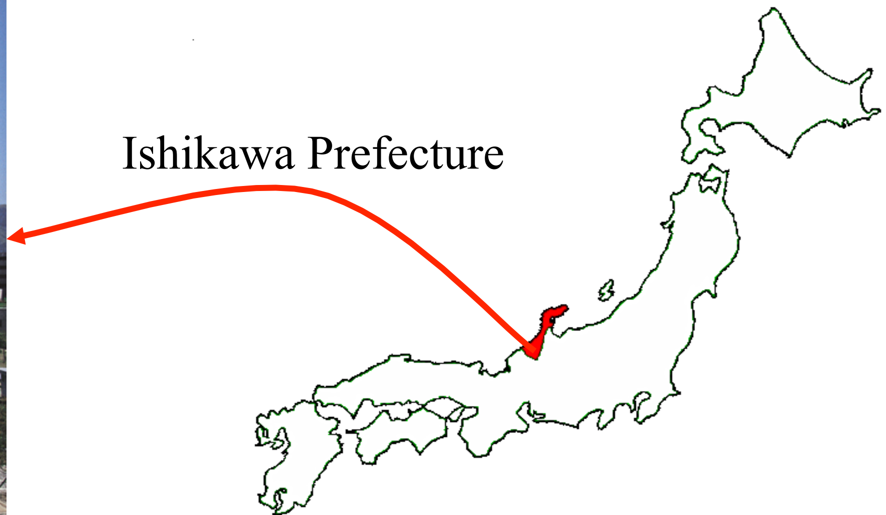
Golden Nuggets of Discovery 2011 (CUG 2011)
Fairbanks, Alaska
May 23-26, 2011

Information Environment in JAIST

Teruo Matsuzawa
(Research Center for Advanced Computing Infrastructure,
Japan Advanced Institute of Science and Technology)



Outline

- JAIST Introduction
- JAIST Research Center for Advanced Computing Infrastructure (RCACI)
- Our Laboratory Activities
  - Air-Flow Simulation in Nasal Cavity
  - Blood Flow Simulation in Thrombosed Aortic Dissection
  - Blood Flow Simulation in Aneurysm with STENT
  - Heart Simulation using Medical Images Voxel Based Fluid-Structure-Cell Interaction Analysis
  - Summaries

JAIST Information

Location

Located in Ishikawa,

an hour's flight from Tokyo

JAIST's Aims and Features

Founded in 1990 to pursue the most advanced graduate education and research in science and technology in Japan.

Advancement of Students

Education

Systematically designed curriculum & course-work

Outstanding Academic Environment

- Scholarships
- Dual Education
- Dual Degrees

Production of Core Researchers

Research

World-class

Active Faculties, Excellent Lab Facilities, International & Open Environment

Contribution to society as a world-class institute of higher education

JAIST pursues

- Accumulation of outstanding scholarly achievements, based on organized research activities of the highest quality
- Systematic education program for future leaders who will serve the welfare of humankind
- Advanced education and research through active collaboration and cooperation among academia, government, and industry

