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Fluid-structure interaction analyses for blood flow related to aortic aneurysms

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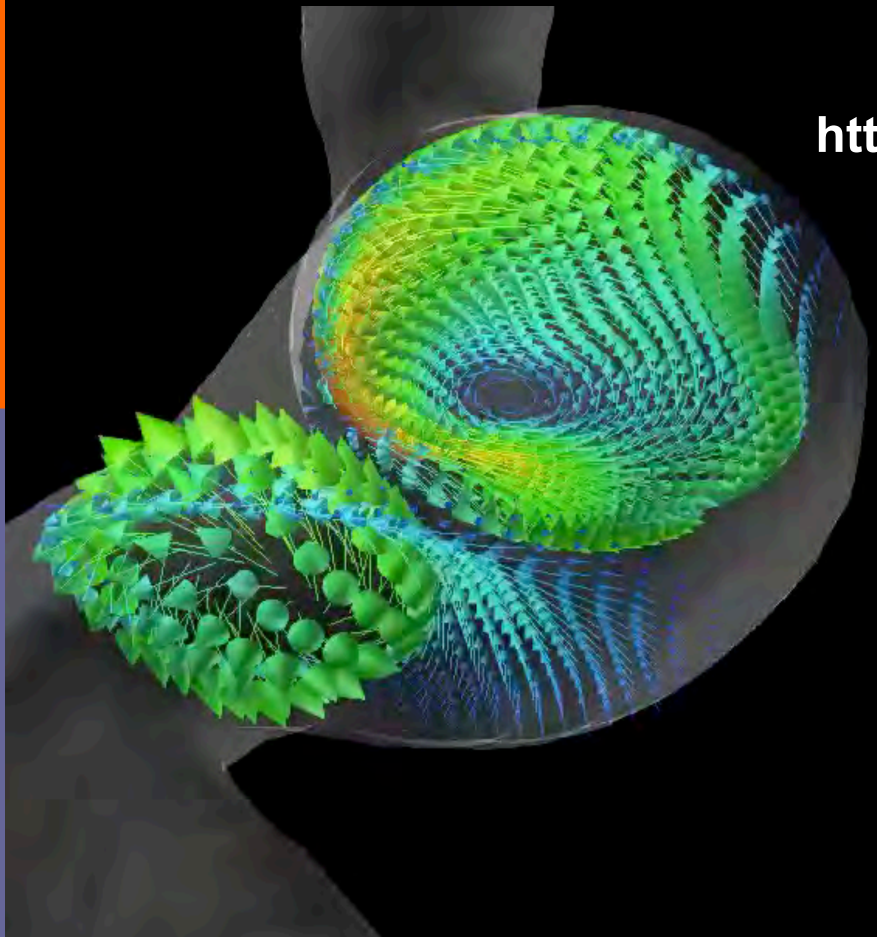

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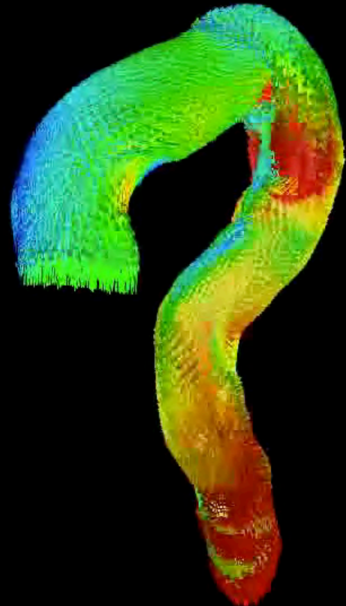
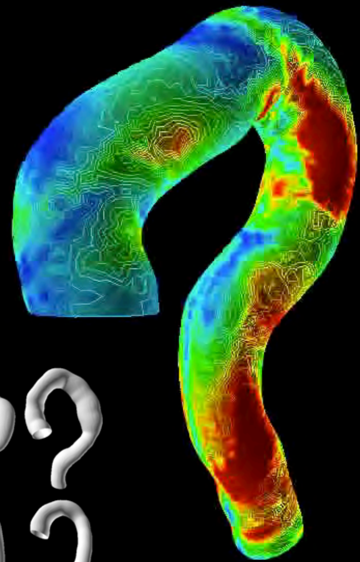
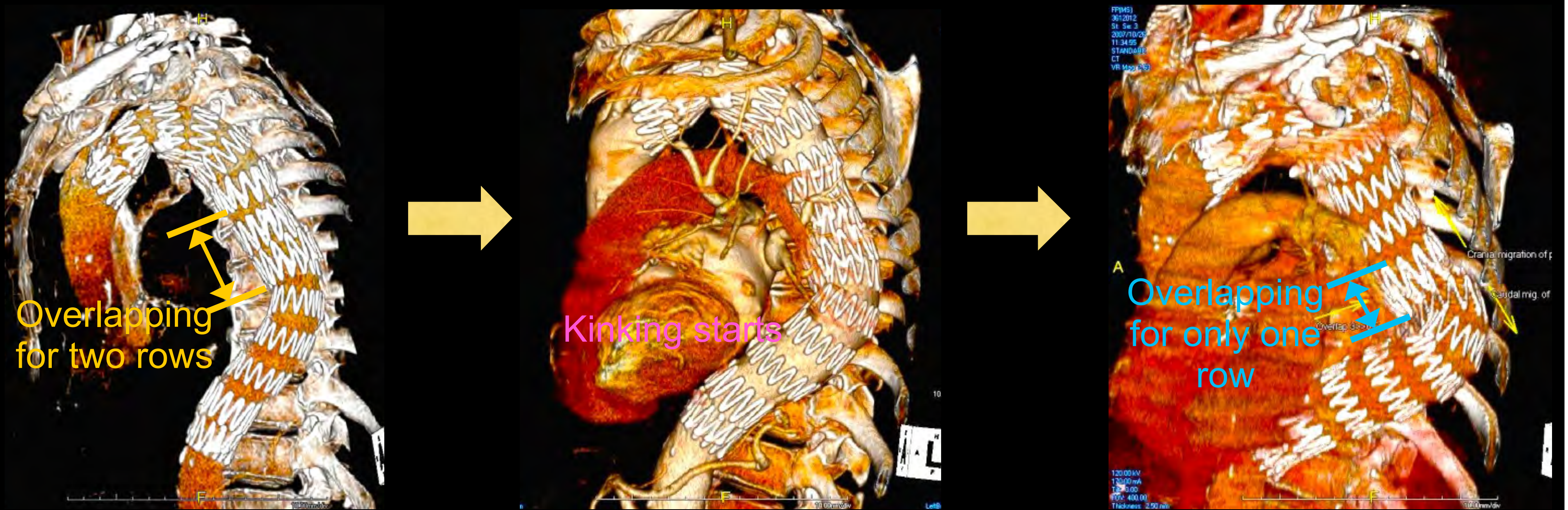
- Secondary flows and geometrical characteristics
- Classification of aorta morphologies



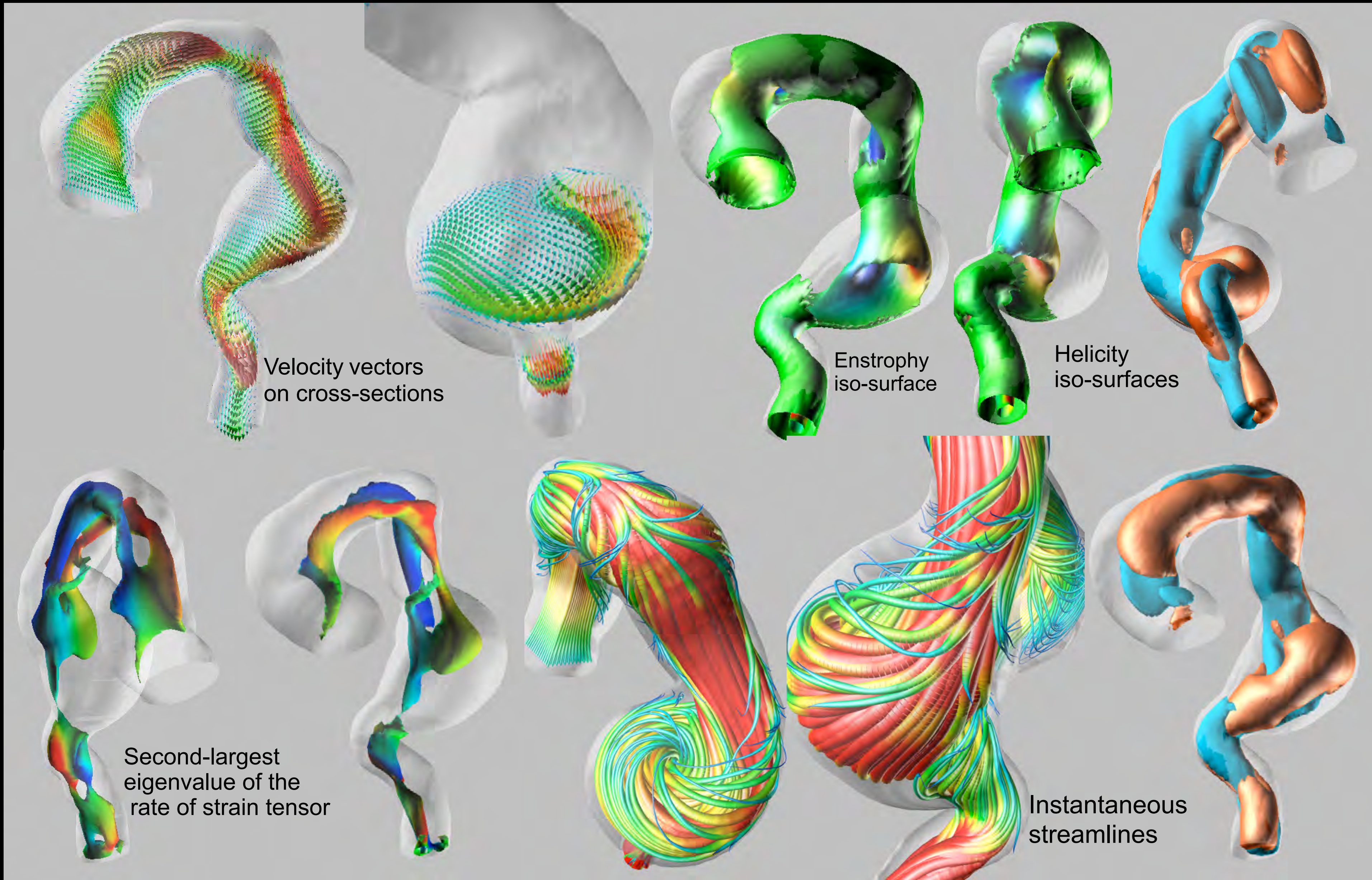


Backgrounds

There are several treatment options such as open surgery or stent graft treatment. Even if the initial treatment technically succeeds, some patients show recurrence and progression of disease many years after treatment.



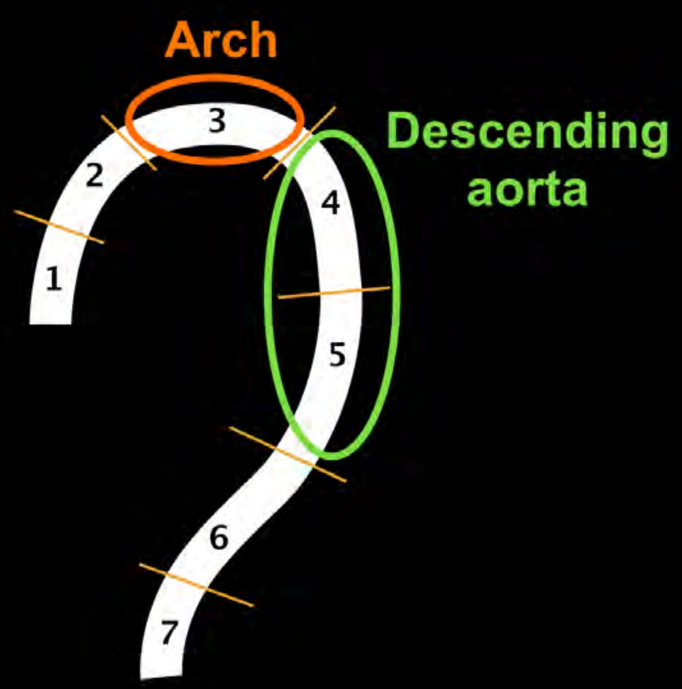
- In this patient's case, kinking slowly started and suddenly accelerated. Such long-term morphological change seems to interact synergically with hemodynamics.
- However, not all the patients show this kind of adverse events. This means that the relation between aorta shapes and WSS distributions seem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


Velocity vectors
on cross-sections
Enstrophy
iso-surface
Helicity
iso-surfaces
Second-largest
eigenvalue of the
rate of strain tensor
Instantaneous
streamlines

Clinical question

- Can we predict where an aneurysm would develop?
- Can we classify the aorta morphologies from the viewpoint of where aneurysms would develop?

The locations where aneurysms would develop play an important role for optimal treatment decision, for example, risks for surgery itself depends on the location.

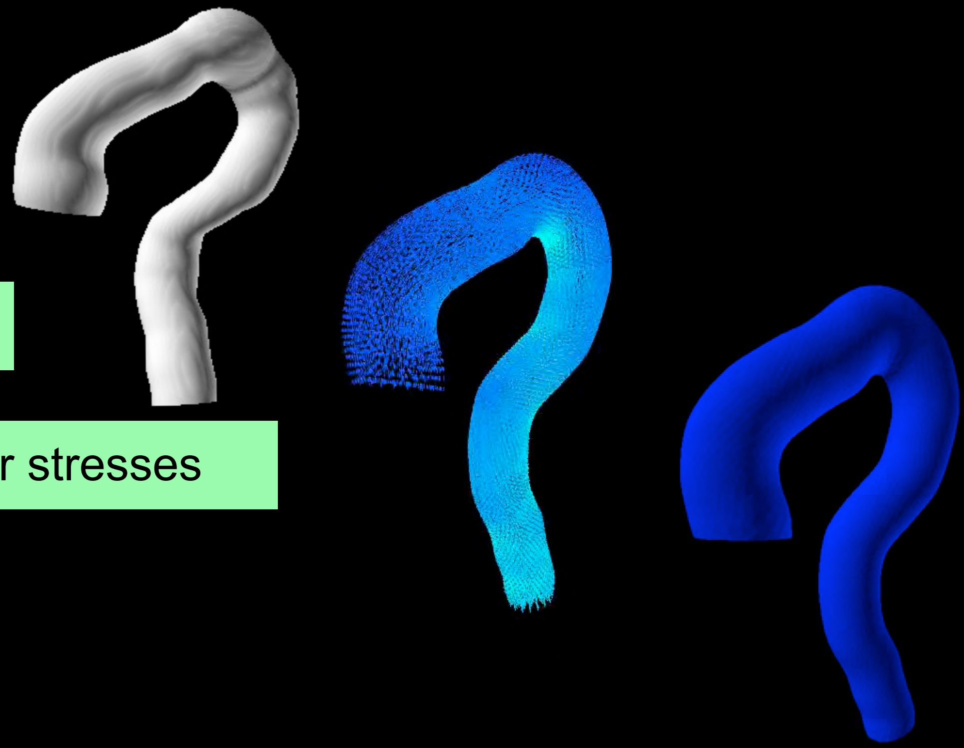


Objectives

Difference in original aorta morphologies

→ Difference in flow fields

→ Difference in wall shear stresses



There are so many parameters affecting the aortic aneurysms, such as tissue remodeling, mechanical properties of the stent graft, etc. We are seeking the most appropriate parameterization of aorta morphologies strongly related to WSS distributions.

Generally speaking, his/her aorta shape might be much simple, when he/she was young. By advancing age, the aorta shape becomes complex.

- Predict where the aneurysm would be developed, depending on patient-specific morphology characteristics.
- Optimize follow-up strategies after cardiovascular treatments depending on patient-specific conditions.

Computational Method
T. Tezduyar and K. Takizawa

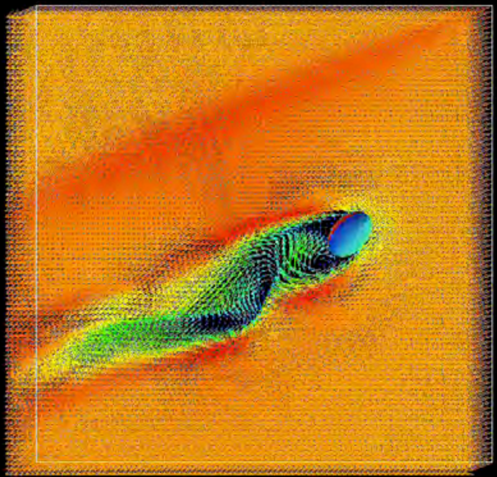
- Deforming-Spatial-Domain/Stabilized-Space–Time Method (DSD/SST)
- Variational Multiscale（VMS) method

[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).

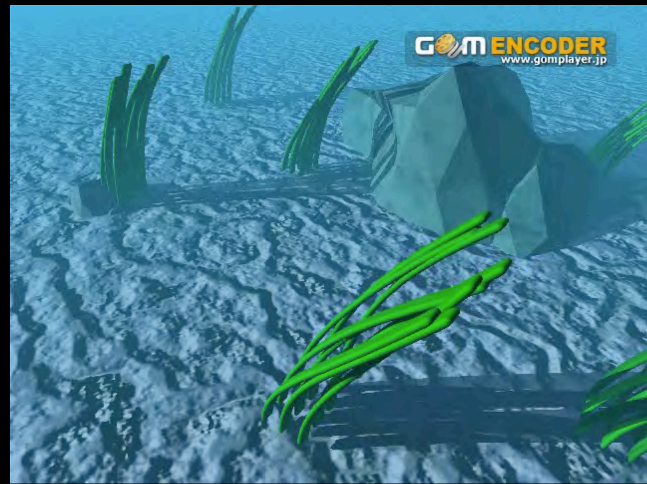
[3] T.E. Tezduyar, K. Takizawa, C. Moorman, S. Wright and J. Christopher, "Multiscale Sequentially-Coupled Arterial FSI Technique", Computational Mechanics, Vol. 46 17–29 (2010).

