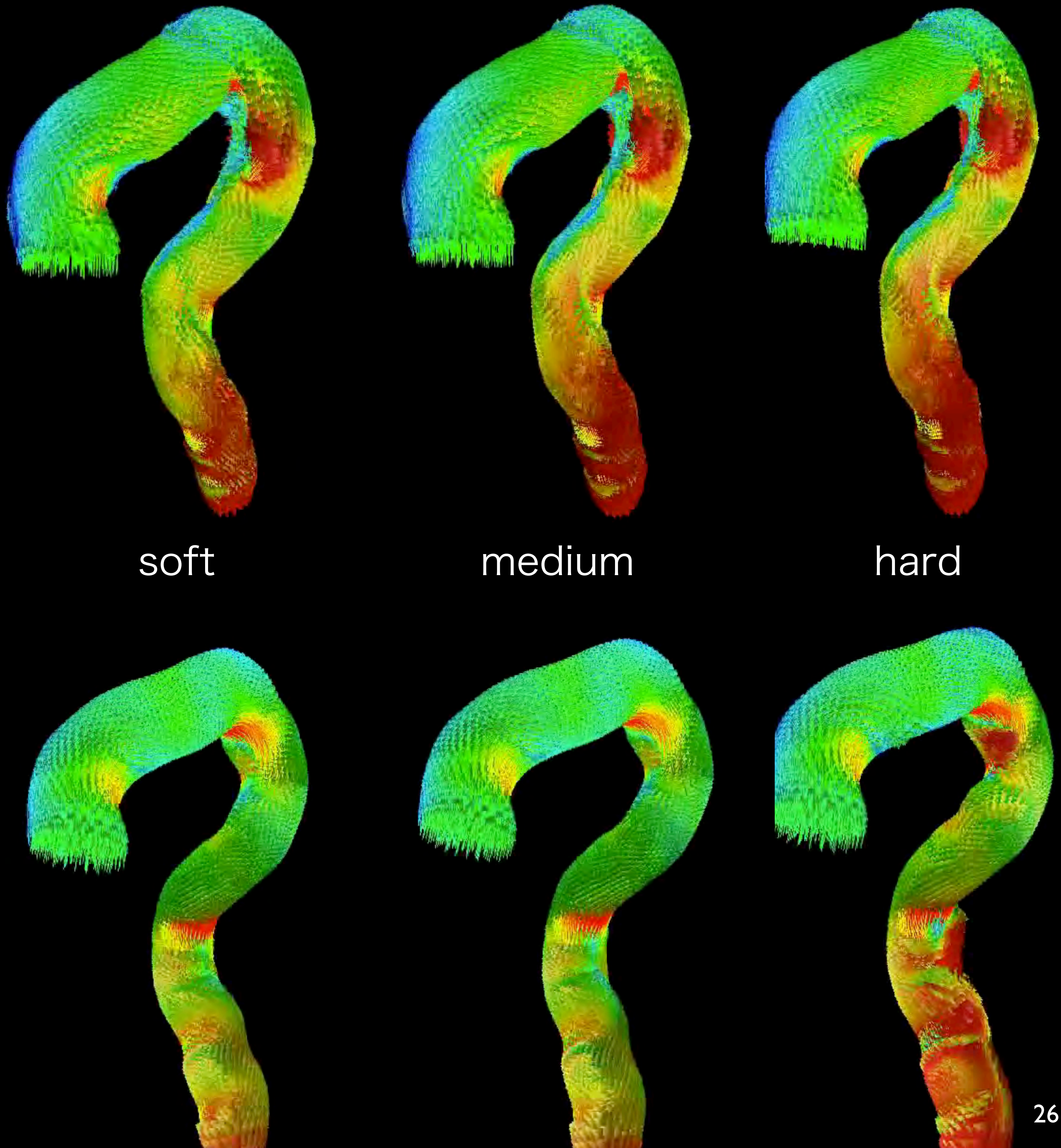
**Artificial shape without torsion**



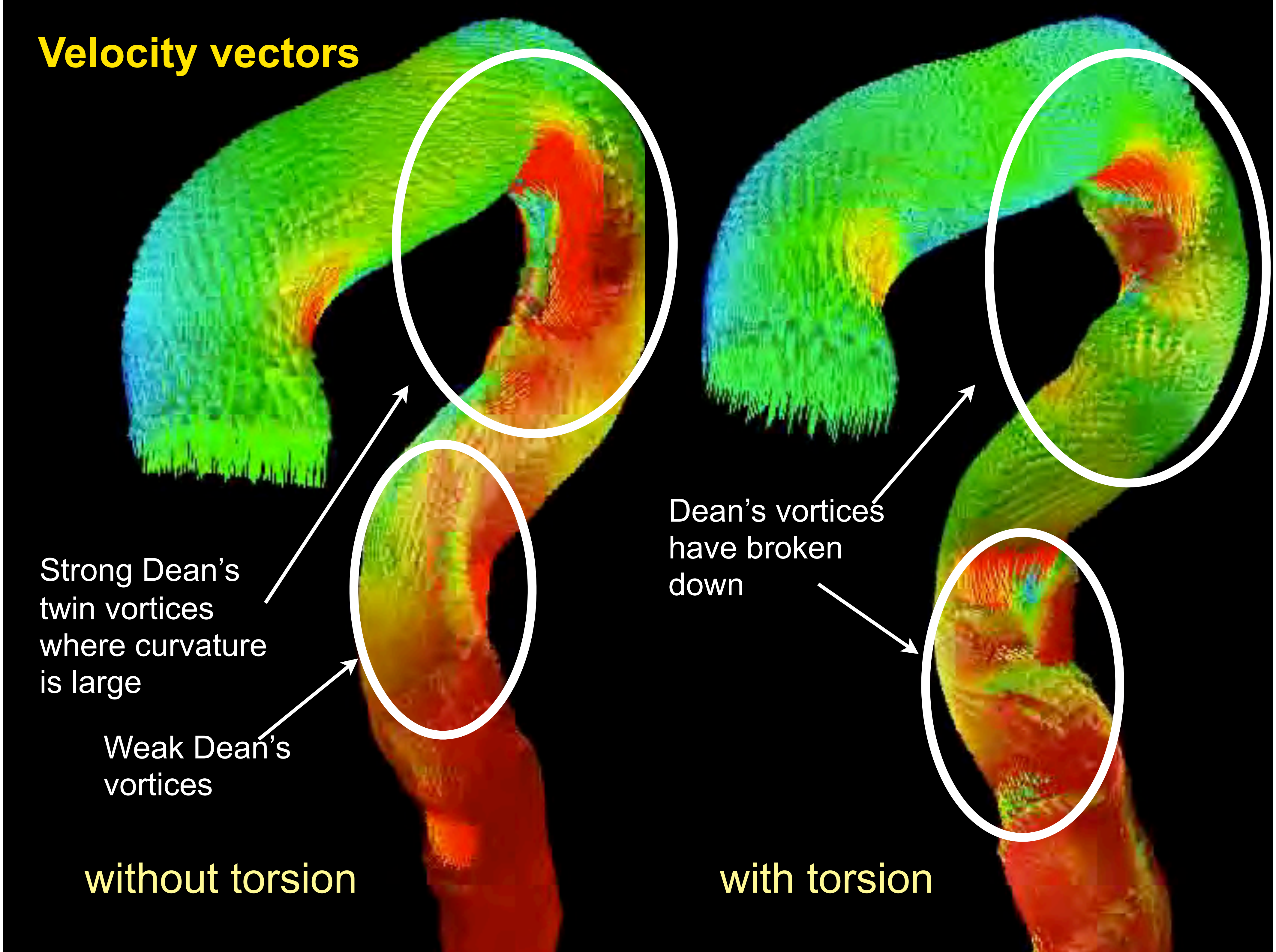
# Velocity vectors
## considering FSI

without torsion

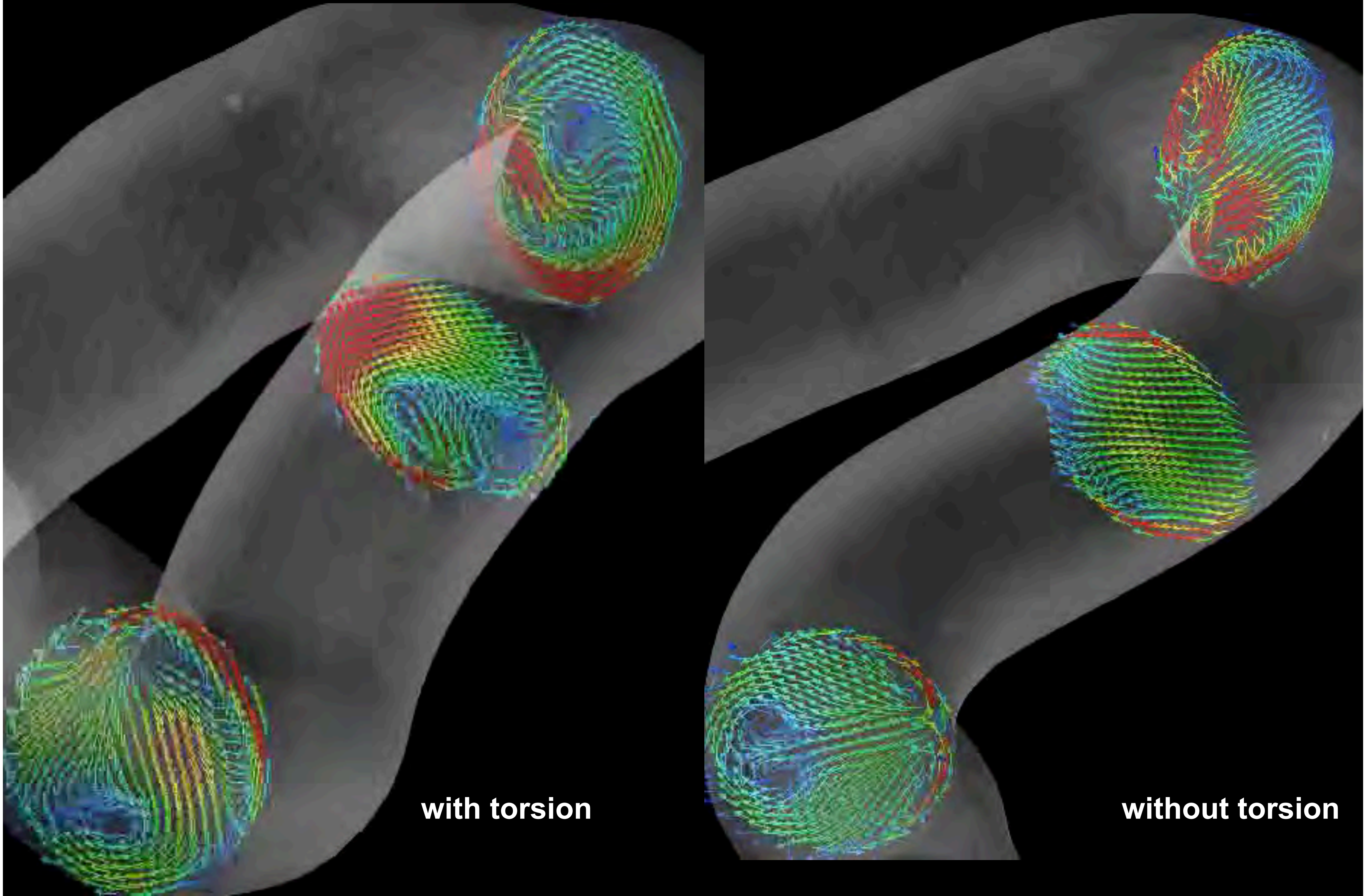
with torsion