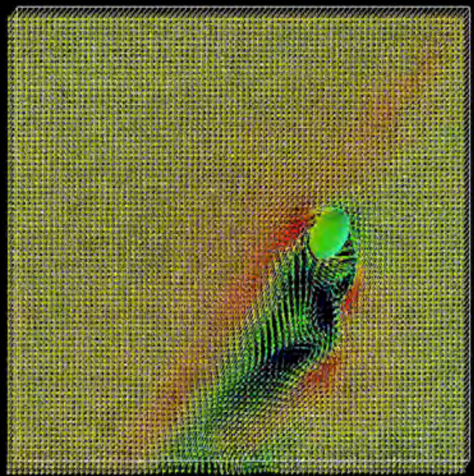
Fluid-structure interaction algorithms

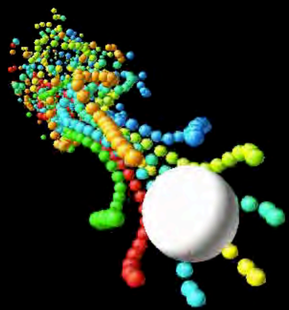


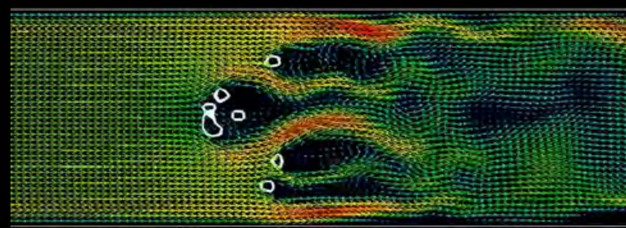
Strong-coupling
(iterative method)

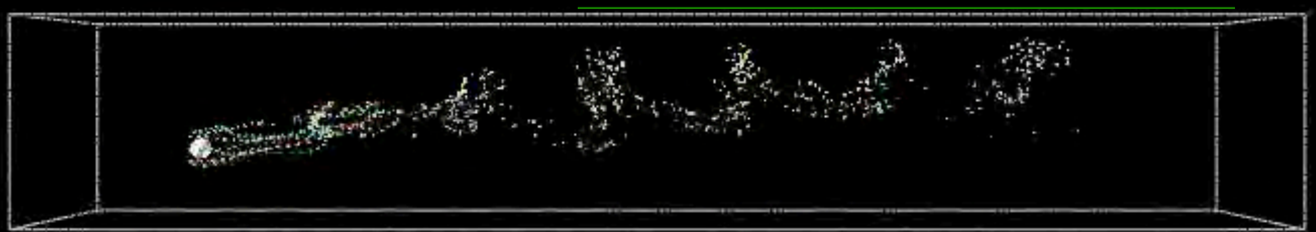
Weak-coupling
(explicit method)











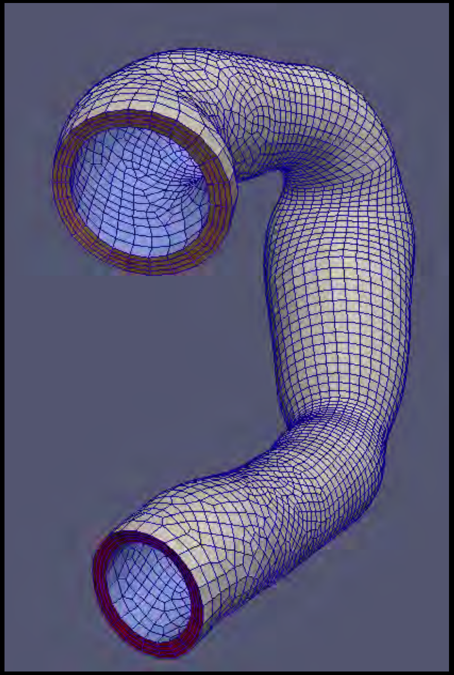
FSI procedure

Sequentially-Coupled Arterial FSI (SCAFSI) Technique

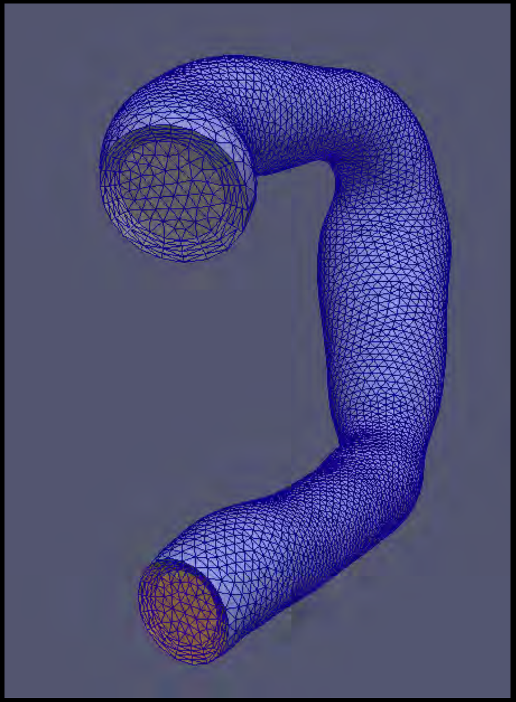
1. Compute the vessel wall motion for one heart period using the equation for structure. A measured pressure history data is given as an external force.

2. Compute the motion of the mesh 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.



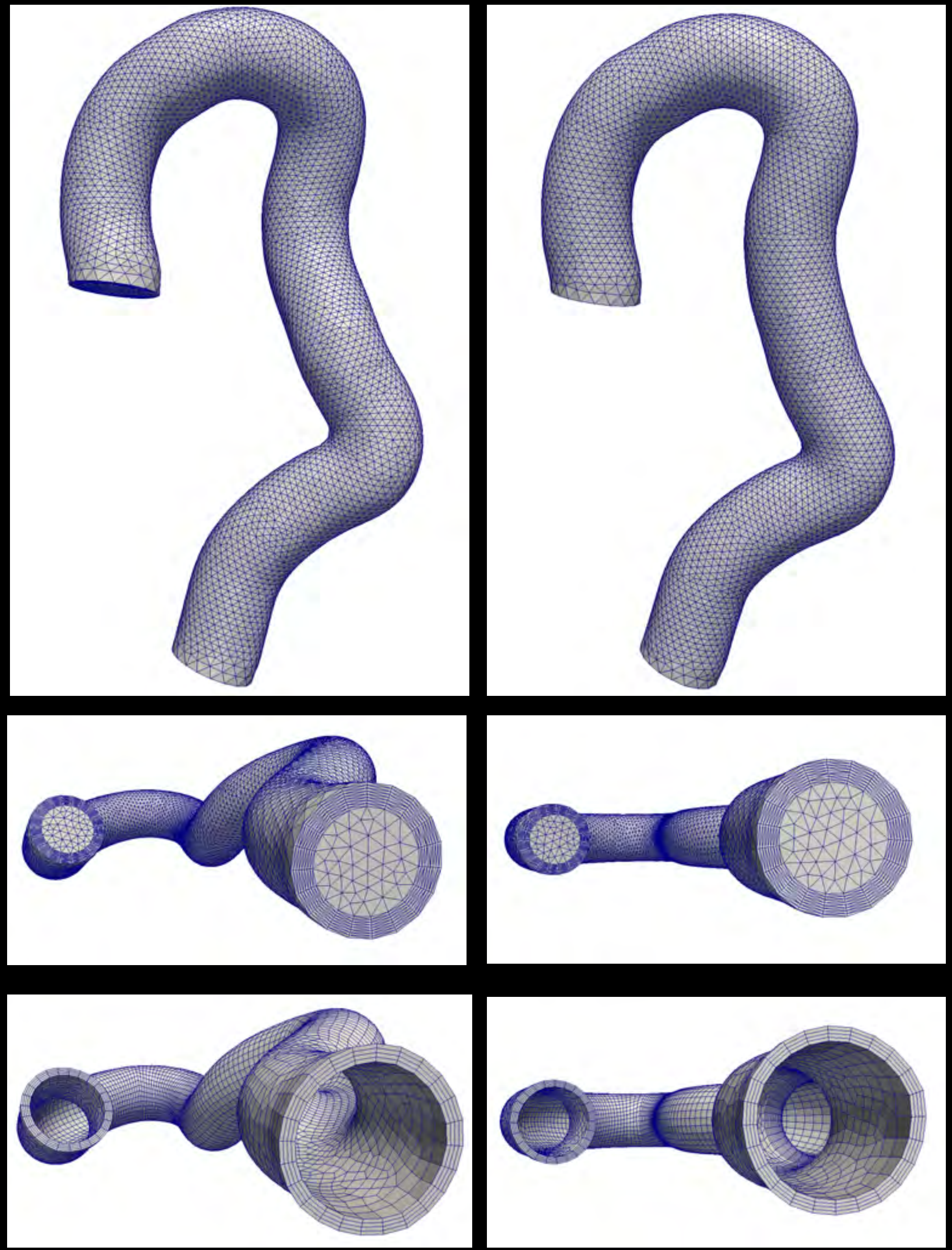
Hexahedral mesh for structure



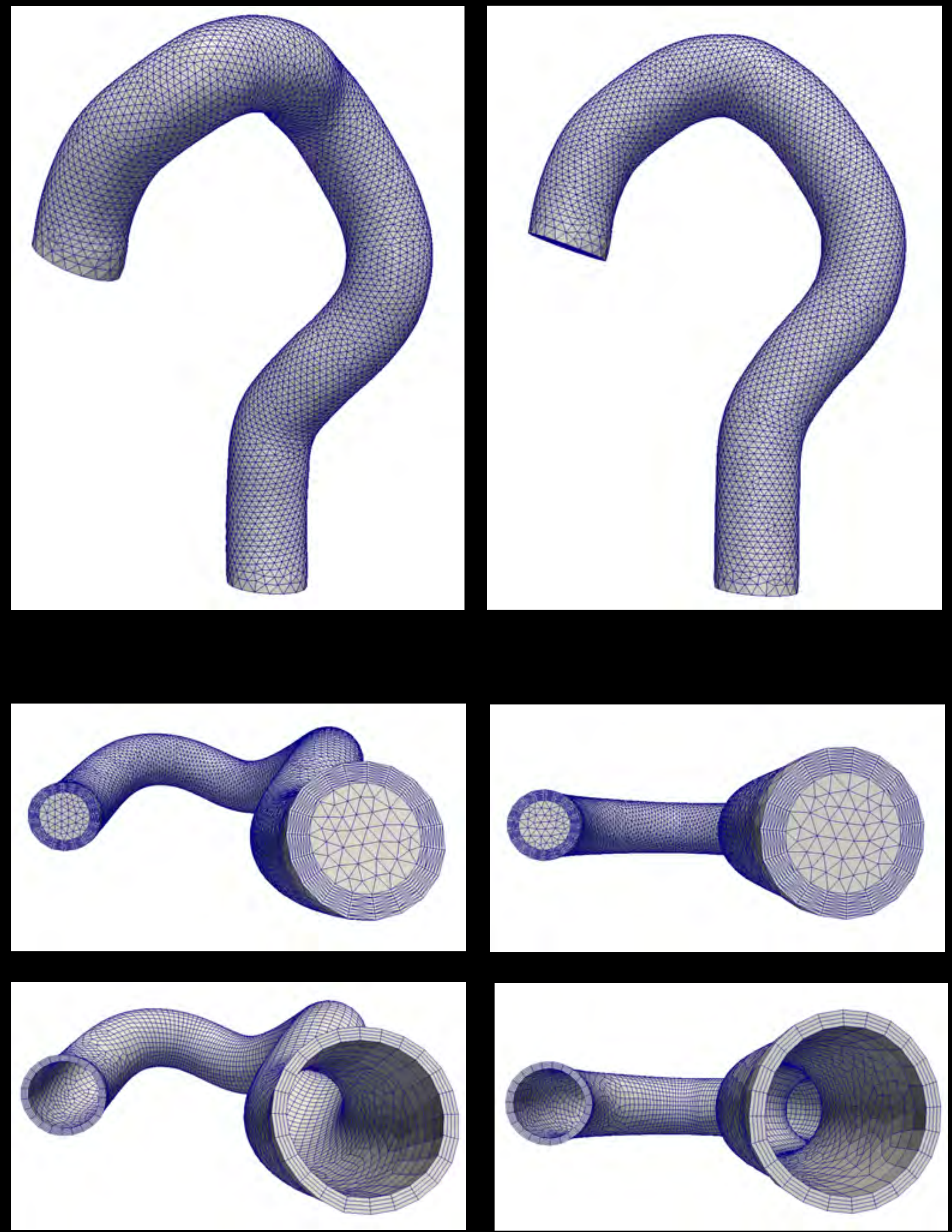
Tetrahedral mesh for fluid

[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).

Case A002



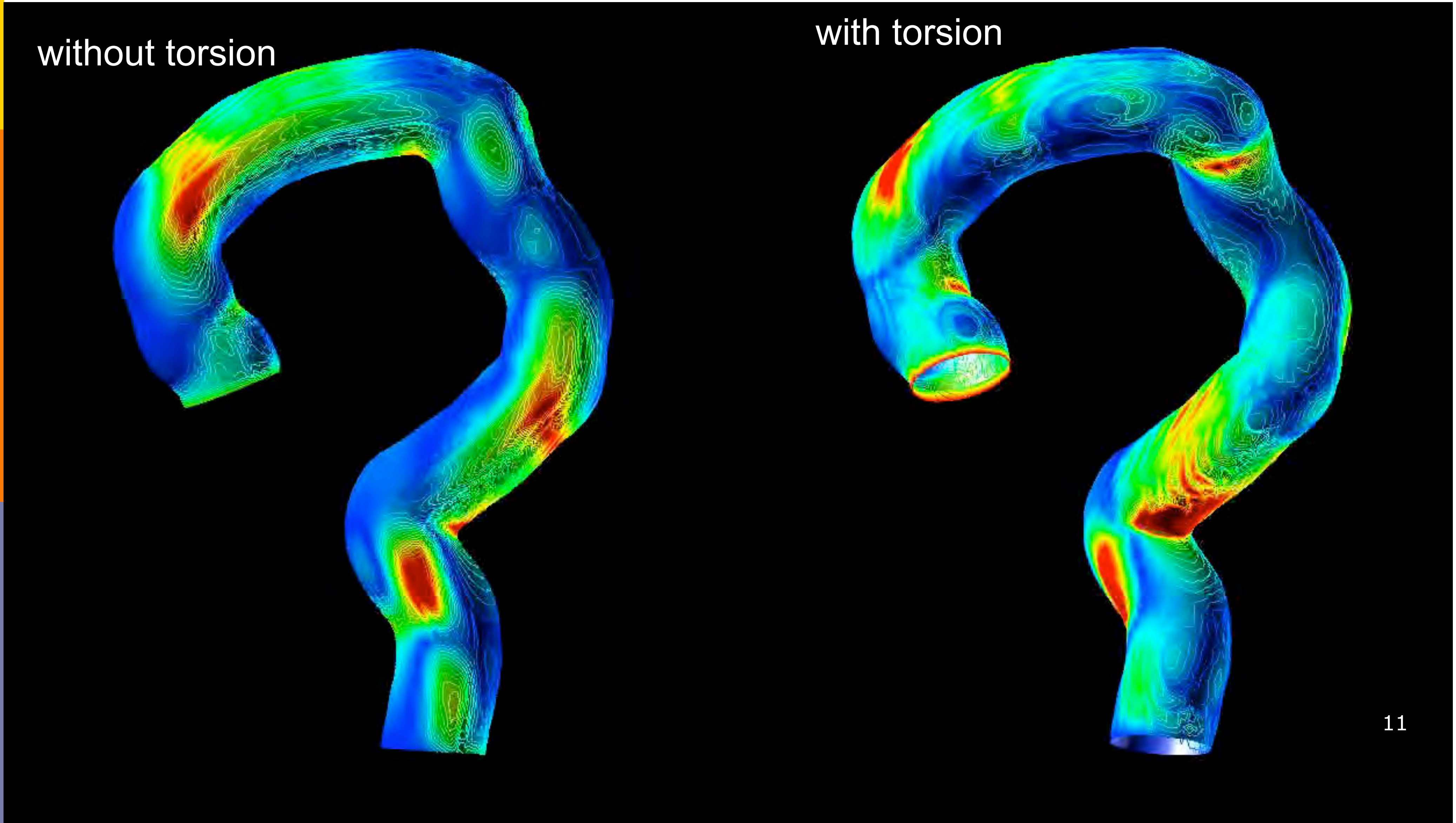
Case A022



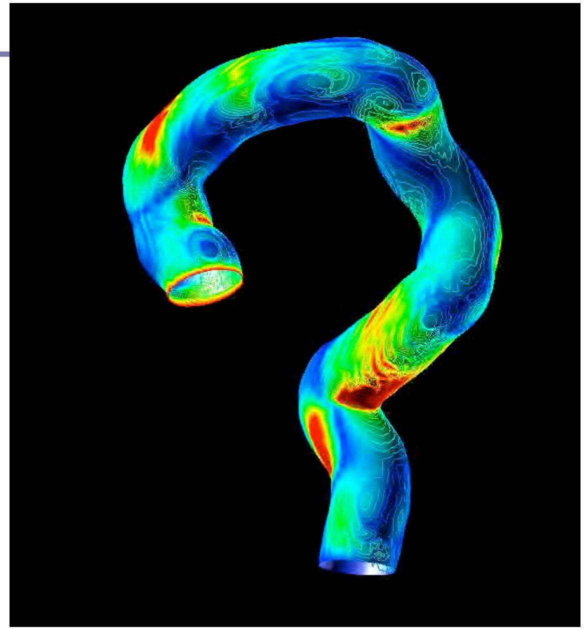
Curvature and torsion

Frenet-Serret formula

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



Geometrical representation of the aorta



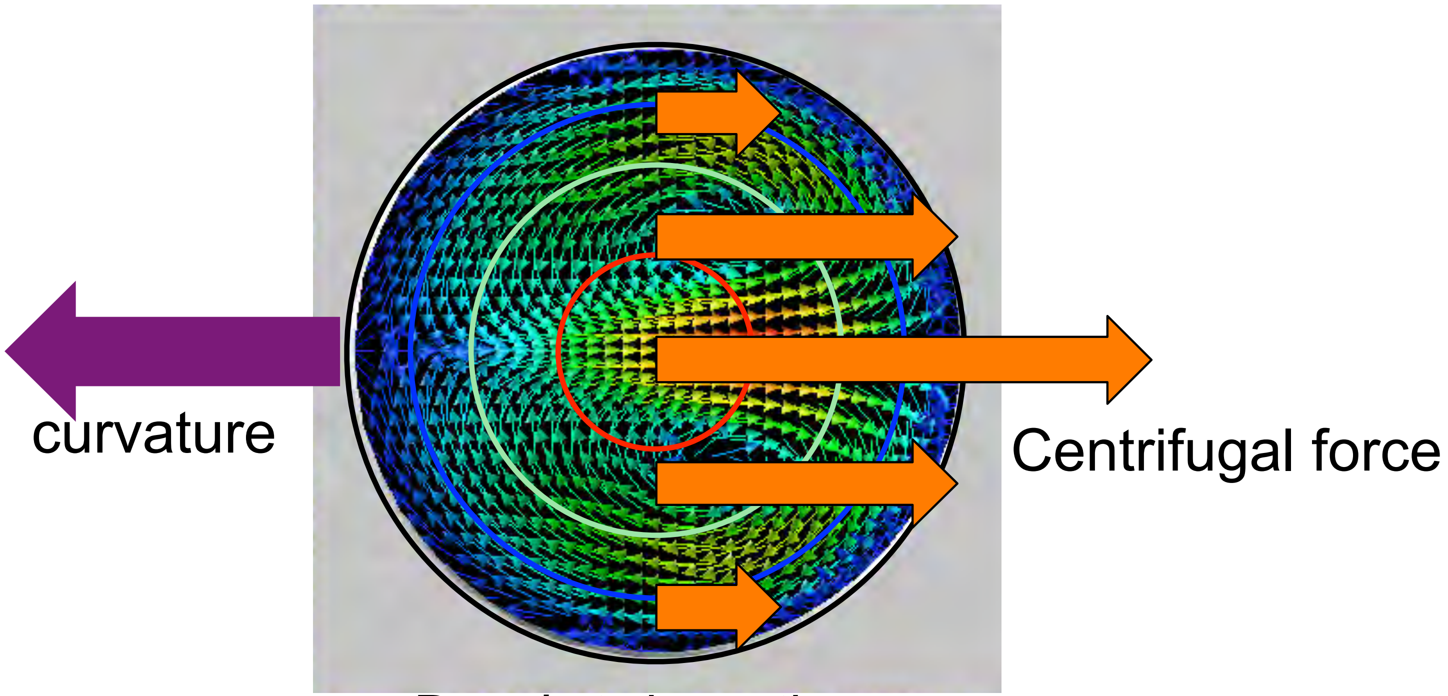
- **Radius**: Almost linearly decreasing for healthy aorta. Not considered here.
- **Curvature**: Human aorta goes upward from heart and then turns downward. Therefore, the difference among individuals is not so large.
- **Torsion**: Human aorta goes through several organs and borns. Therefore, the difference of its torsion is large among individuals.

Frenet-Serret formula

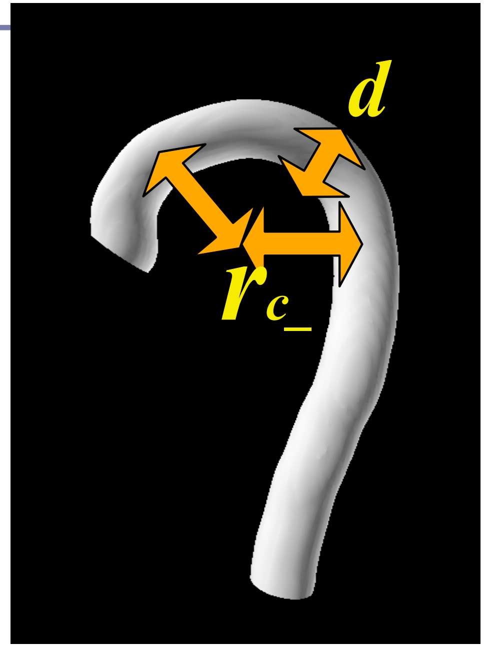
$$\frac{d}{ds}\begin{pmatrix} \boldsymbol{\tau} \\ \boldsymbol{n} \\ \boldsymbol{b} \end{pmatrix} = \begin{pmatrix} 0 & Cv & 0 \\ -Cv & 0 & To \\ 0 & -To & 0 \end{pmatrix} \begin{pmatrix} \boldsymbol{\tau} \\ \boldsymbol{n} \\ \boldsymbol{b} \end{pmatrix}$$

Dean’s vortices

Characteristic secondary flows are observed in curved tubes.