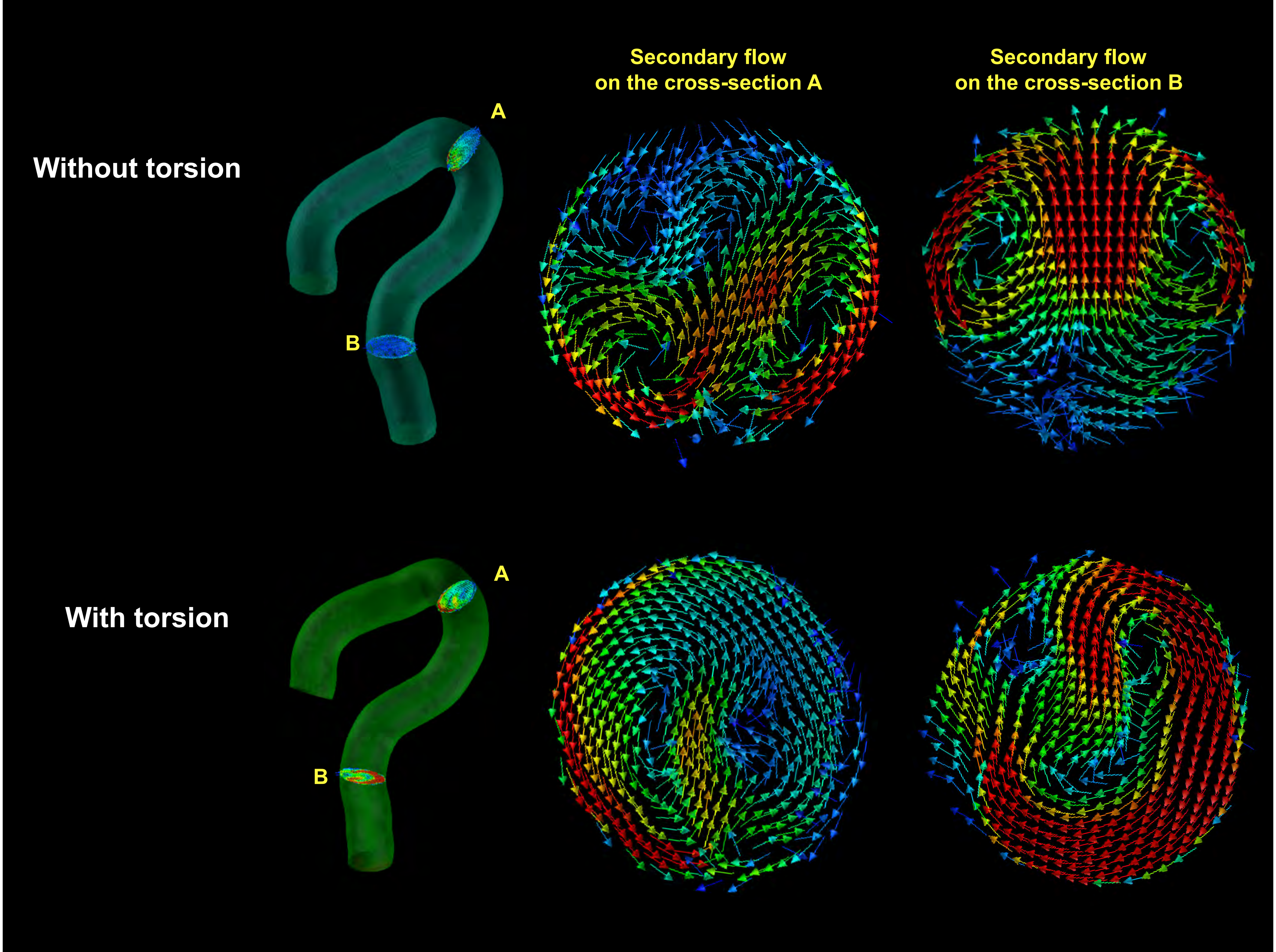


# Velocity vectors

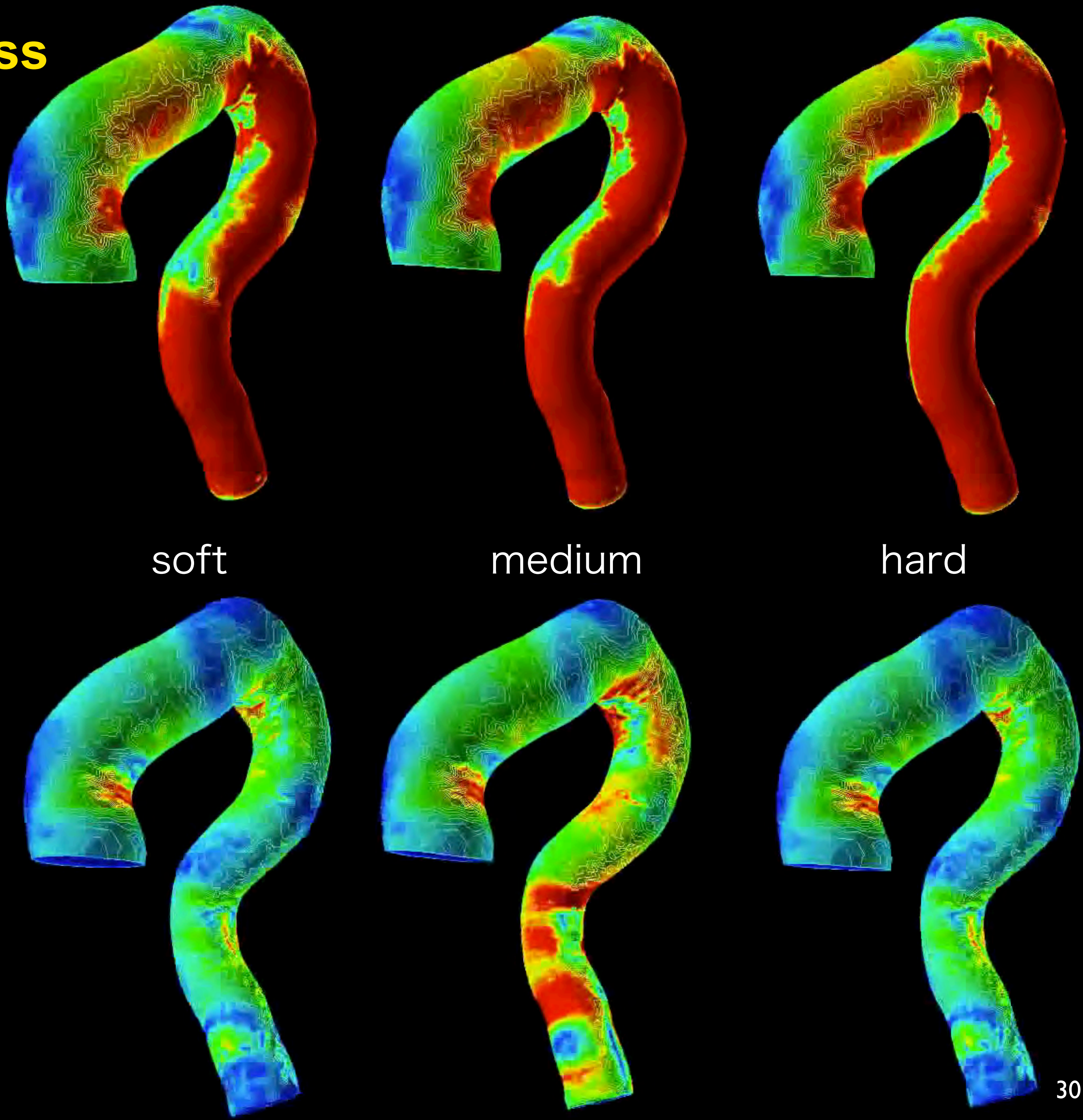


## Secondary flows




Secondary flow
on the cross-section A
Secondary flow
on the cross-section B
Without torsion
A
B
With torsion
A
B