Dean’s twin vortices

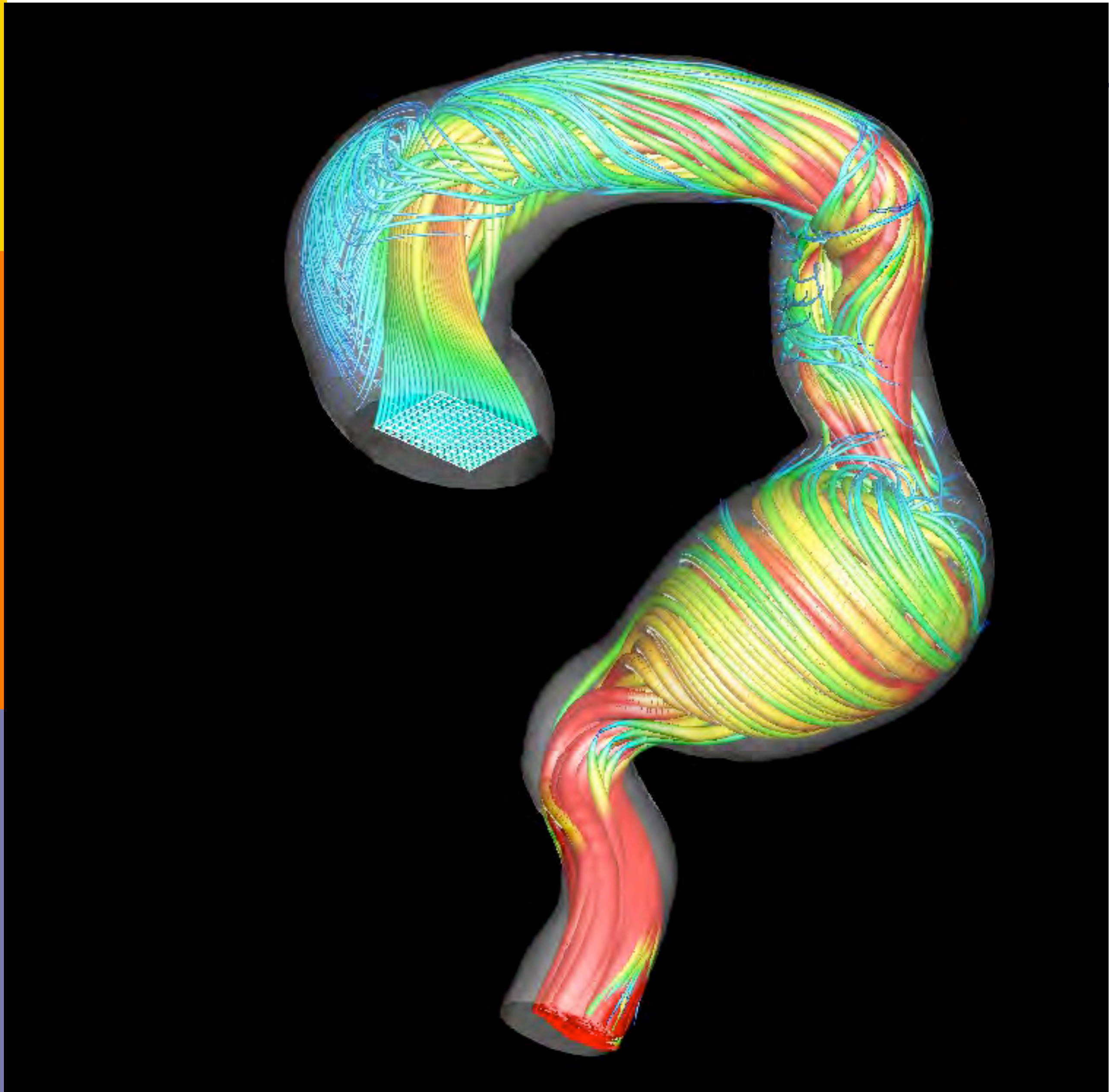


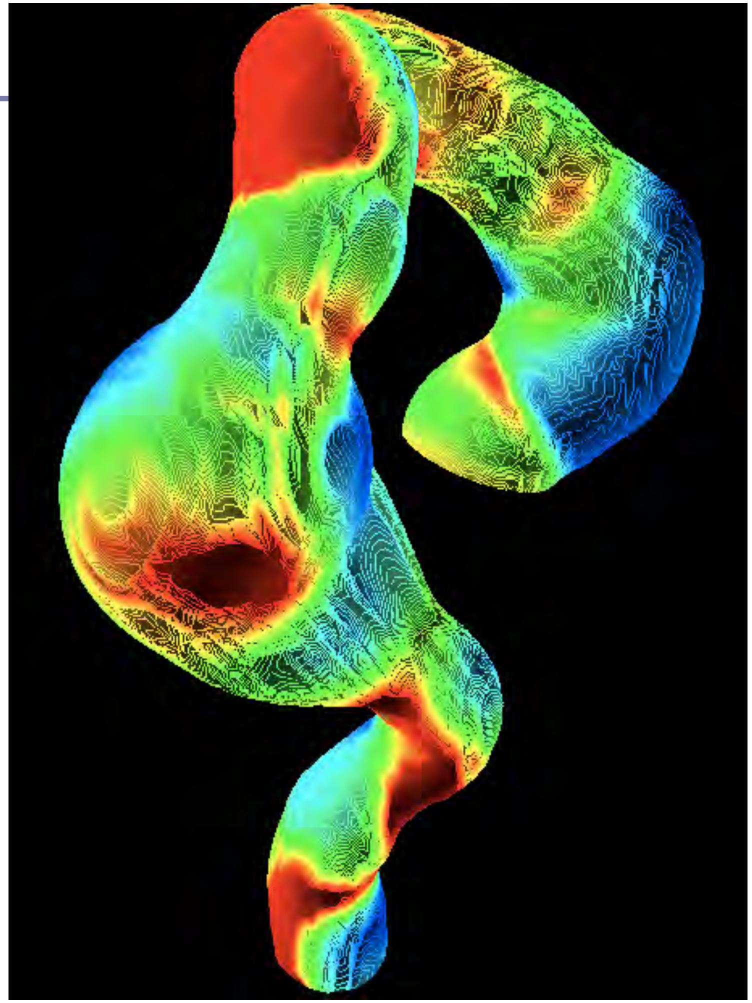
Dean number

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

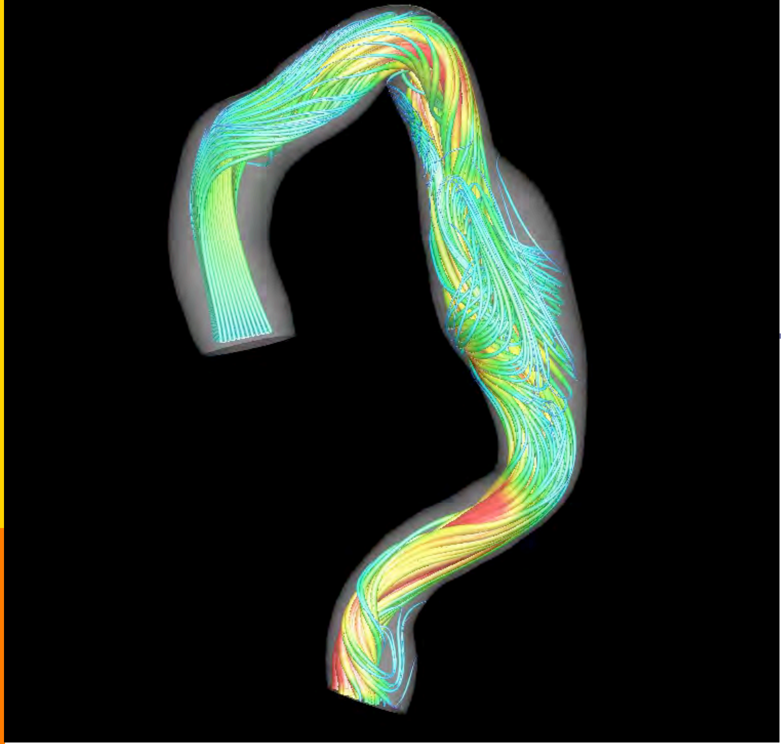
(1) In the straight circular tube, Hagen-Poiseuille flow profile is achieved.
(2) If the tube has a curvature, the centrifugal force acts in the opposite direction of the curvature.
(3) The centrifugal force is proportional to the velocity in the axis direction.
(4) Consequently, a set of opposite-sign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

Naked flow visualized by instantaneous streamlines (A003)

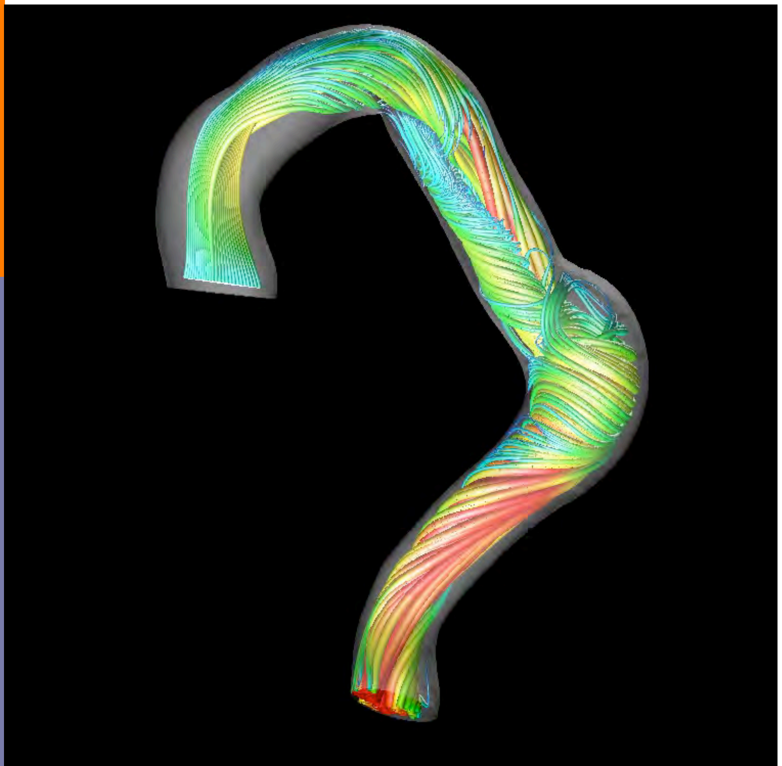




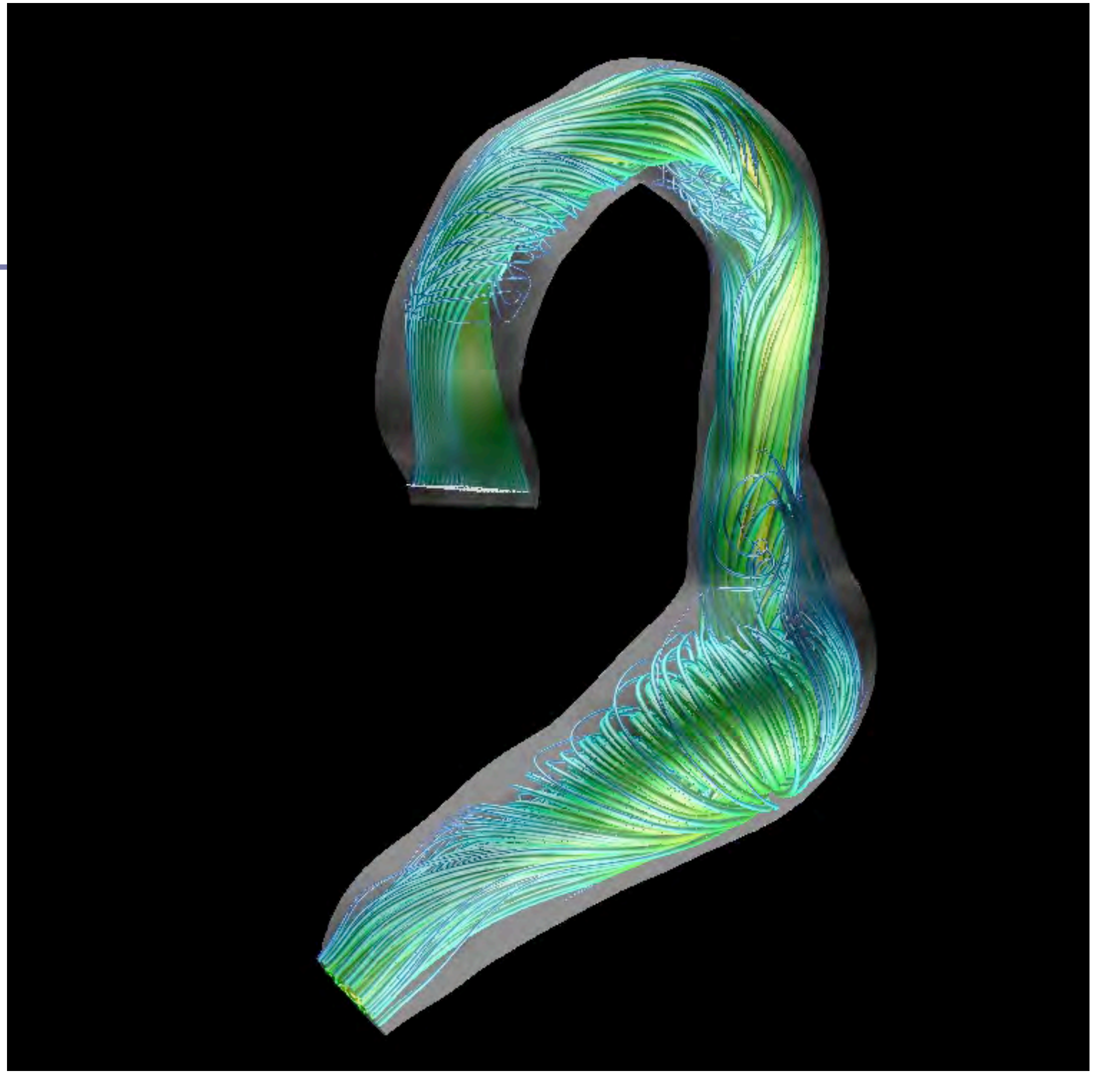
Distribution of time averaged wall shear stress



A004

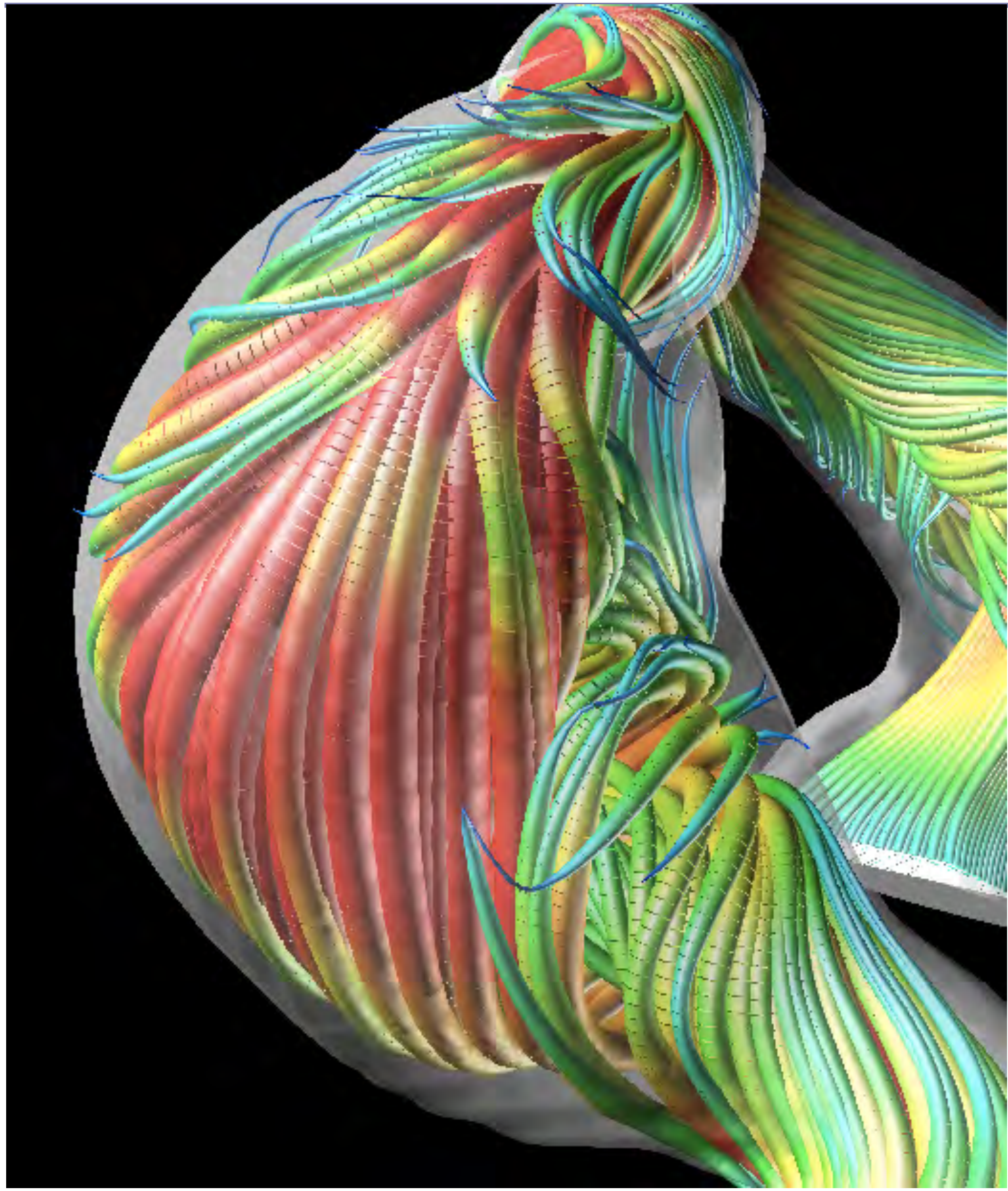


A006

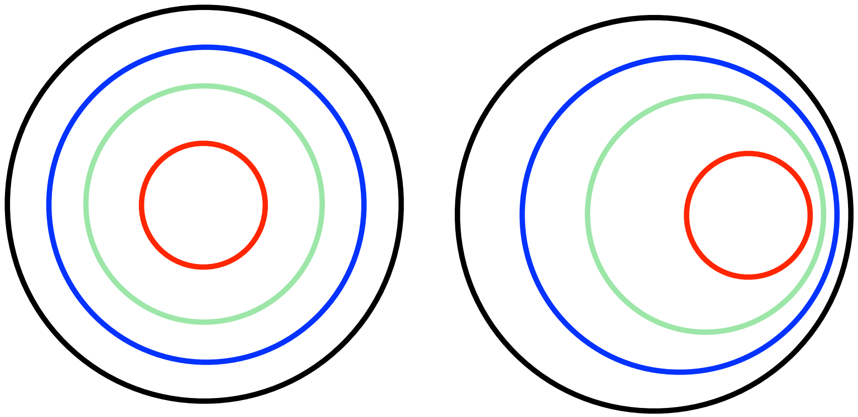


A010 with stagnation point

Naked flow

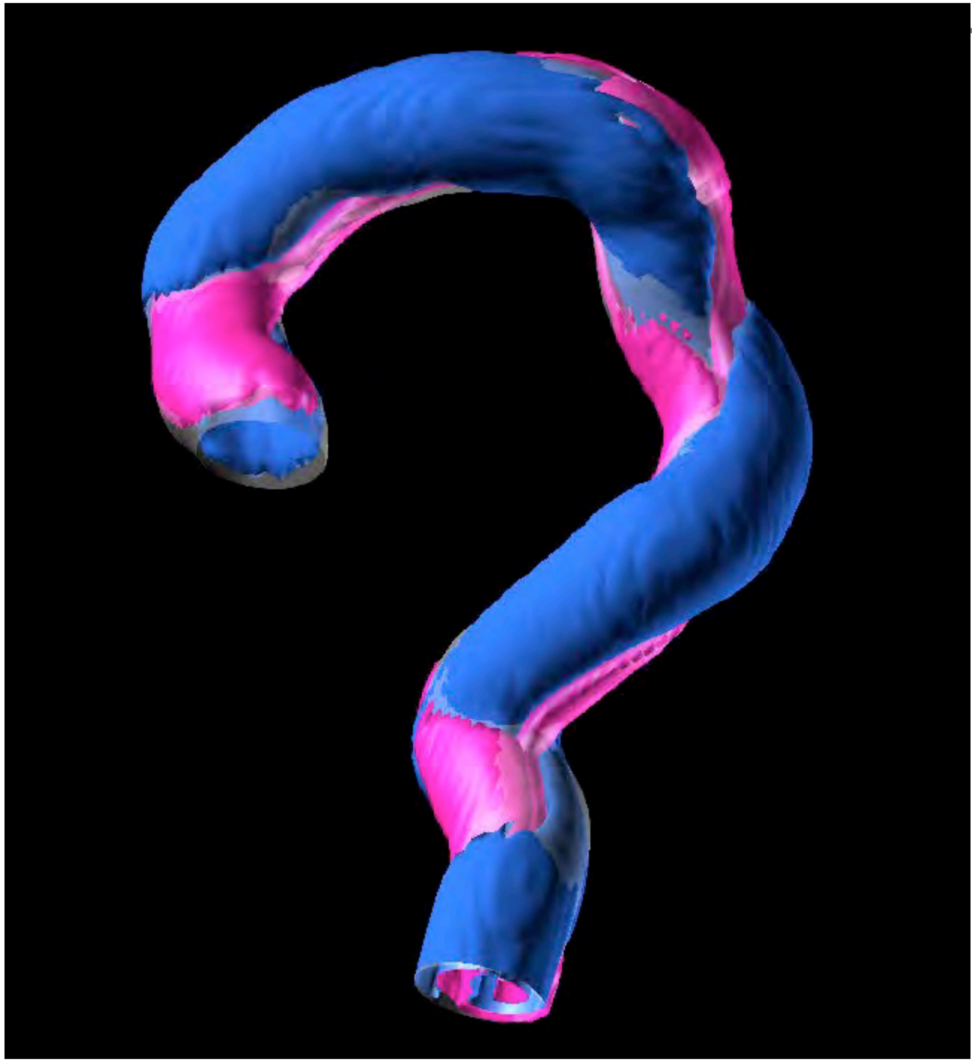


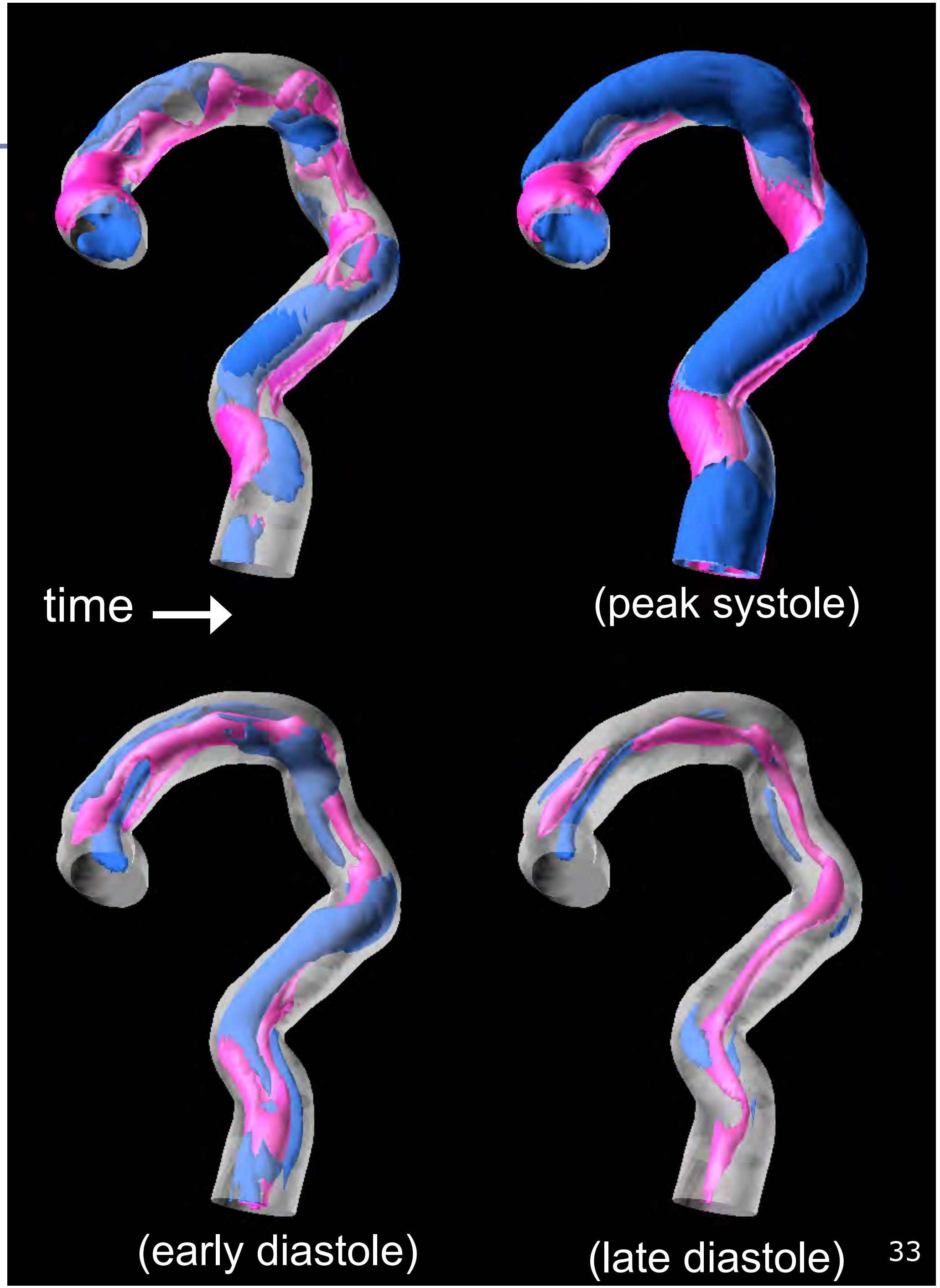
- If the vessel is straight, Poiseuille-like flow profile is achieved and the strong velocity is confined in the center region of the vessel.
- In the case with curvature and torsion, this strong velocity is conducted to near-wall region and causes strong wall shear stress.



Streamwise vorticity contours

red: clockwise, blue: unti-clockwise





Simple spiral tubes

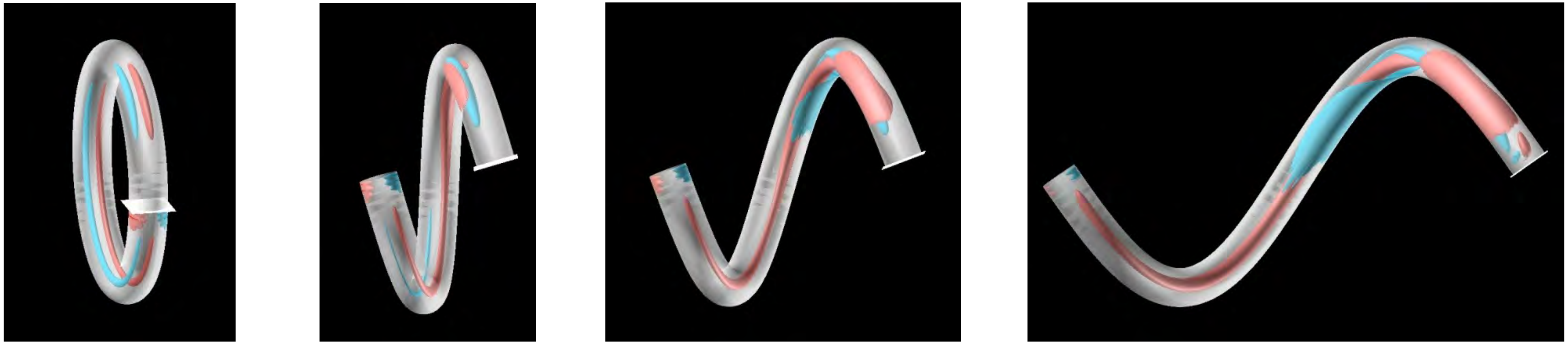
$$\begin{cases} x = a\cos u \\ y = a\sin u \\ z = hu \end{cases}$$

Frenet-Serret formula

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

$$\mathrm{Cv} = \frac{a}{a^2 + h^2}$$

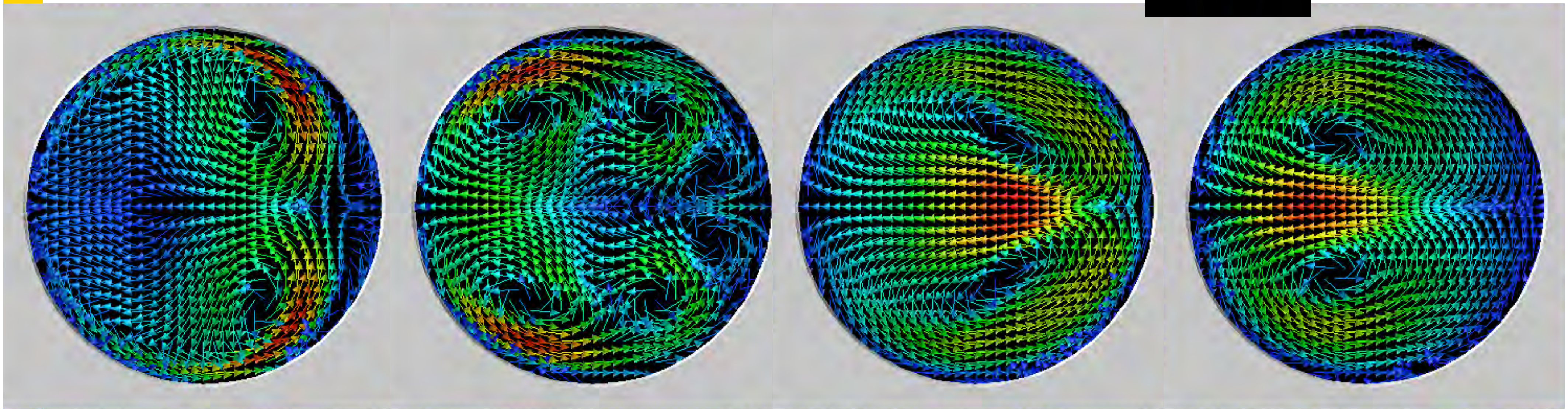
$$\mathrm{To} = \frac{h}{a^2 + h^2}$$



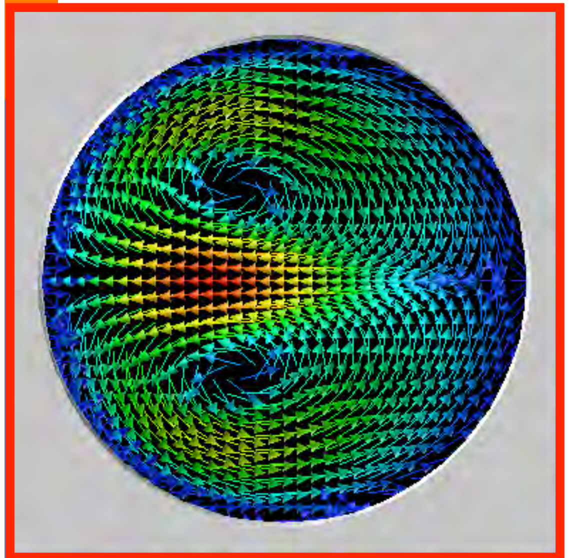
$\chi = 16.7$, $\tau = 0.0$ | $\chi = 16.2$, $\tau = 2.7$ | $\chi = 15.0$, $\tau = 5.0$ | $\chi = 11.5$, $\tau = 7.7$

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 flow in a simple spiral tube (zero torsion case)



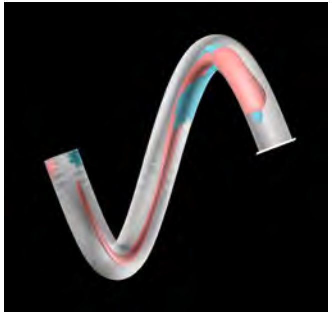
(peak systole) (late systole) (early diastole) (late diastole)

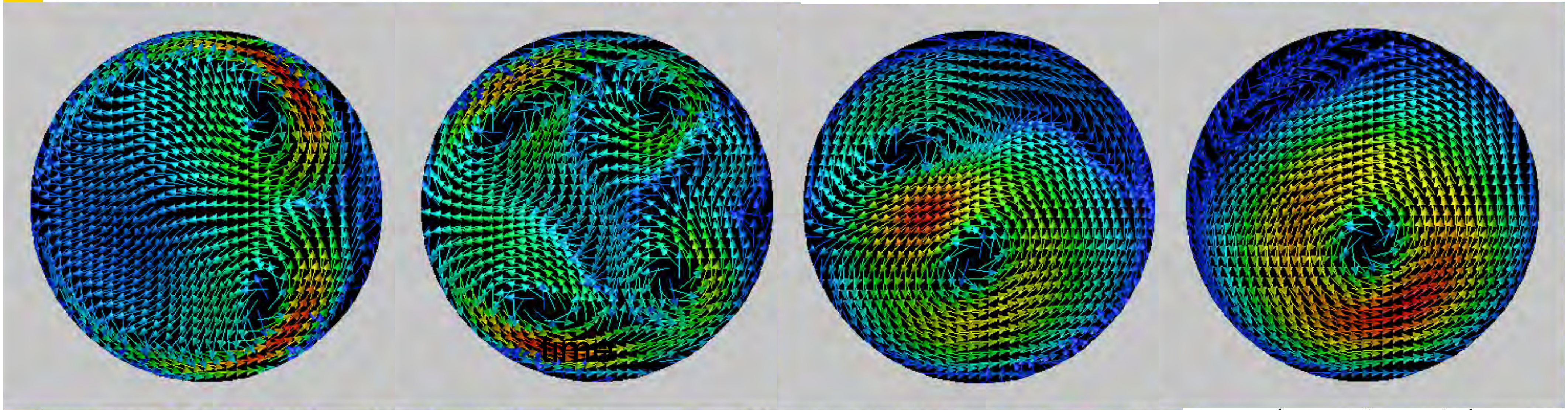


steady case

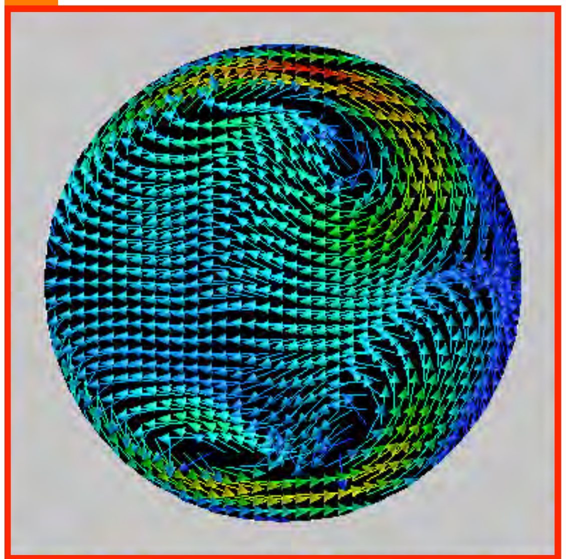
In the zero-torsion case, two Dean's vortices are apparent throughout the whole cardiac cycle. Furthermore, these characteristics are the same for the steady case. In other words, the Womersley's number is not so important in the zero-torsion case.

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





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



steady case

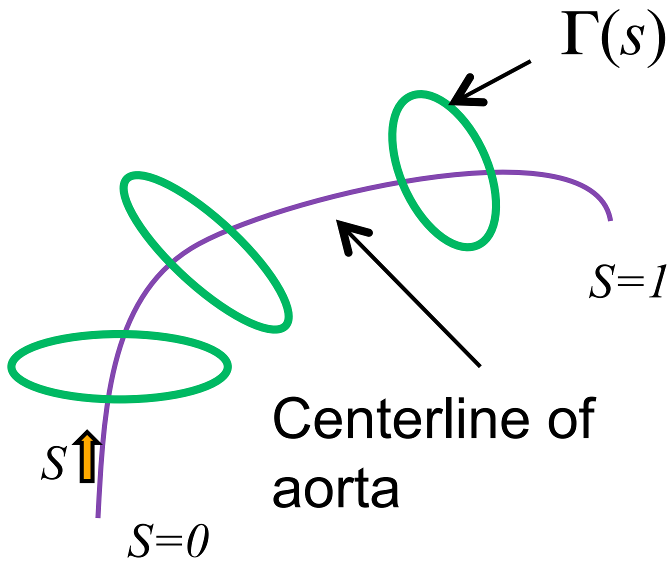
In the peak systole phase, symmetric Dean's vortices are generated just as in the zero-torsion case. However, in the diastole phase, they merge; one of them dominates the other. Actually, the lower right small vortex in the second figure persists and expands.

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

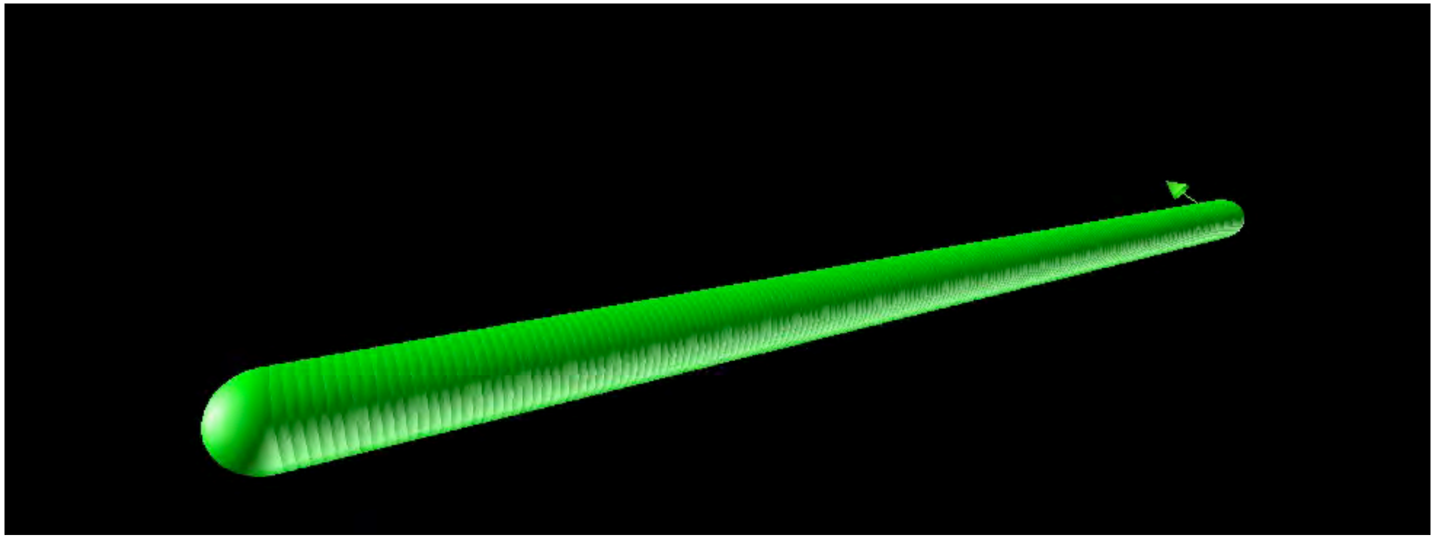
Torque on the aortic wall

In order to evaluate the effect of the swirling flow, we compute the torque which is defined as;

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



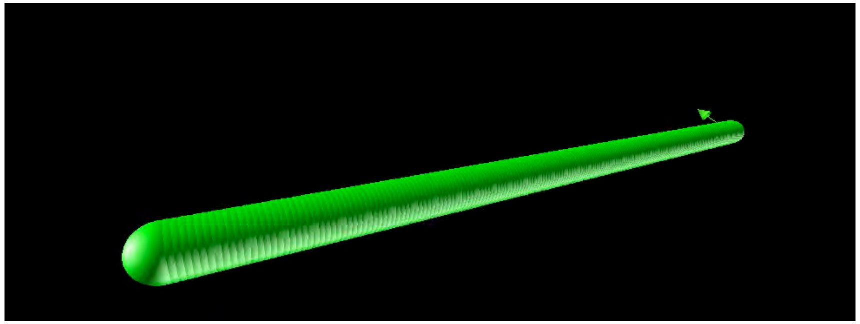
1D elastic rod (Kirchhoff rod)