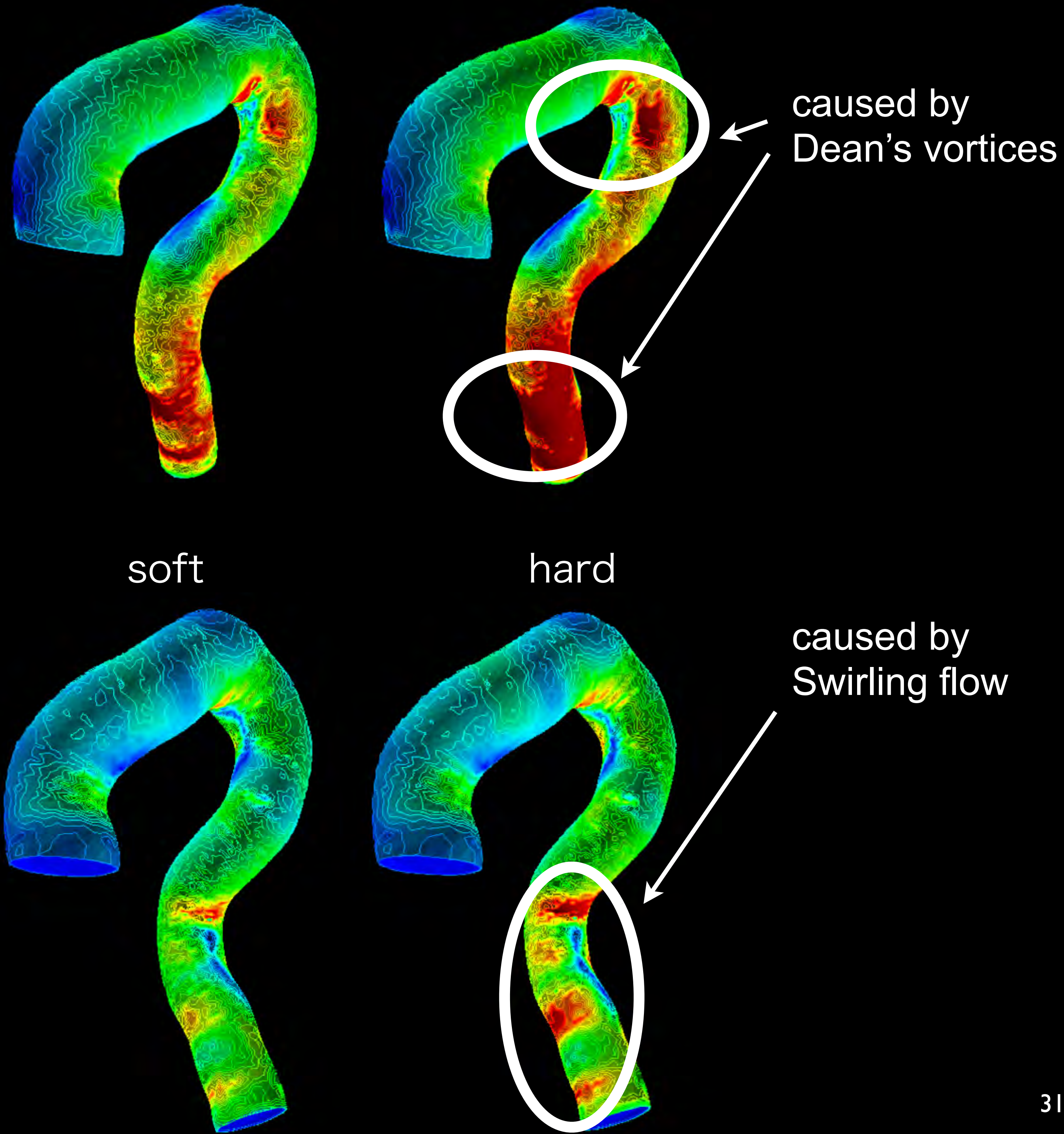
# Wall Shear Stress



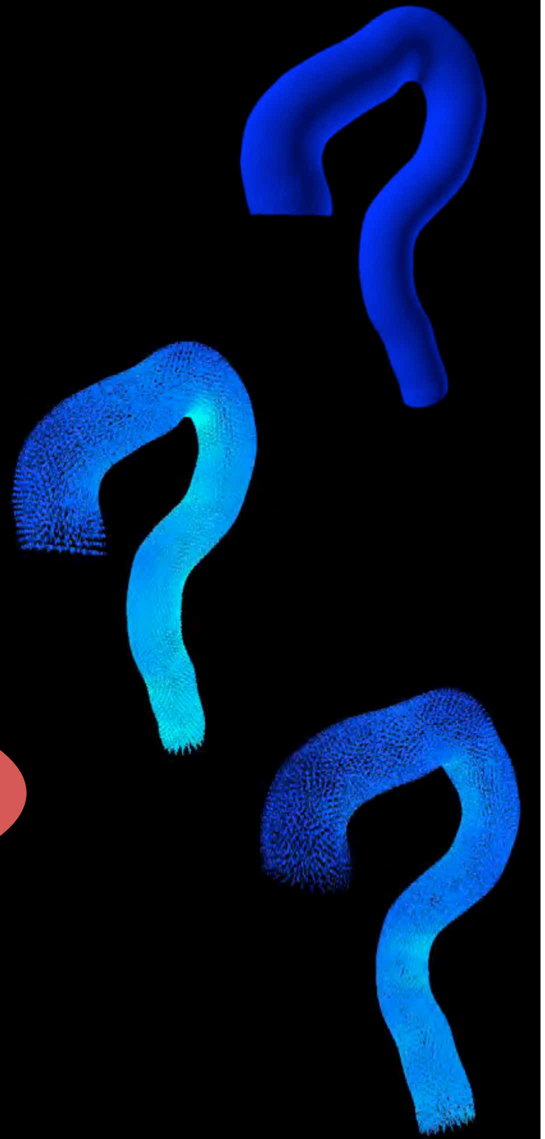
# Wall shear stress (at peak systole)

without torsion

with torsion



As this presentation has shown up to this point



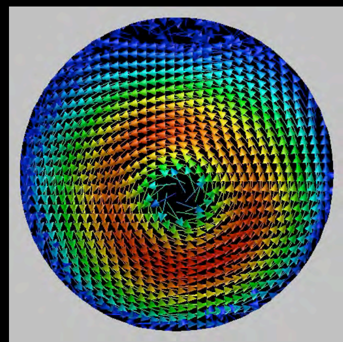
- Curvature of the aorta brings about strong Dean's twin vortices and strong WSS in the aortic arch

Difference among individuals for curvature: small

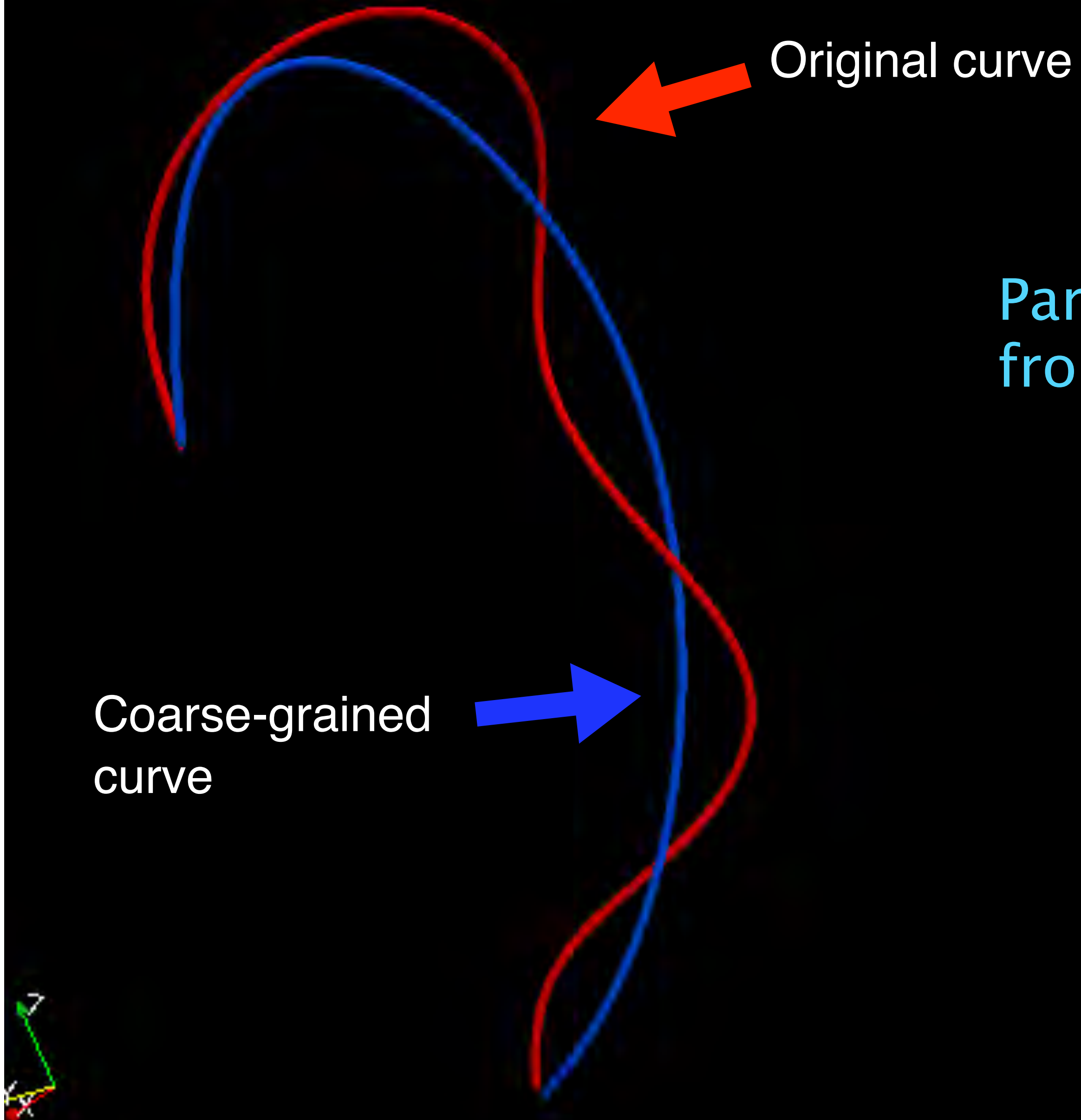
Difference among individuals for torsion: large

- Torsion in the aortic arch breaks down the Dean's vortices, which makes WSS weaker.

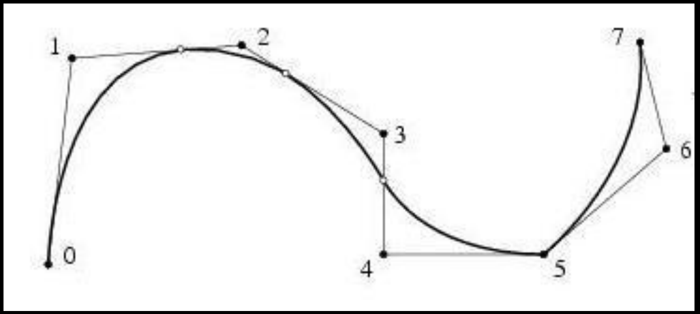
- Torsion brings about merging of Dean's vortices and generates swirling flow, which makes WSS stronger.