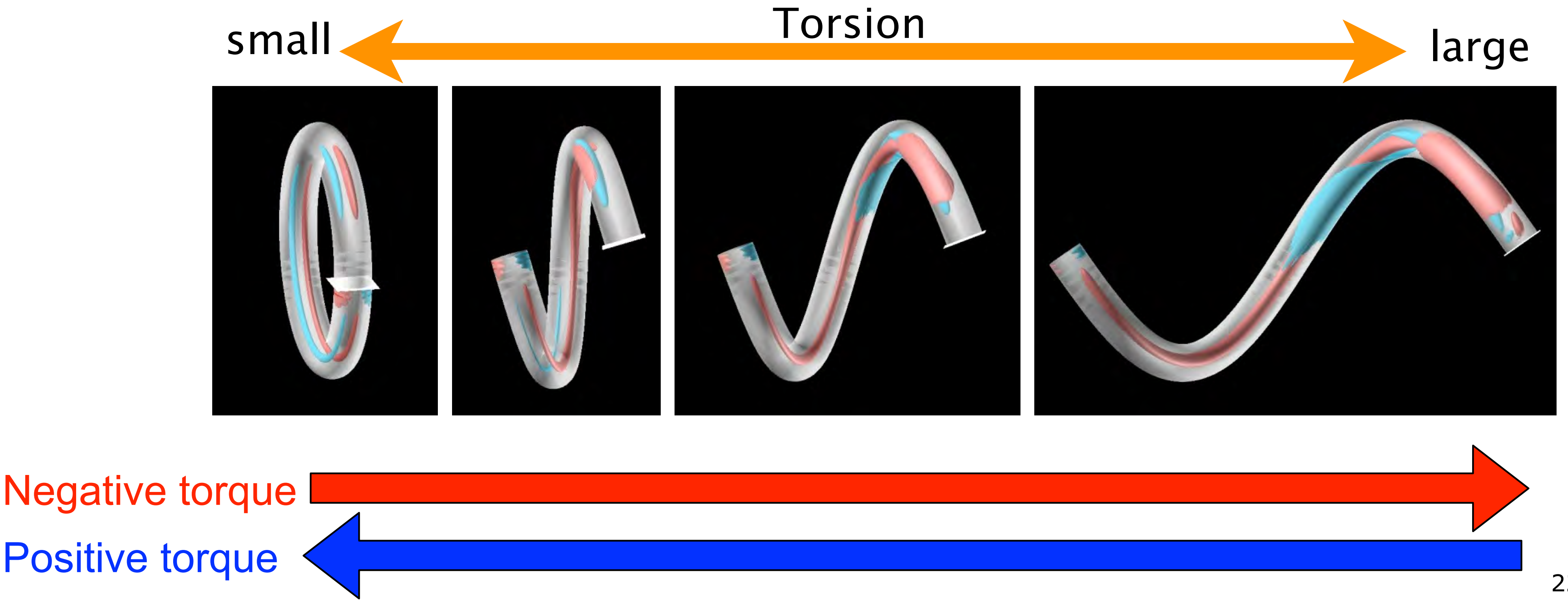


It is apparent that the rod forms a spiral if the positive torque is applied at the end.

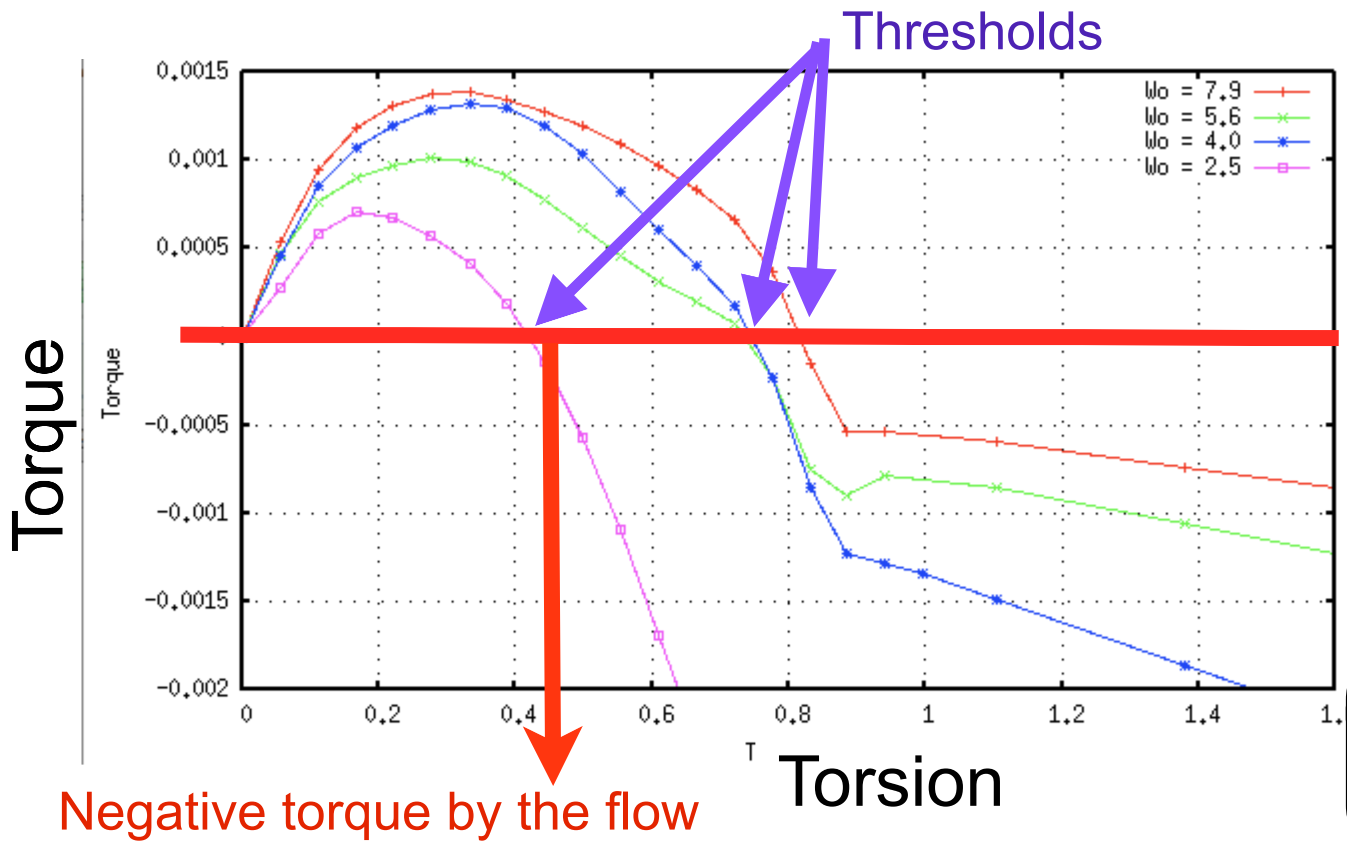
Relation between torque and torsion

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



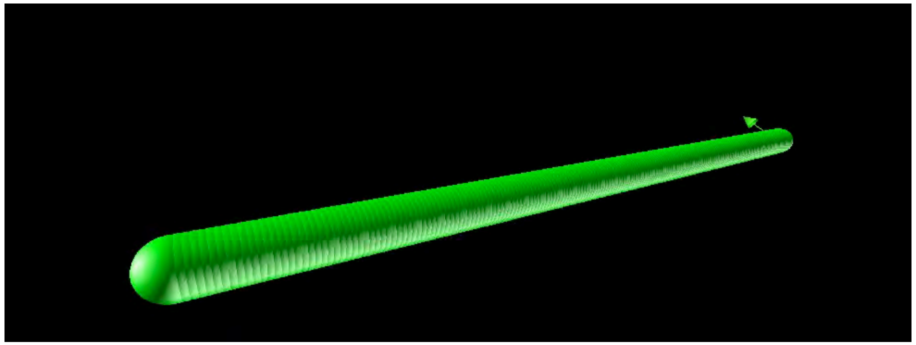


Diagram



- 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.

Fluid dynamics

- Dean's vortices and swirling flow in systolic phase
- Swirling flow remaining to diastolic phase
- Transition from Dean's vortices to swirling flow
- Threshold on torque

↓

Clinical question

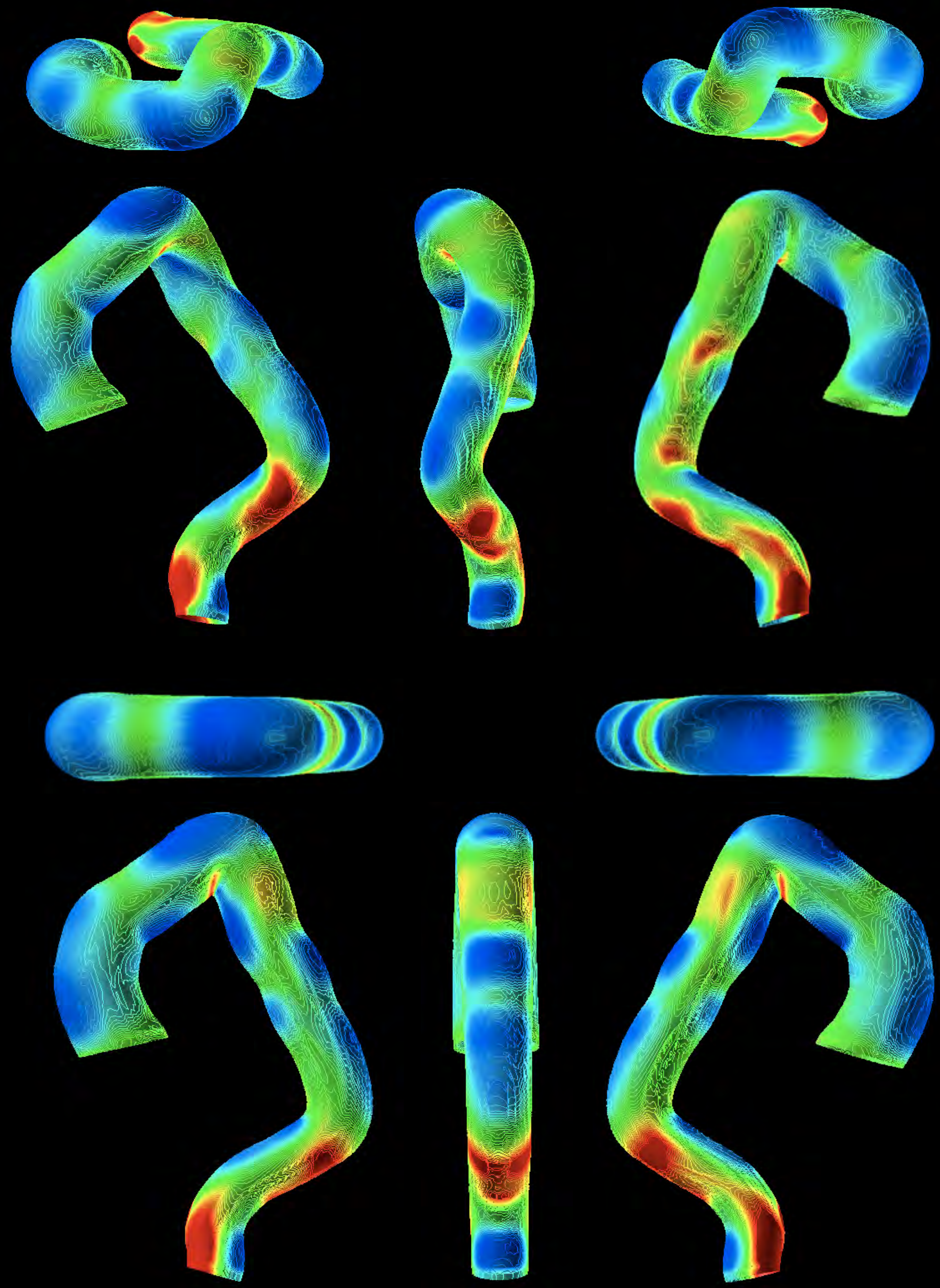
- Where the aneurysms occurred in actual patient cases?
- Is it possible to explain from the morphology and flow behavior?

Comparison for wall shear stress patters for with and without torsion

Original shape

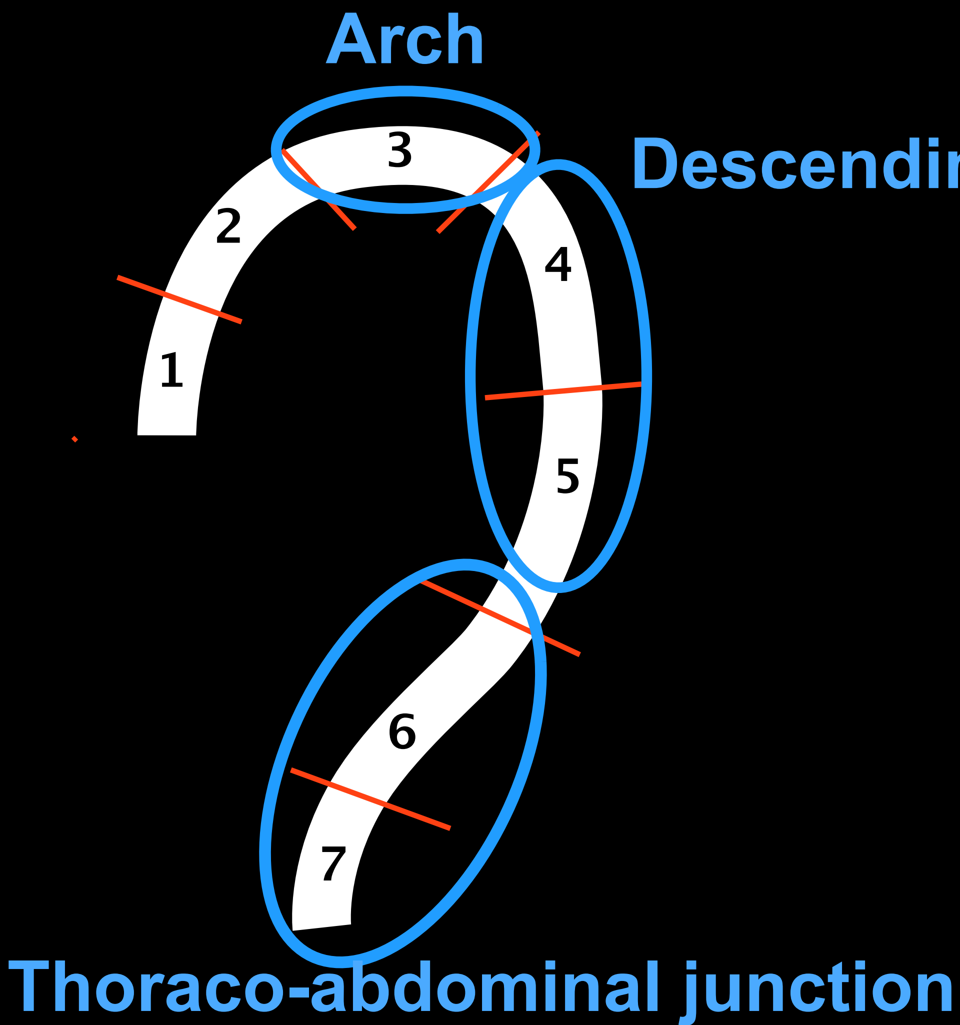
Projection onto a plane of curvature

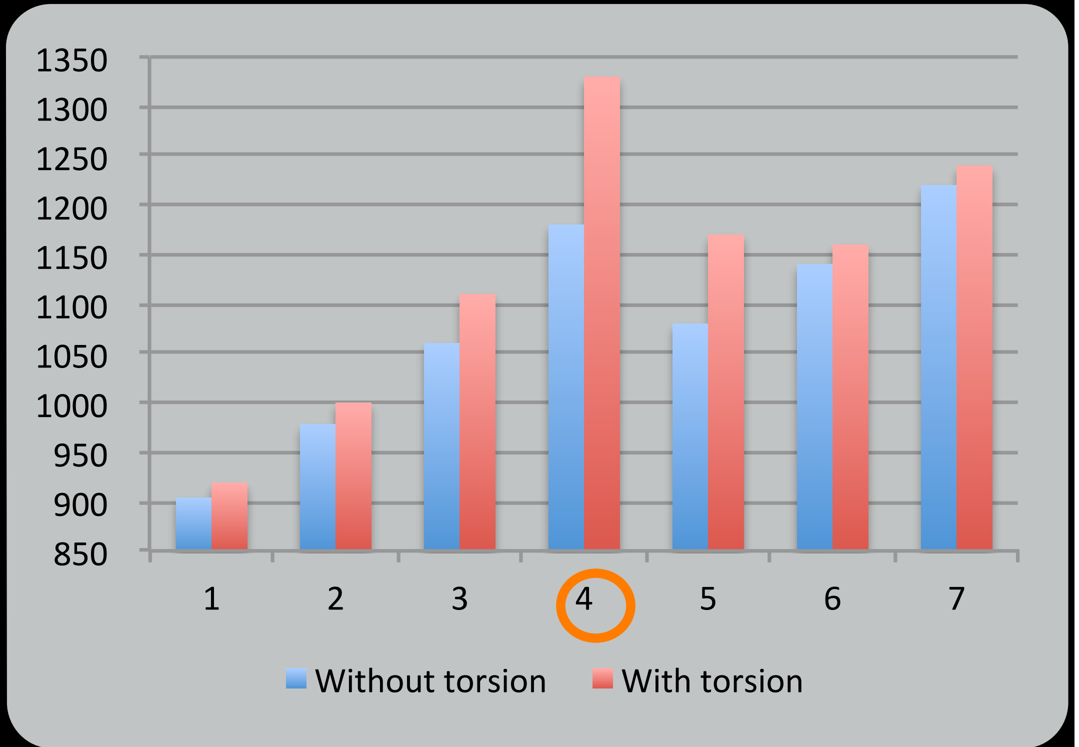
Artificial shape without torsion



Wall shear stress w or w/o torsion

- Divide each thoracic aorta into seven parts from the anatomical point of view.
- Compute average wall shear stress of each part for original and projected shapes
- ◯ indicates the part where the aneurysm developed.



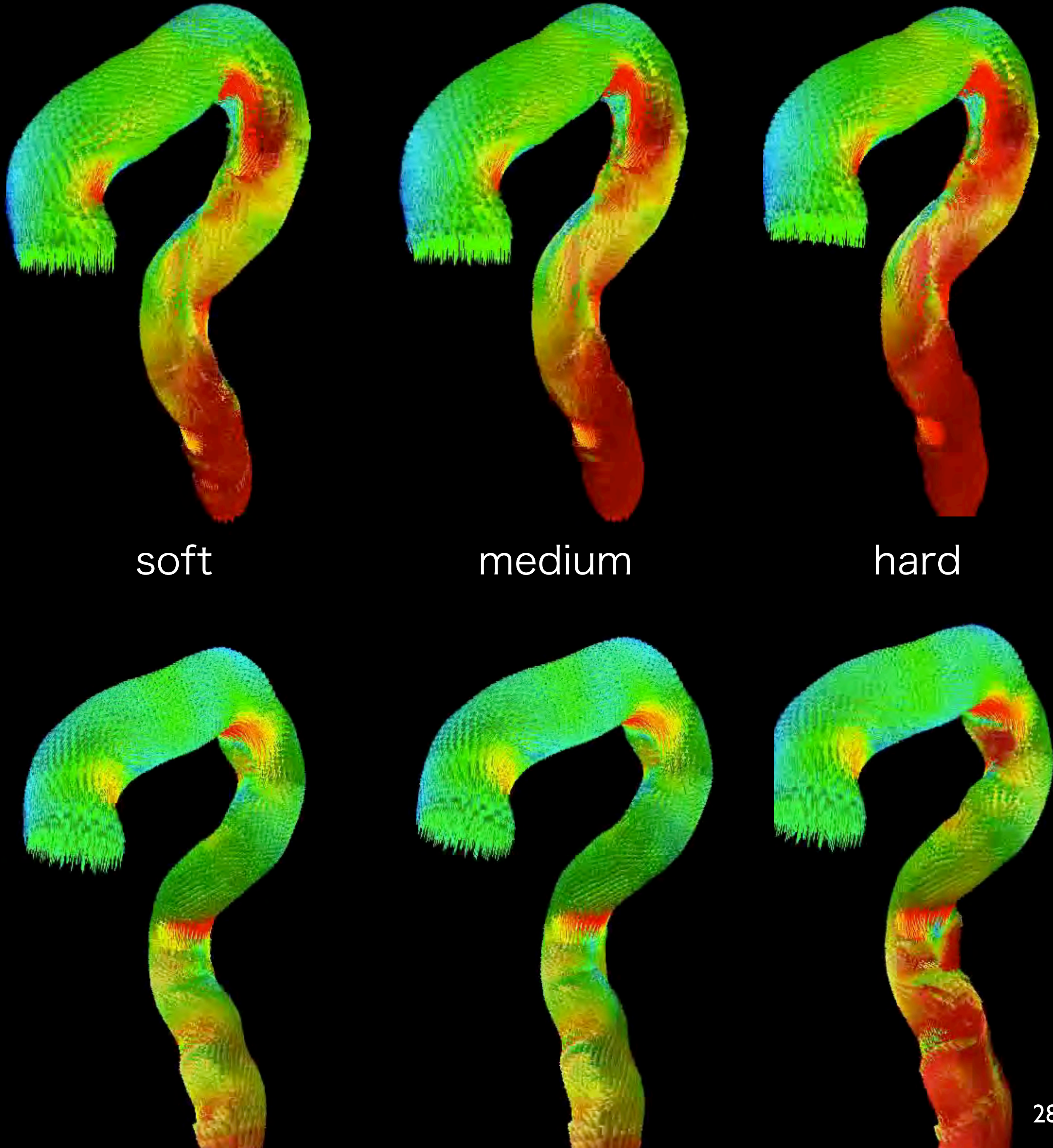


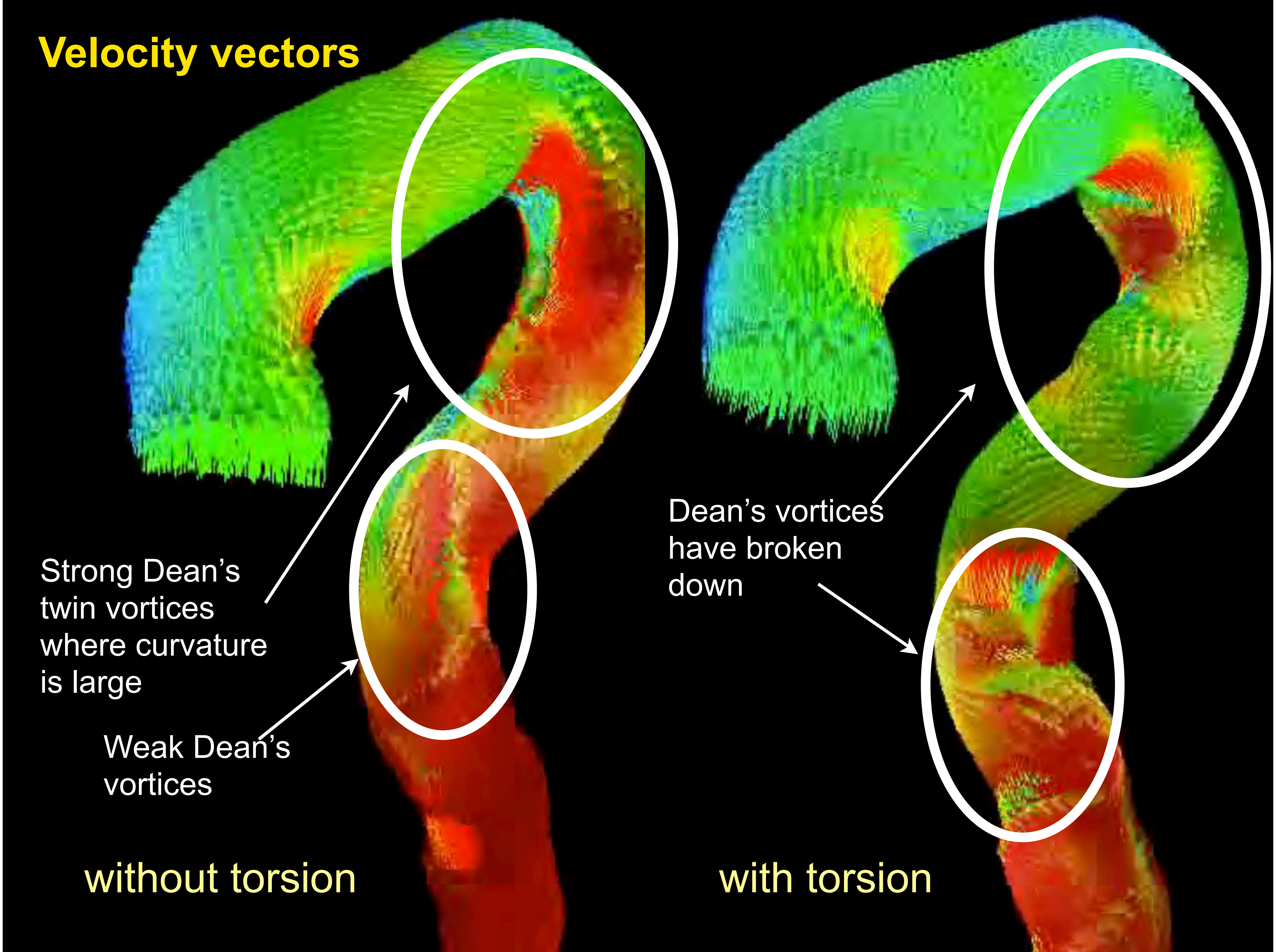

A019
Normal
with torsion
without torsion
A001
A003
A022
Arch
(3)
Desc
(4, 5)
A021
A028
A034
Thoracoabdominal junction
(6, 7)
1
2
3
4
5
6
7

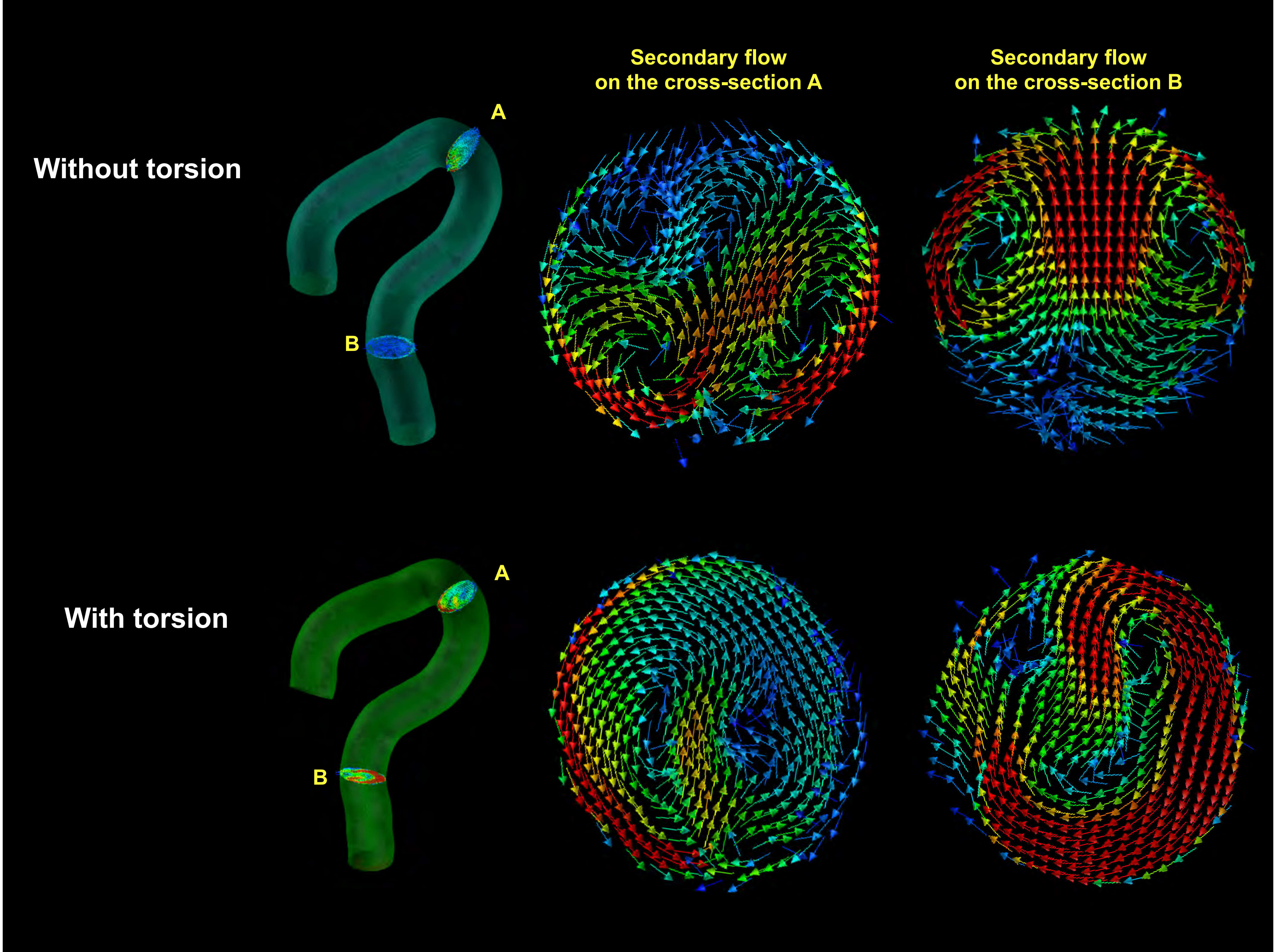
Velocity vectors
considering FSI

without torsion

with torsion



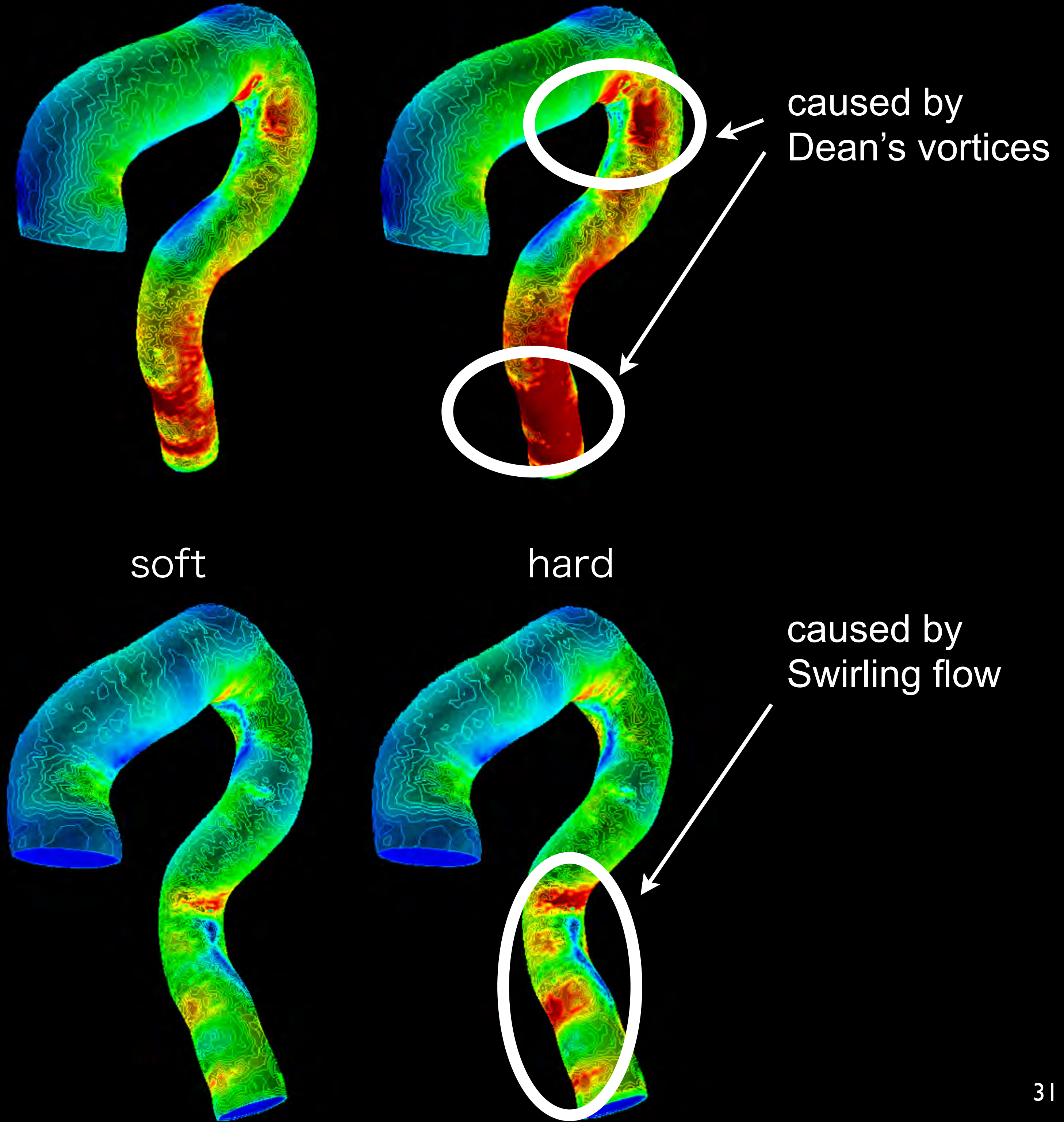

Velocity vectors
Strong Dean's twin vortices where curvature is large
Weak Dean's vortices
without torsion
Dean's vortices have broken down
with torsion



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

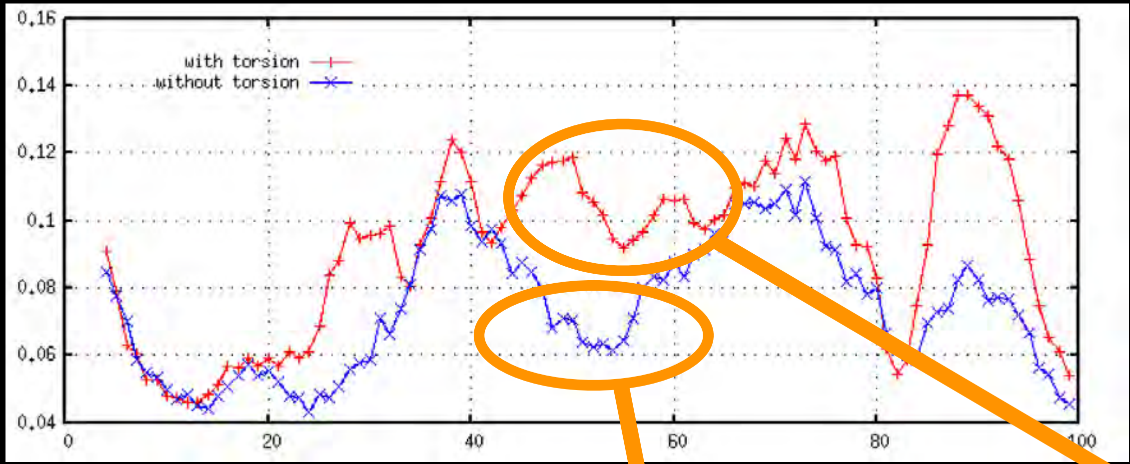
Wall shear stress (at peak systole)