# Another means of understanding the characteristic difference between shapes




Parameterization using deviation from the coarse-grained curve

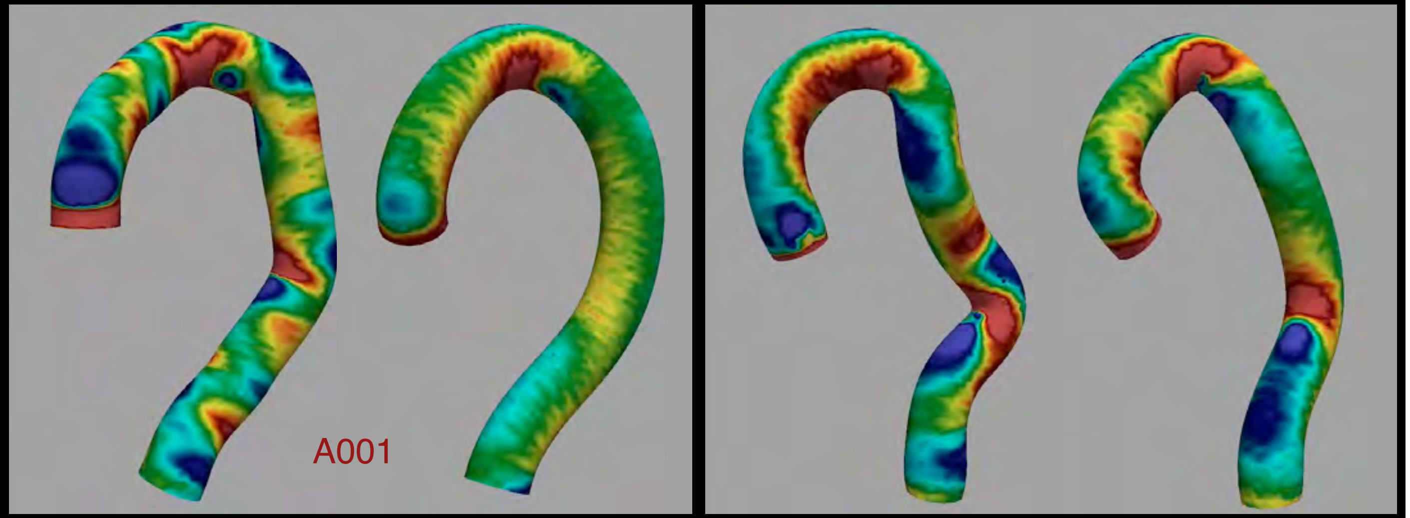


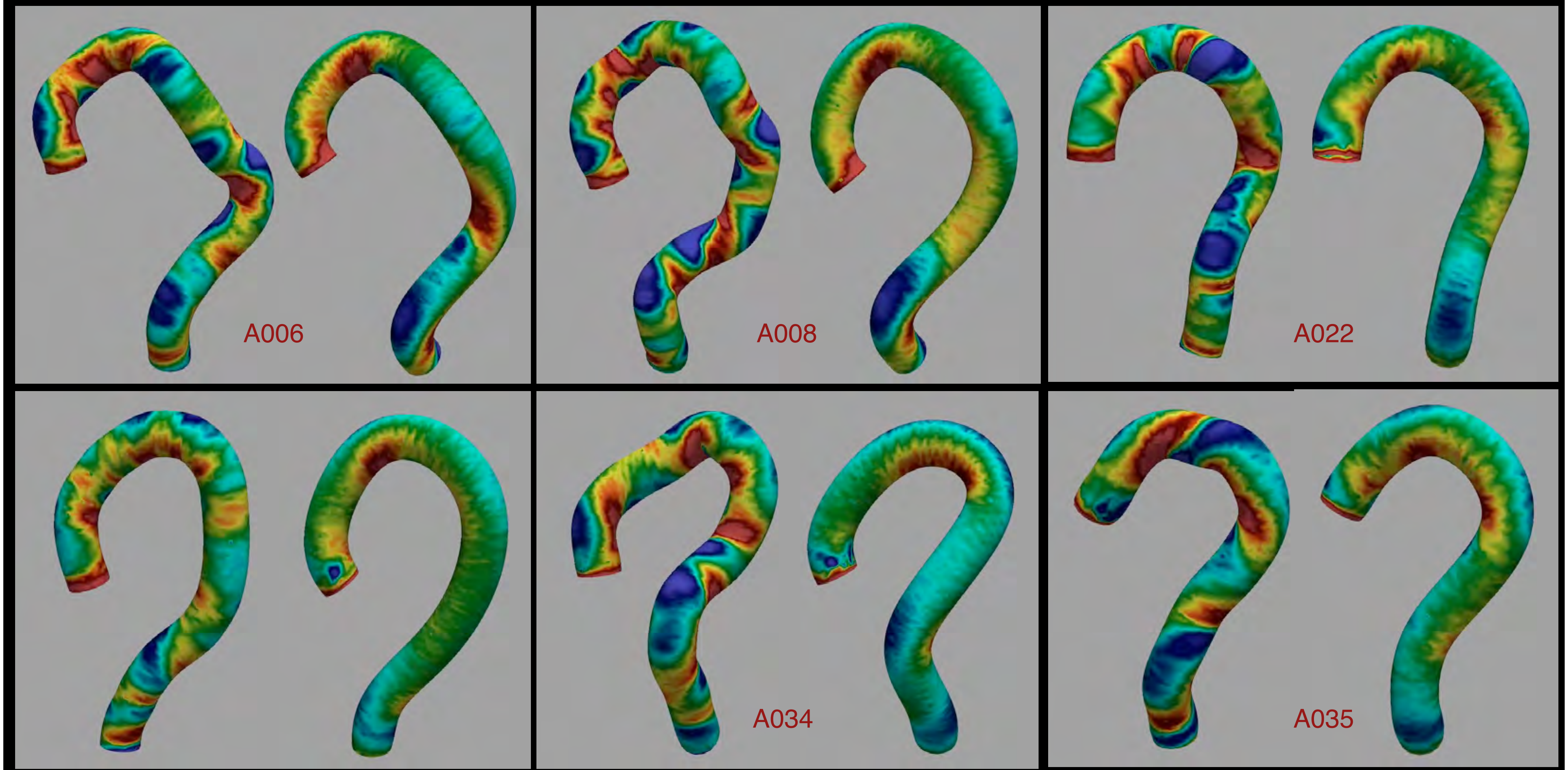

**based on NURBS representation**

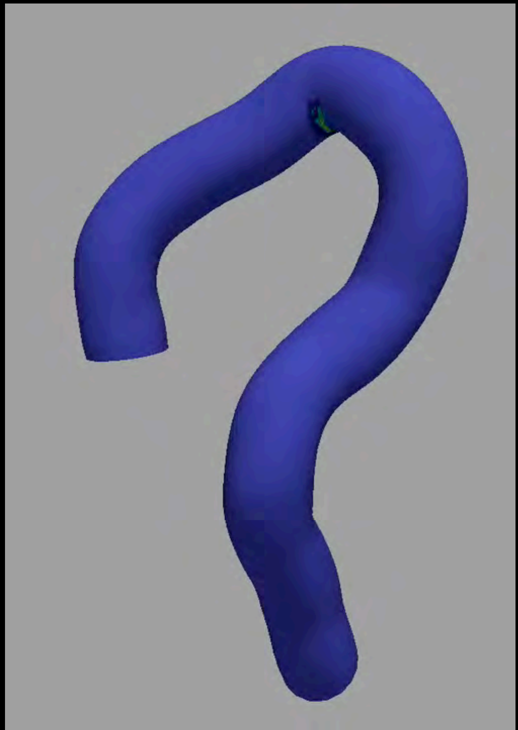
**(NURBS: Non-Uniform Rational Basis Spline)**

# Comparison for WSS

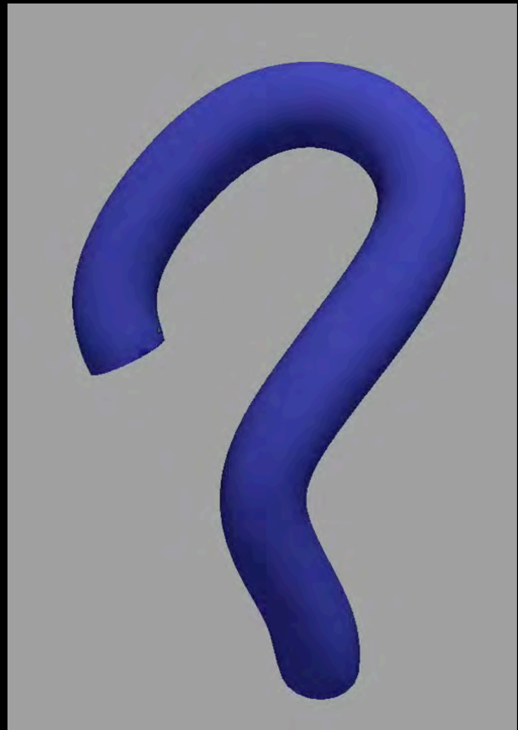
Left: original shape
Right: coarse-grained shape