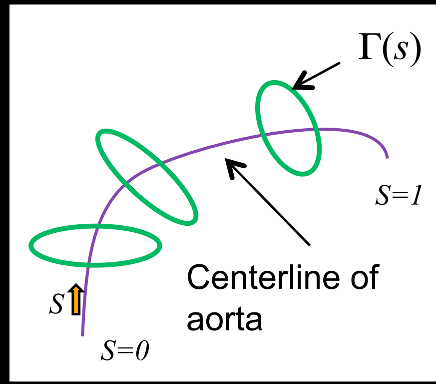
without torsion



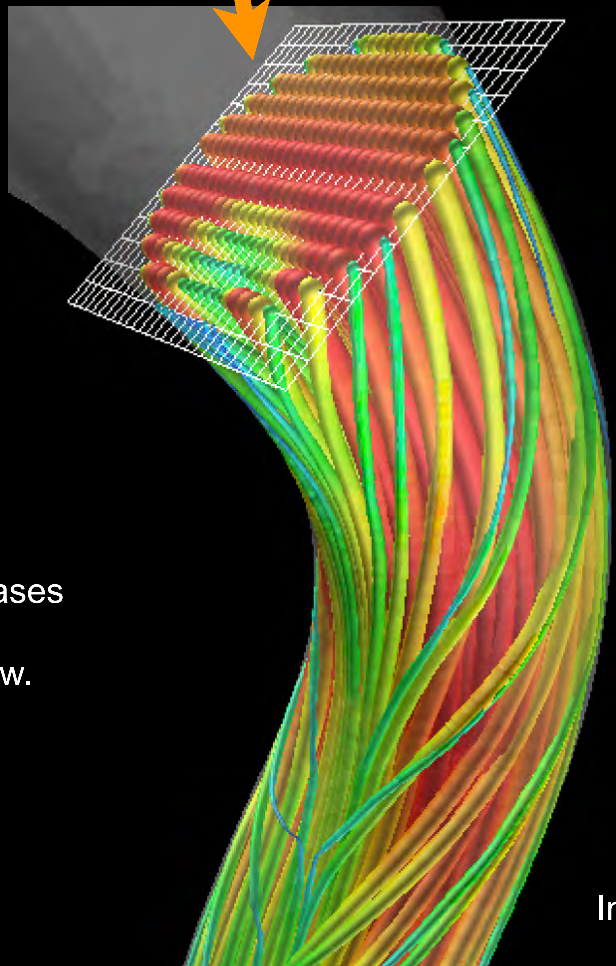
with torsion

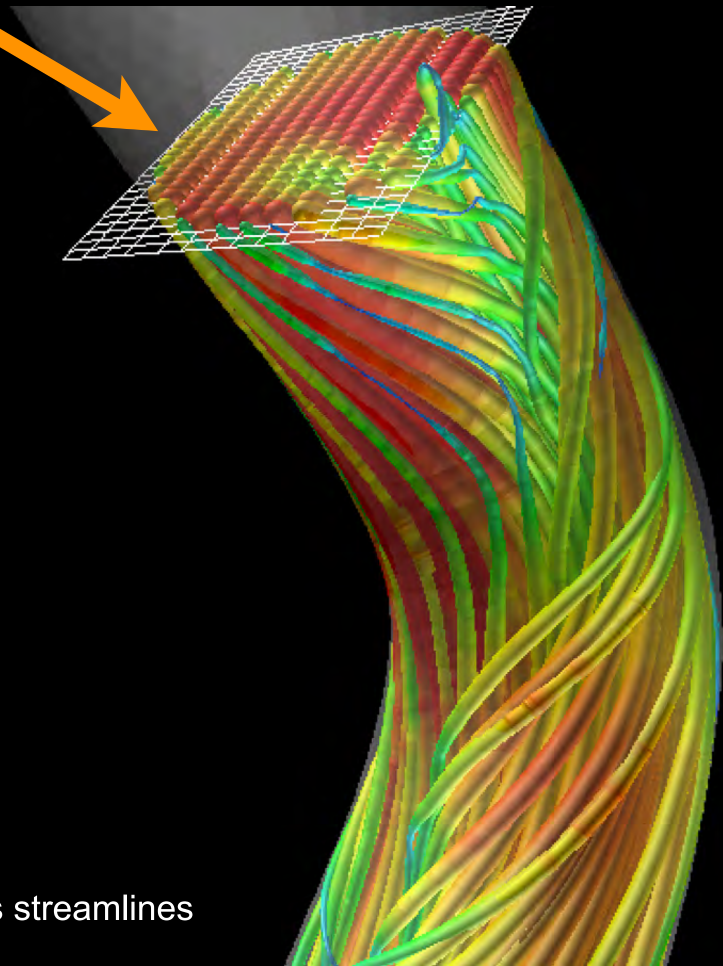
Torsion increases the WSS





Time-averaged wall shear stress



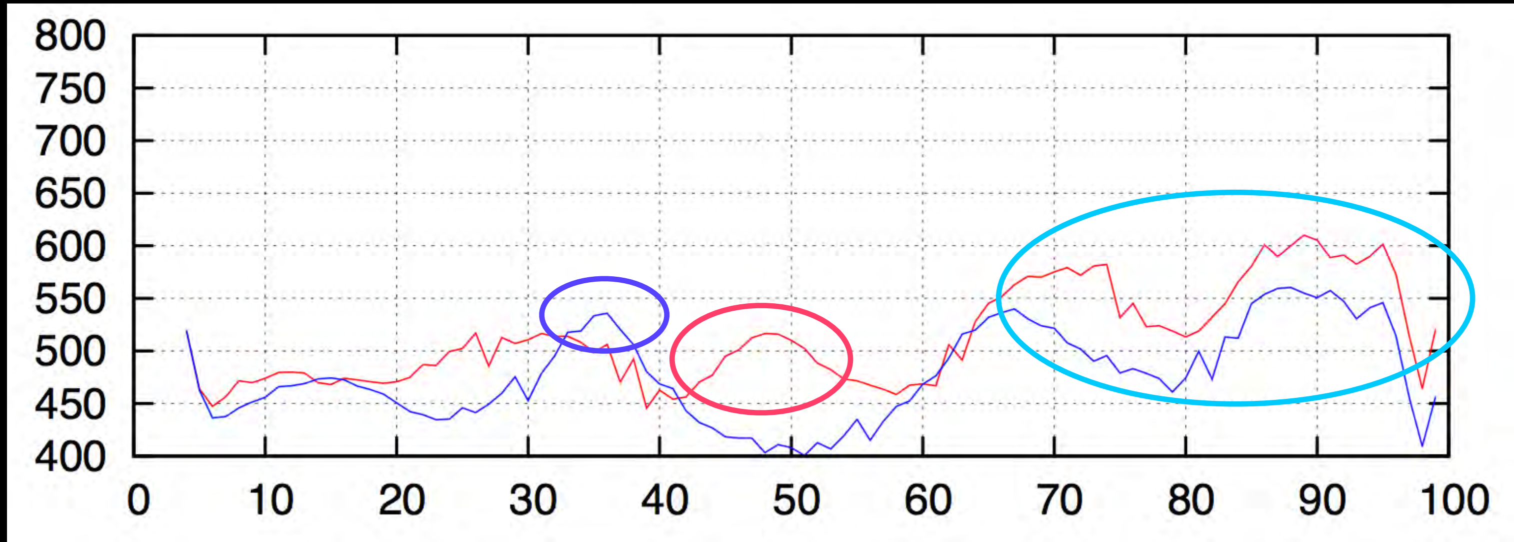


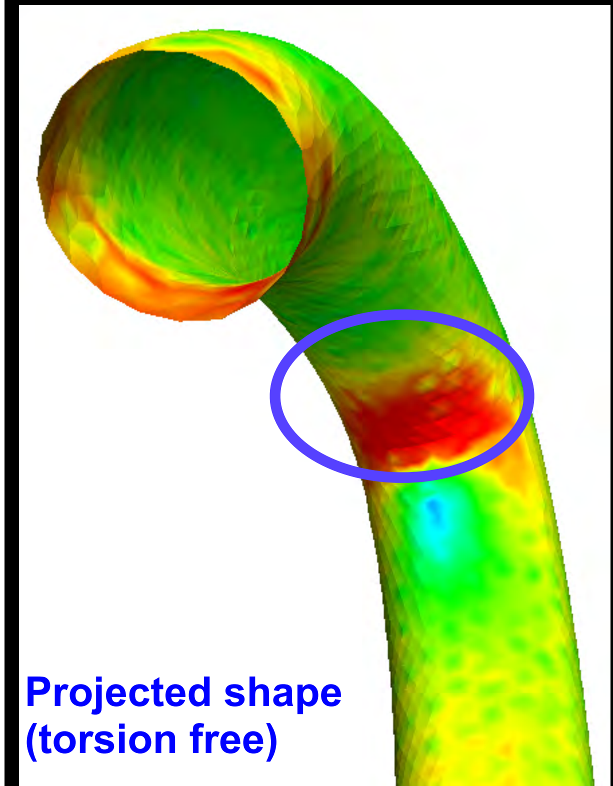
In this case, torsion increases the wall shear stress by generating the swirling flow.

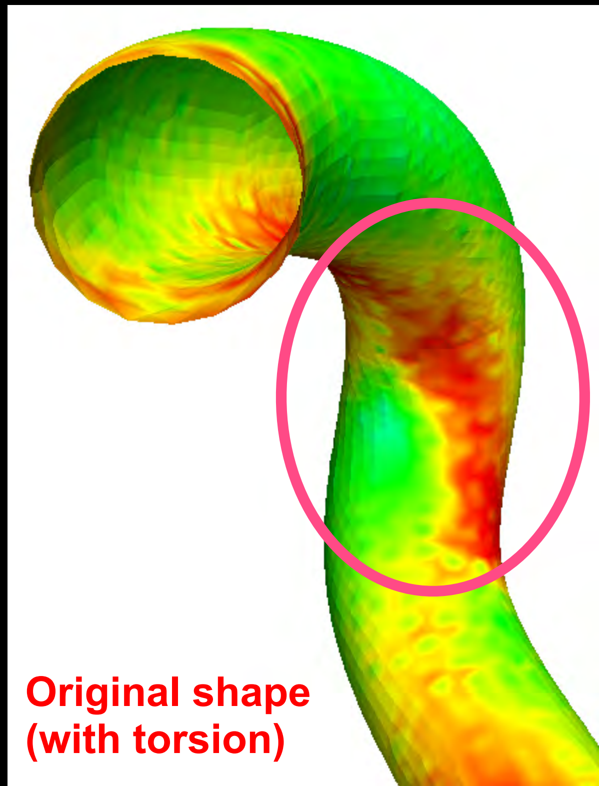
Instantaneous streamlines

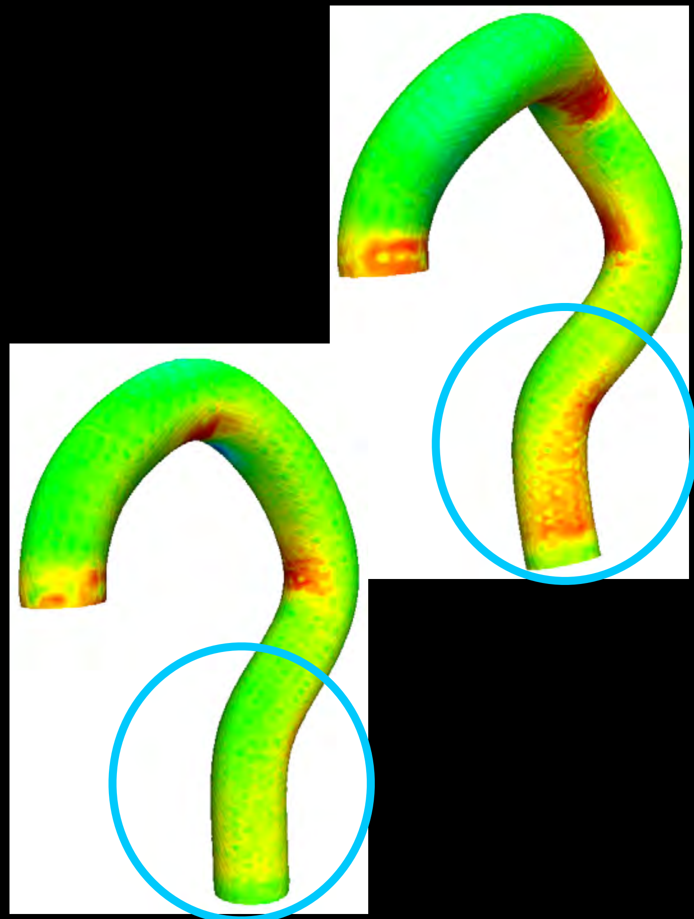
Case A022

In the projected case, high WSS is concentrated around s=35\%, whereas in the original case it expands in a spiral way both upstream and downstream directions.



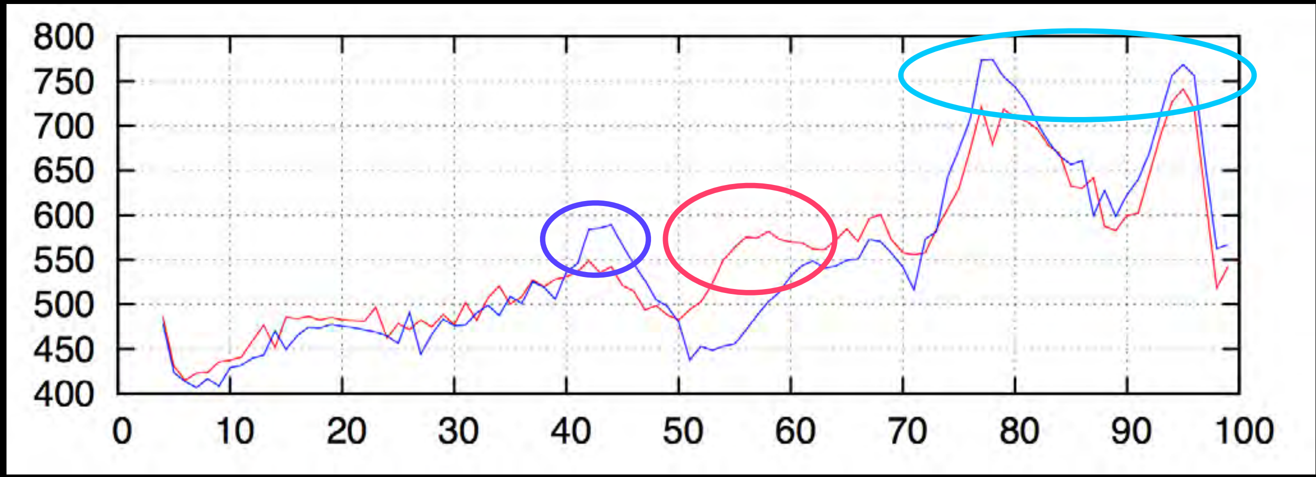


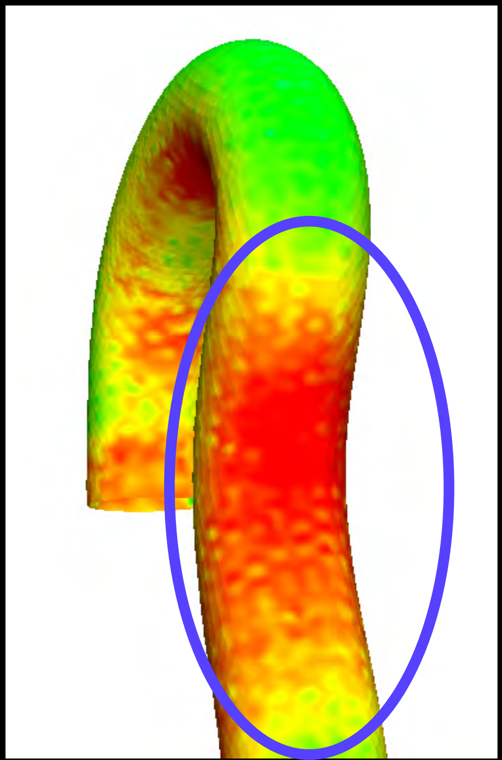


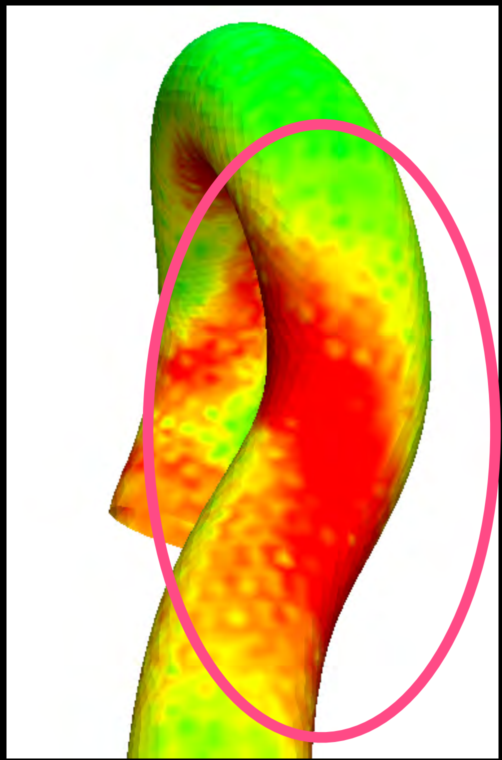


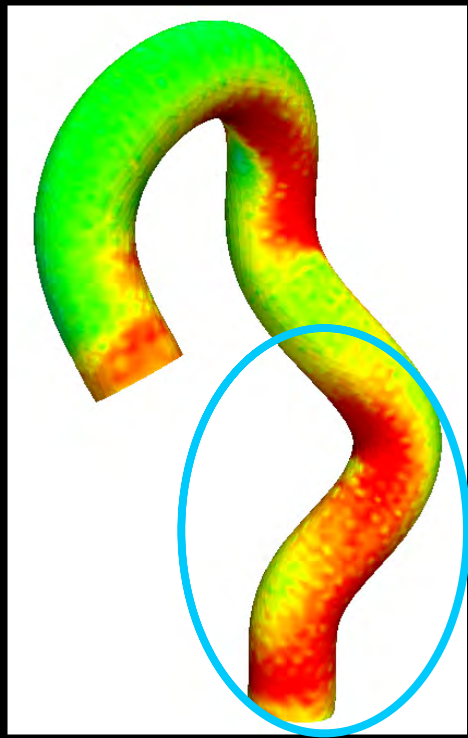
Case A002

In the original shape, the region of high WSS expands in a spiral way.

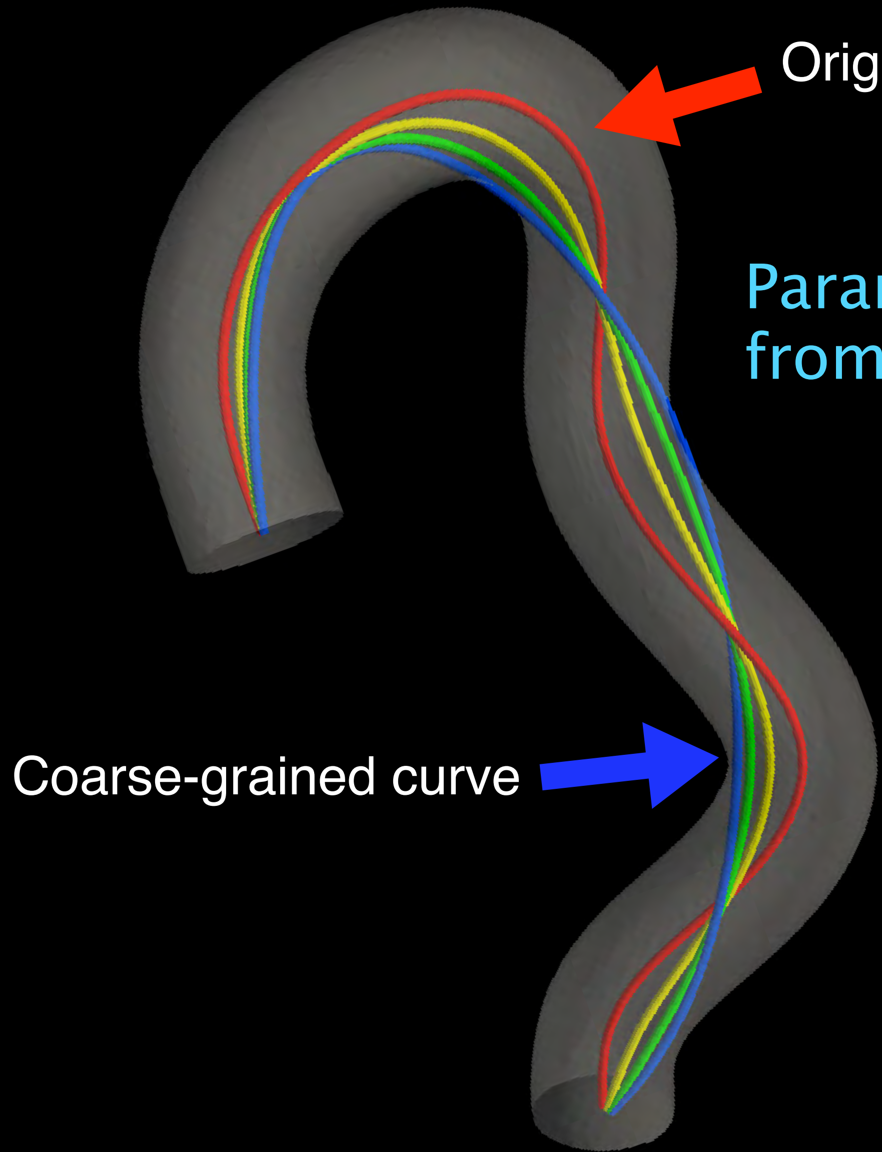




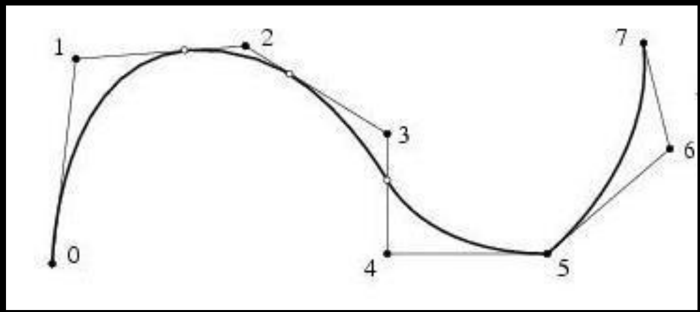




Parameterization of aorta shapes to understand the flow structure and wall shear stresses