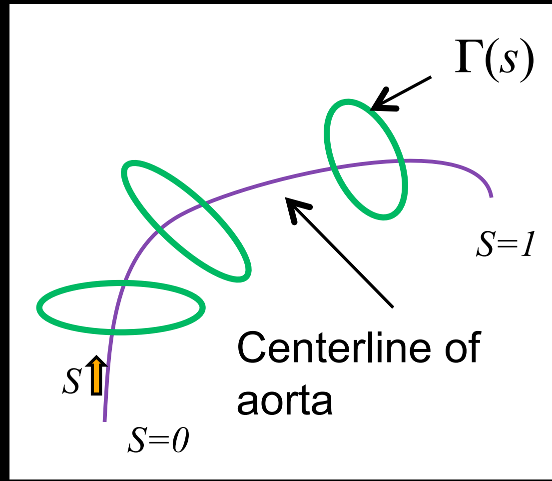





Original shape

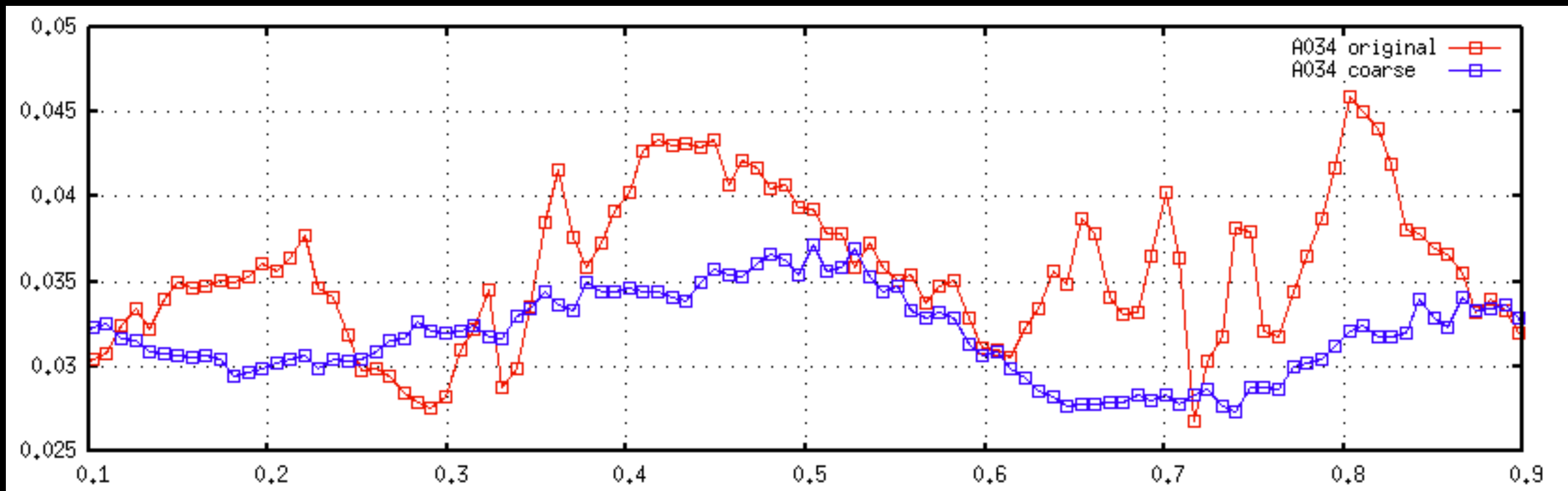


Coarse-grained shape



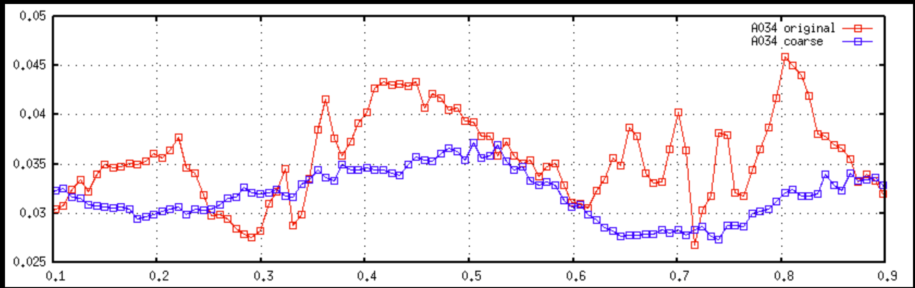

$$\tilde{\sigma}(s) = \int_{\Gamma(s)} \int_0^T |\sigma_\tau| \, dt \, d\Gamma$$

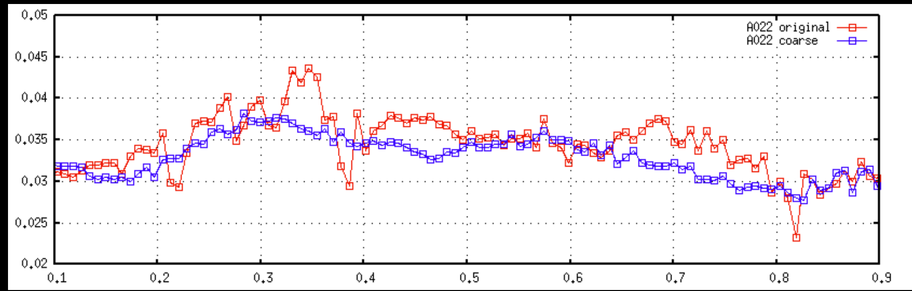
$\tilde{\sigma}(s)$

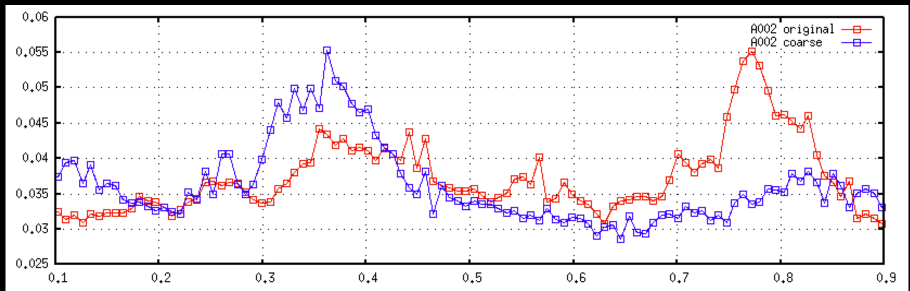


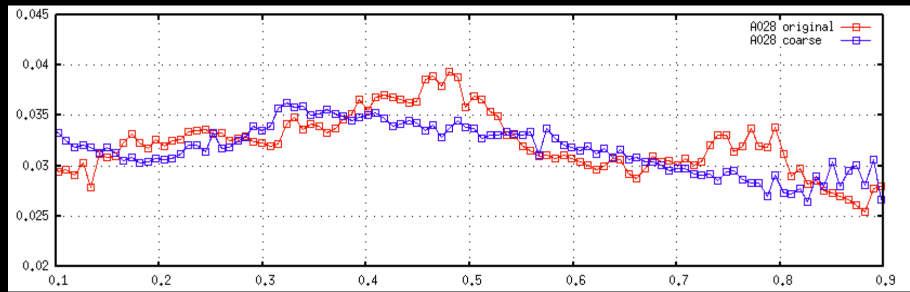

$s$

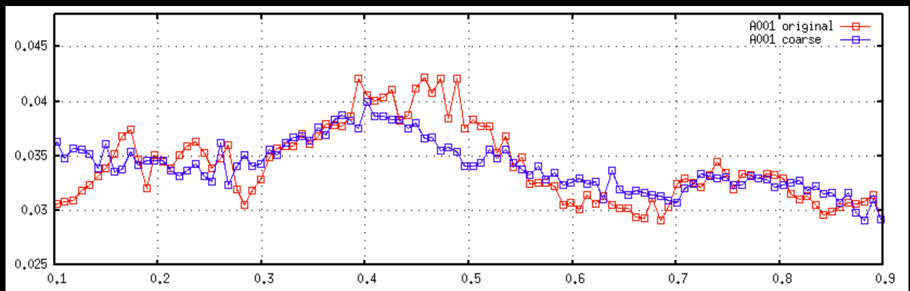
# Integration of time-averaged wall shear stress on cross-sections perpendicular to the centerline

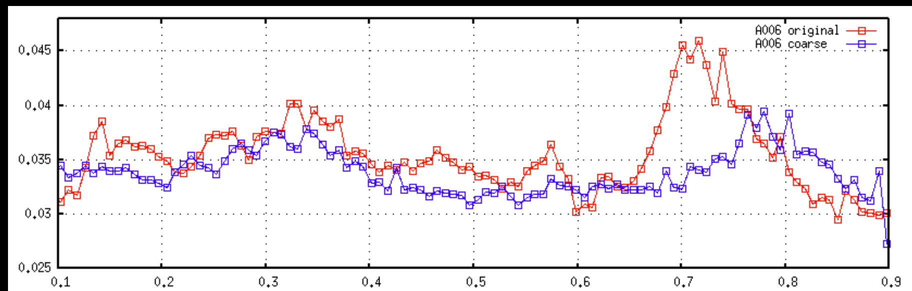


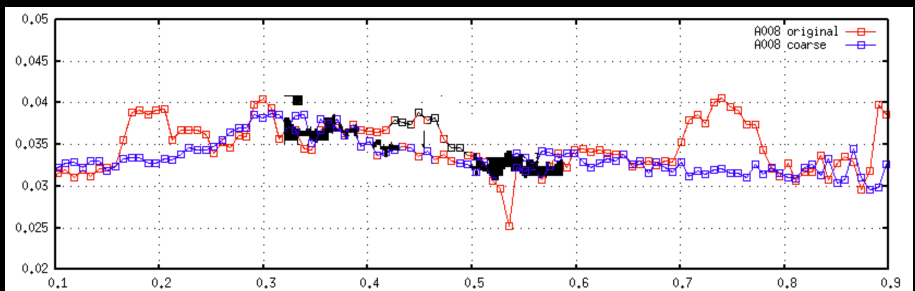



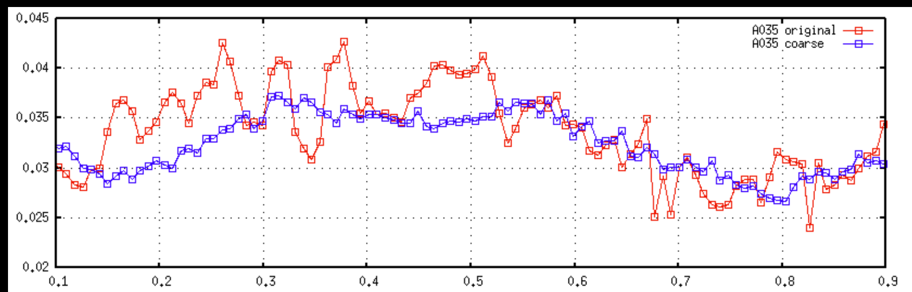



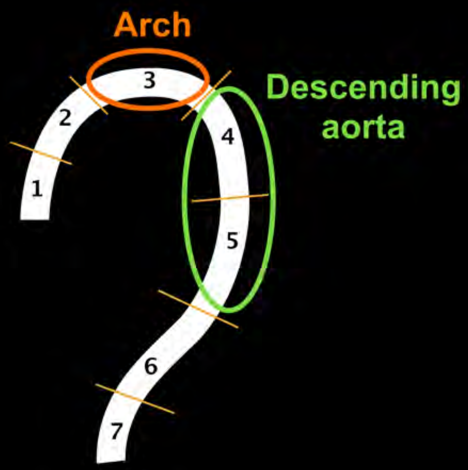



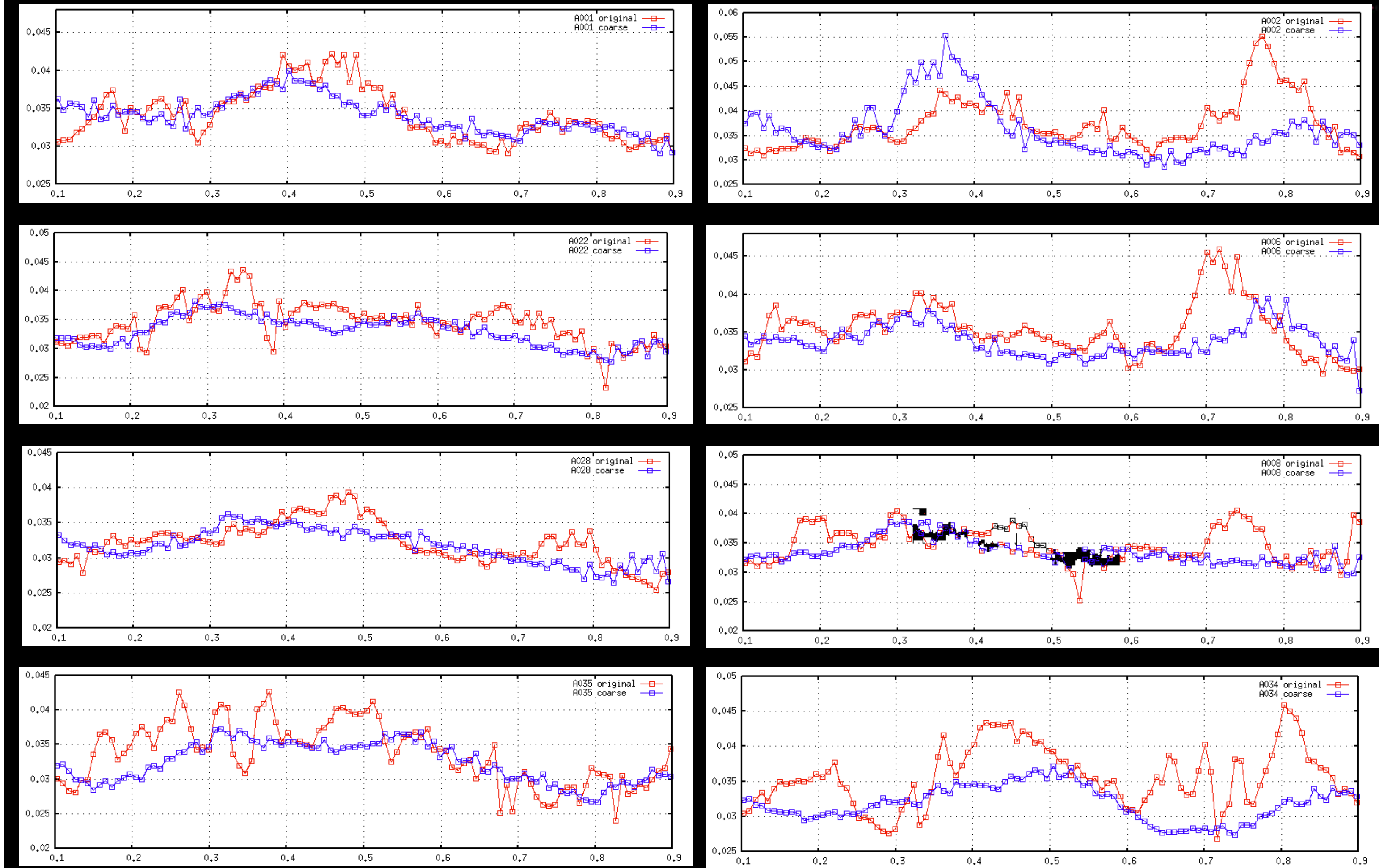



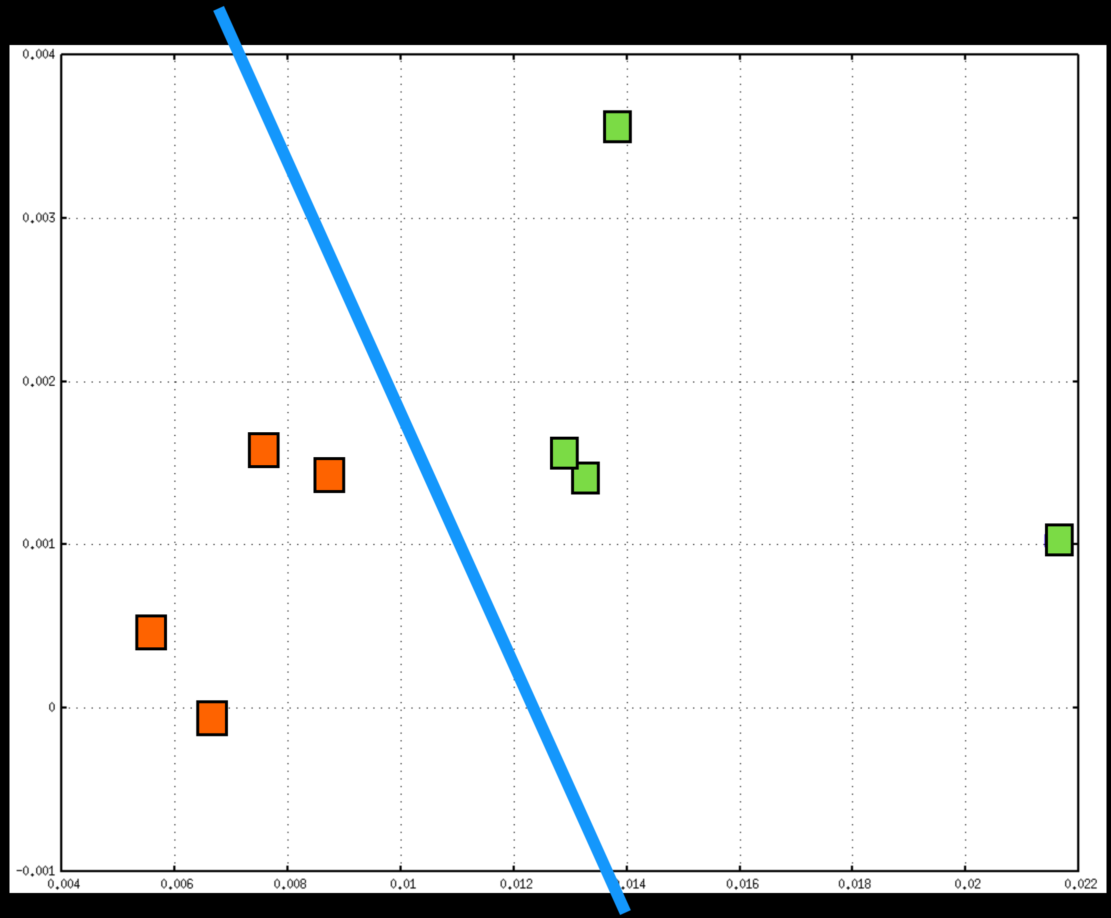
Patient cases can be classified in locations where the aneurysm developed



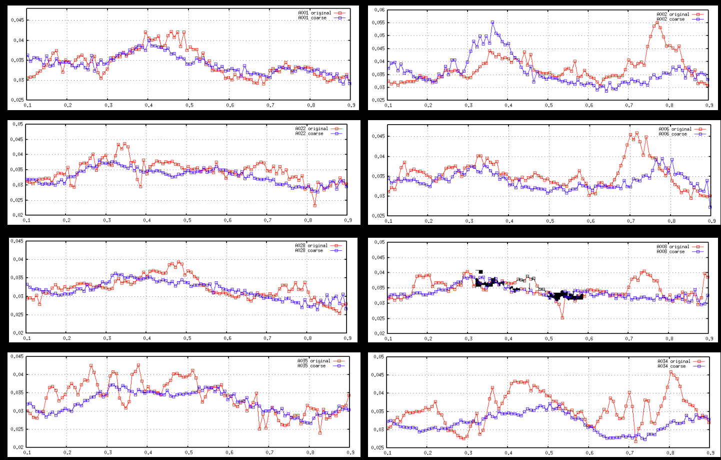

developed on aortic arch    developed on descending aorta