Parameterization using deviation from the coarse-grained curve

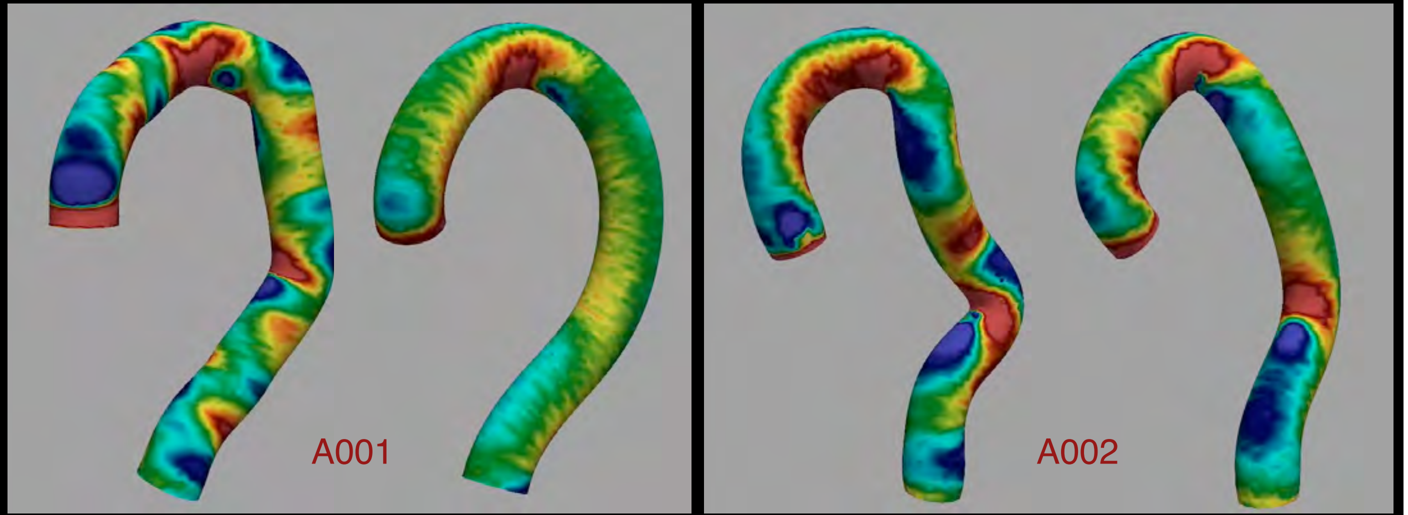


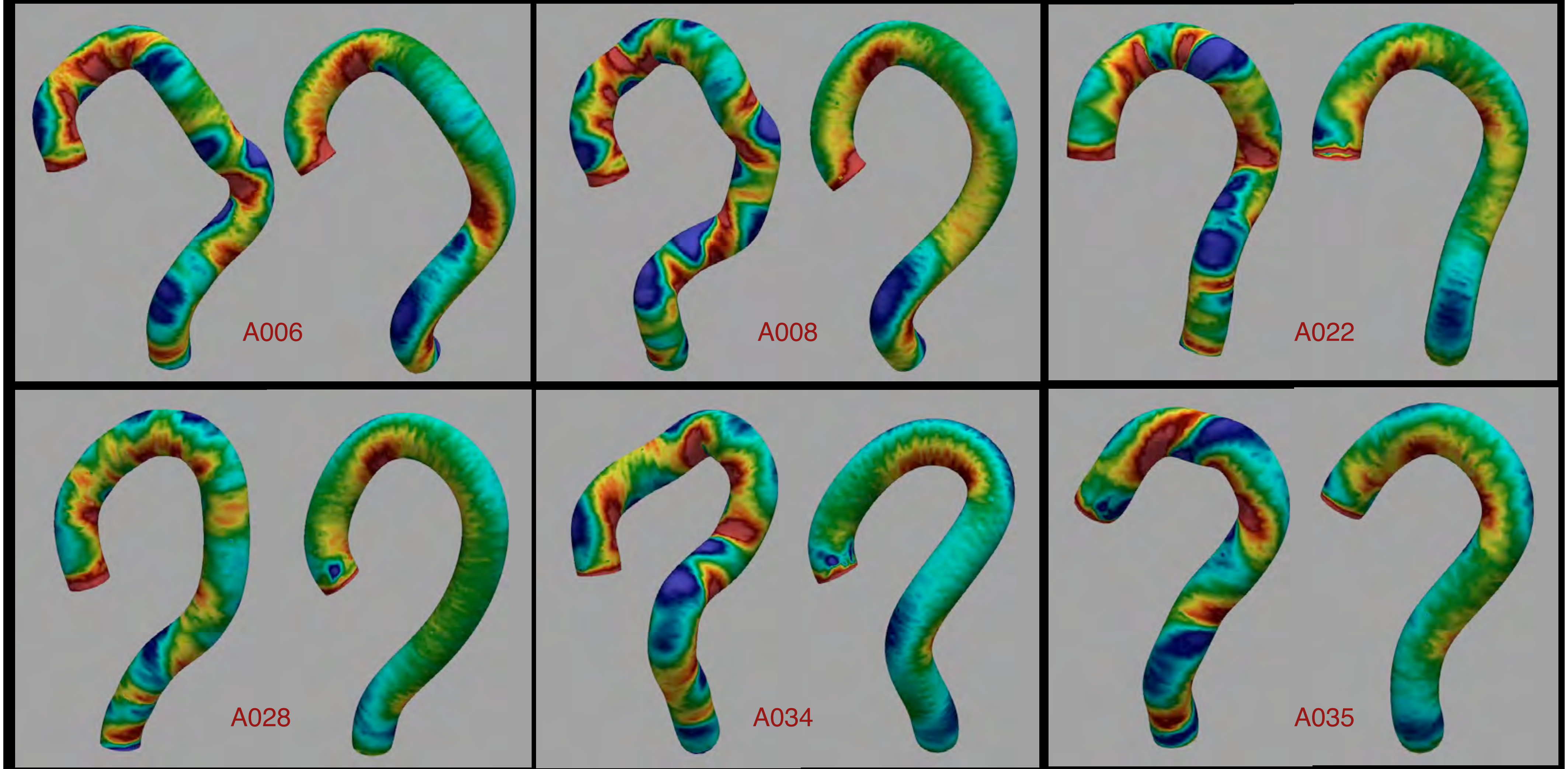
based on NURBS representation

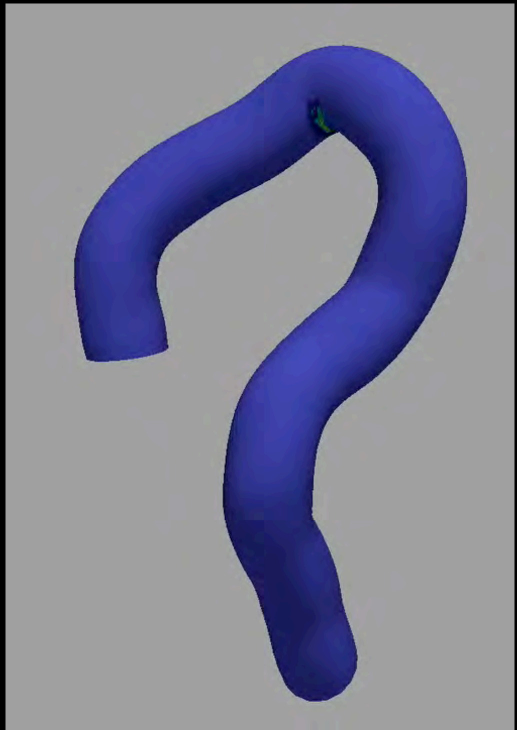
(NURBS: Non-Uniform Rational Basis Spline)

Comparison for WSS

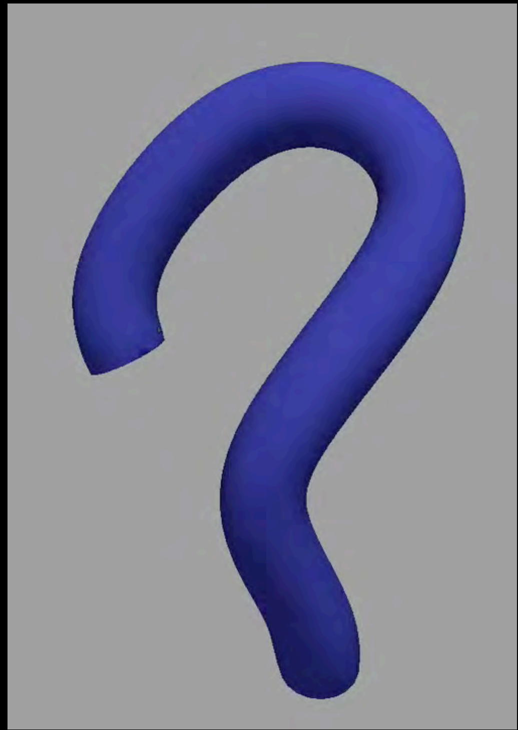
Left: original shape
Right: coarse-grained shape



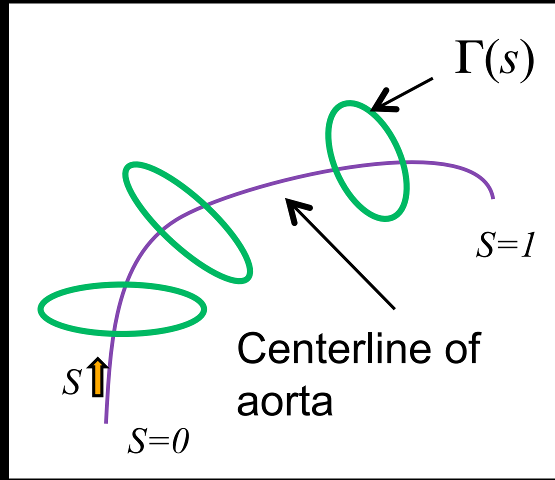




Original shape

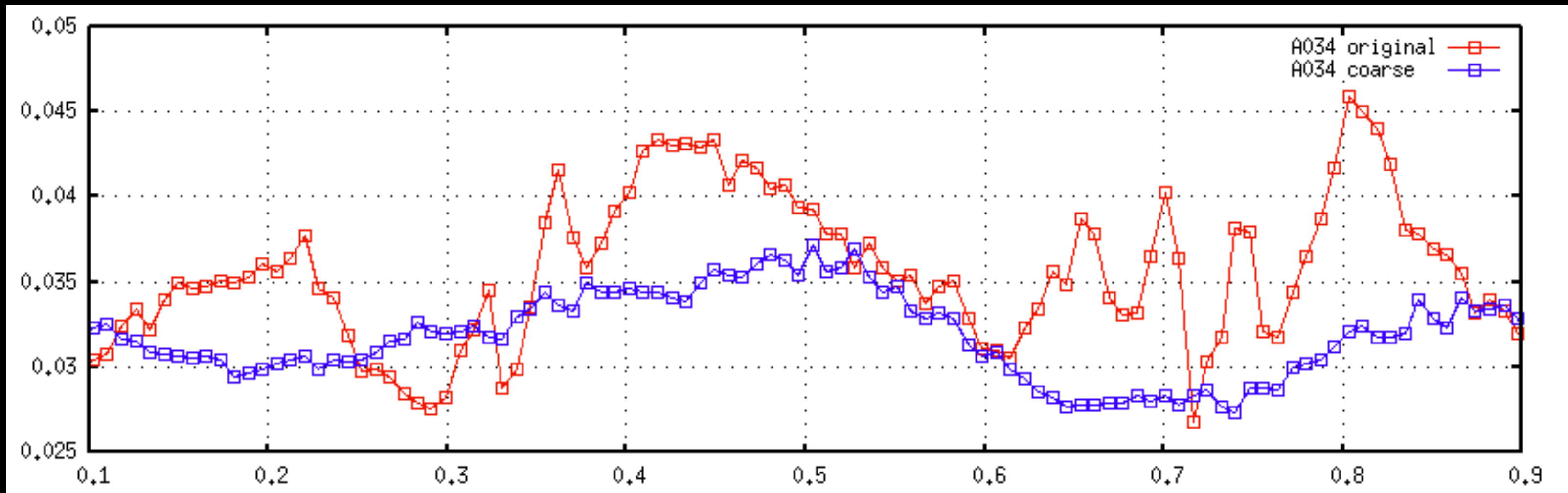


Coarse-grained shape



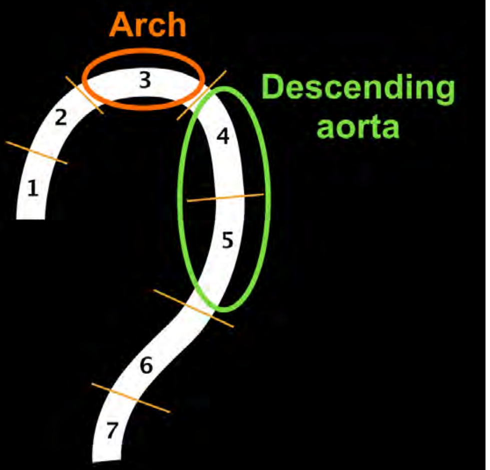
$$\tilde{\sigma}(s) = \int_{\Gamma(s)} \int_0^T |\sigma_\tau| \, dt \, d\Gamma$$

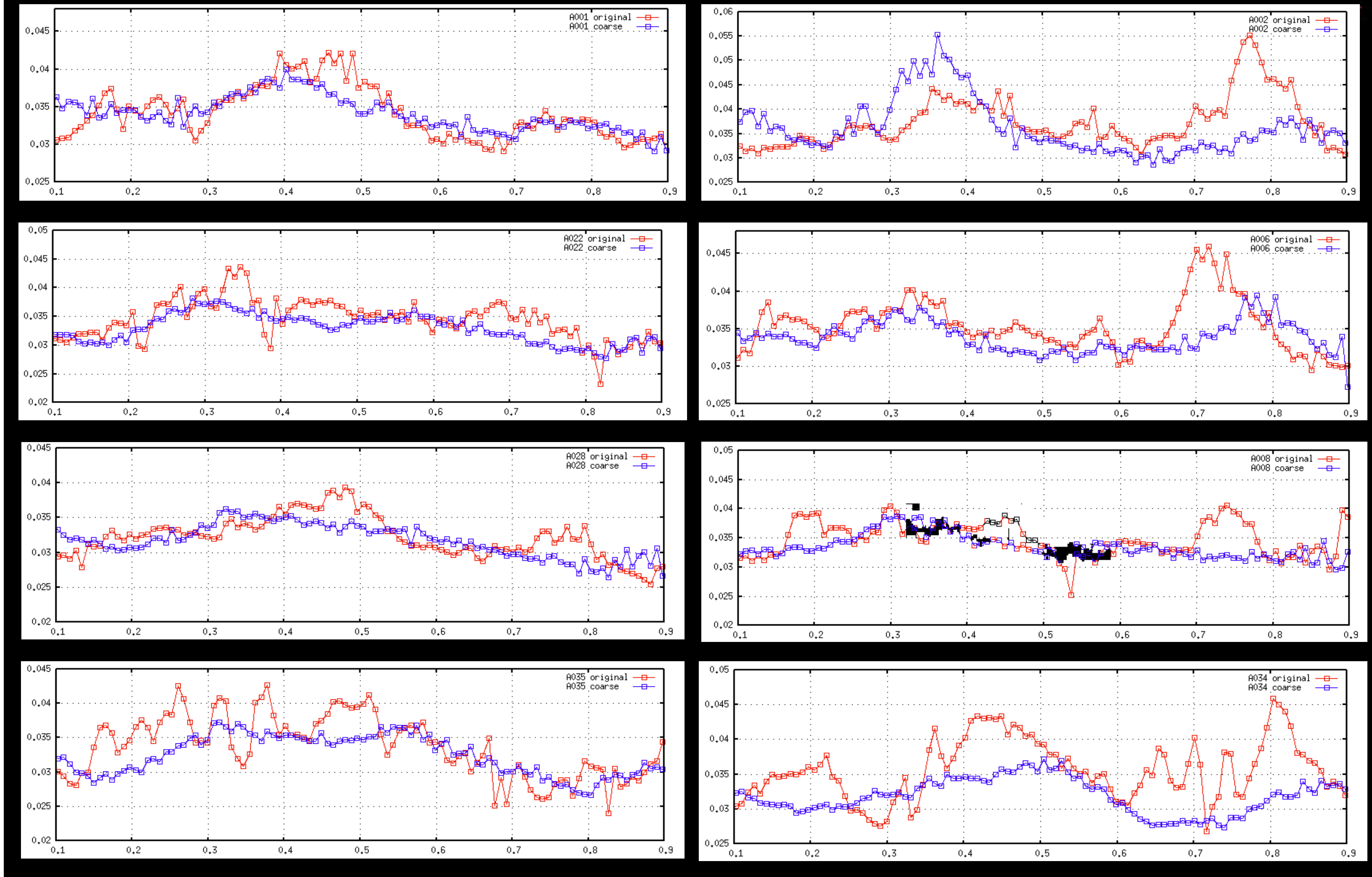
$\tilde{\sigma}(s)$



s

Patient cases can be classified in locations where the aneurysm developed

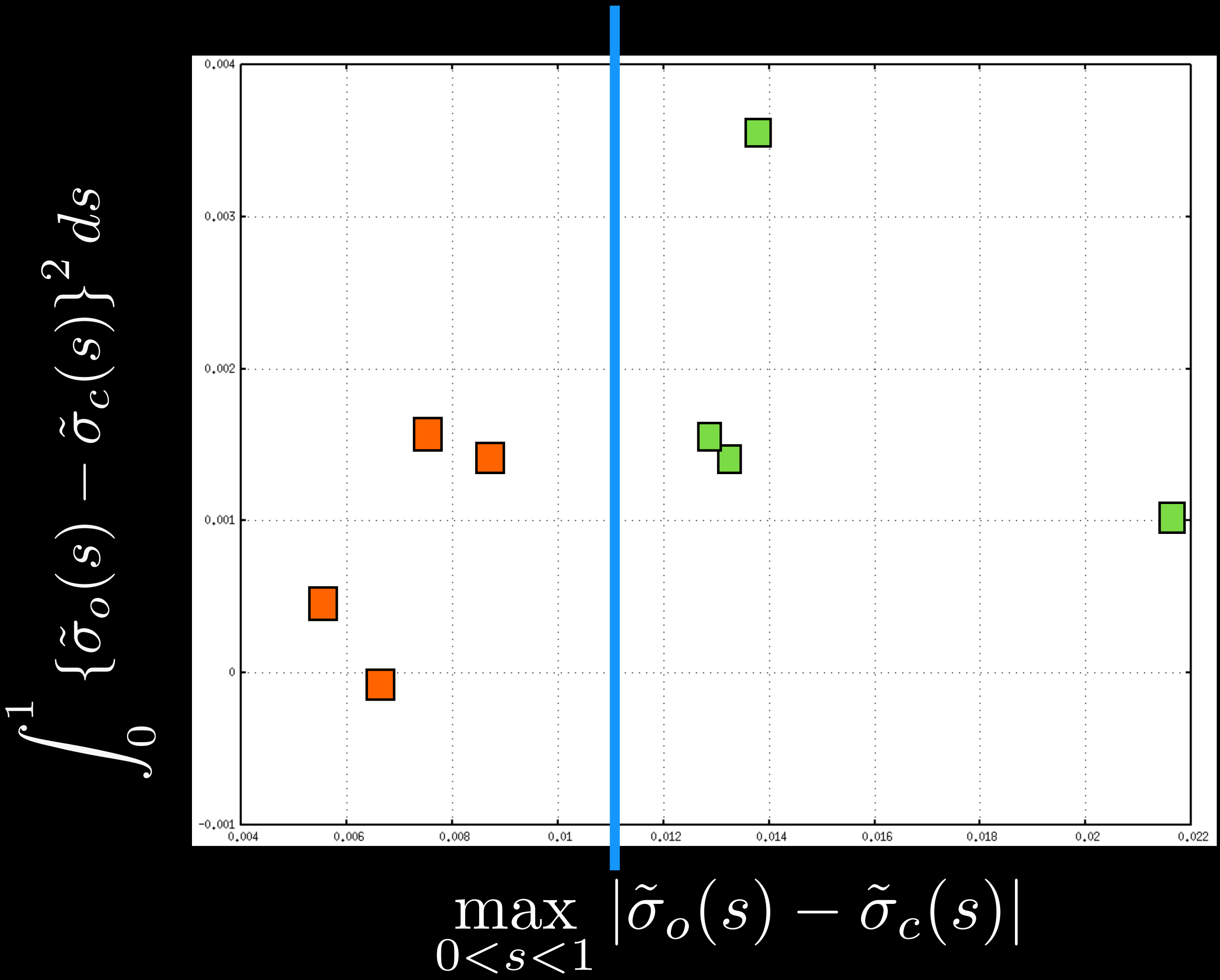


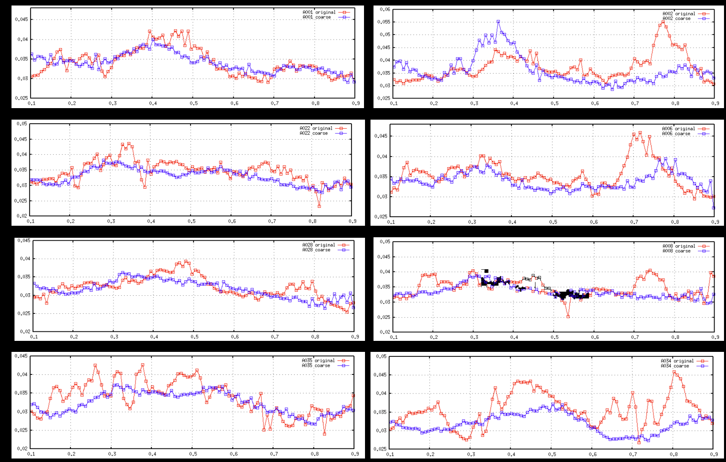


developed on aortic arch

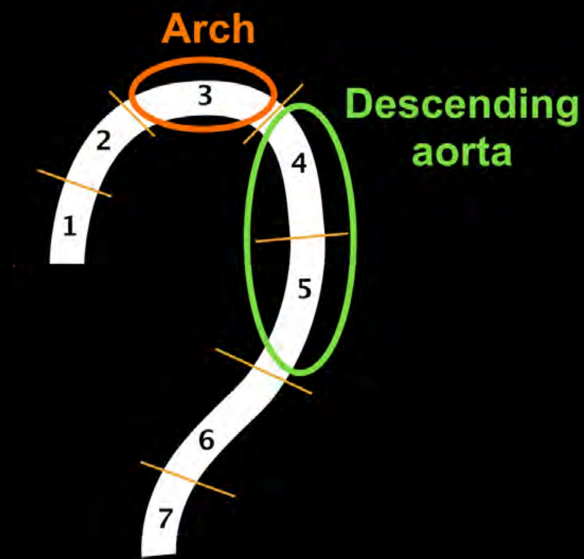
developed on descending aorta

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





on aortic arch   on descending aorta



■ Patient cases with the aneurysms on the aortic arch

■ Patient cases with the aneurysms on the descending aorta

Conclusions

We have examined the relationship between aorta morphology and WSS distributions.

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

Difference among individuals for curvature : small

Difference among individuals for torsion : large

- Clinically important characteristics of the aorta morphology can be represented by the difference between coarse-grained and original morphologies.

Medical doctors can classify the patients from morphological characteristics