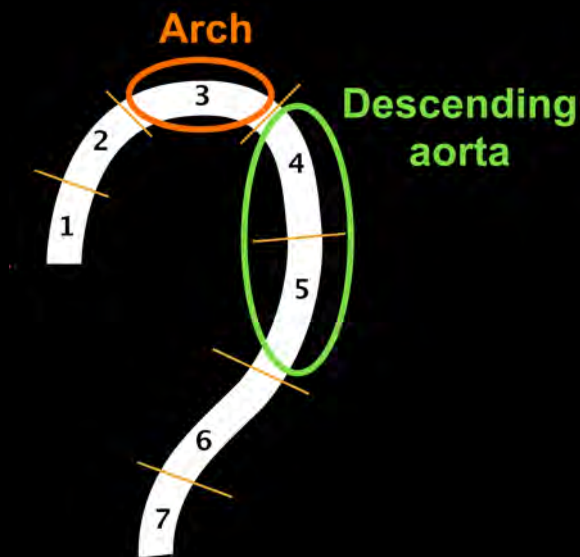
# Differences in WSSs integrated along the centerlines between original and coarse-grained shapes




$$\int_0^1 \{\tilde{\sigma}_o(s) - \tilde{\sigma}_c(s)\}^2 \, ds$$

$$\max_{0<s<1} |\tilde{\sigma}_o(s) - \tilde{\sigma}_c(s)|$$




Patient cases with the aneurysms on the aortic arch

Patient cases with the aneurysms on the descending aorta