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1990

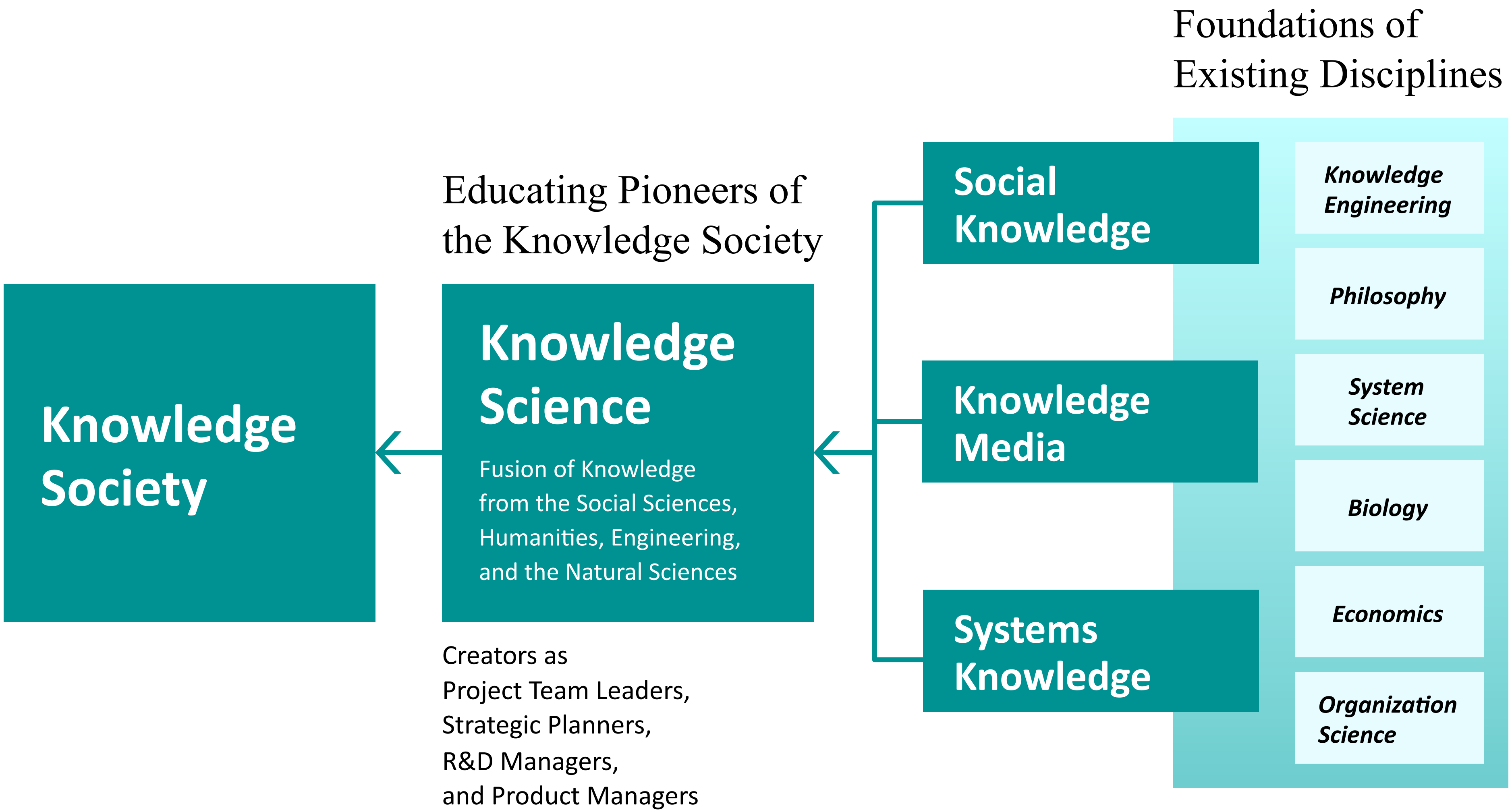
Three Schools

Knowledge Science

Information Science

Materials Science

School of Knowledge Science



School of Information Science

Japan's Largest Education and Research Institute Specializing in Information Science

- Theoretical Information Science
- Human Information Processing
- Artificial Intelligence
- Computer Systems and Networks
- Software Science

Advanced Information Systems

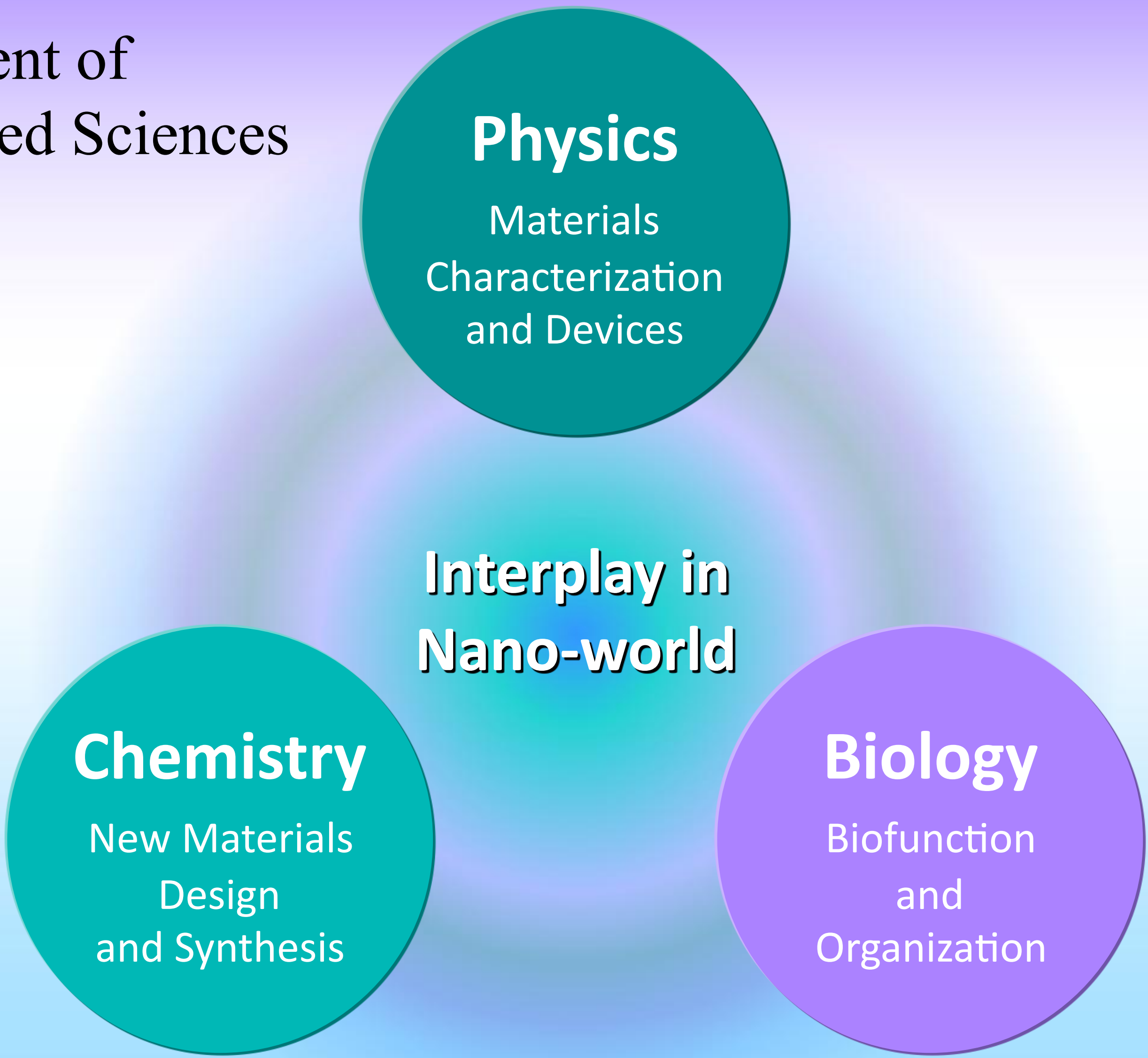
Cray XT5 massive parallel processing system

SGI Altix 4700 high-speed database processing system

Campus Network 10-Gigabit backbone, high-speed access available everywhere on campus

School of Materials Science

Development of
New Applied Sciences



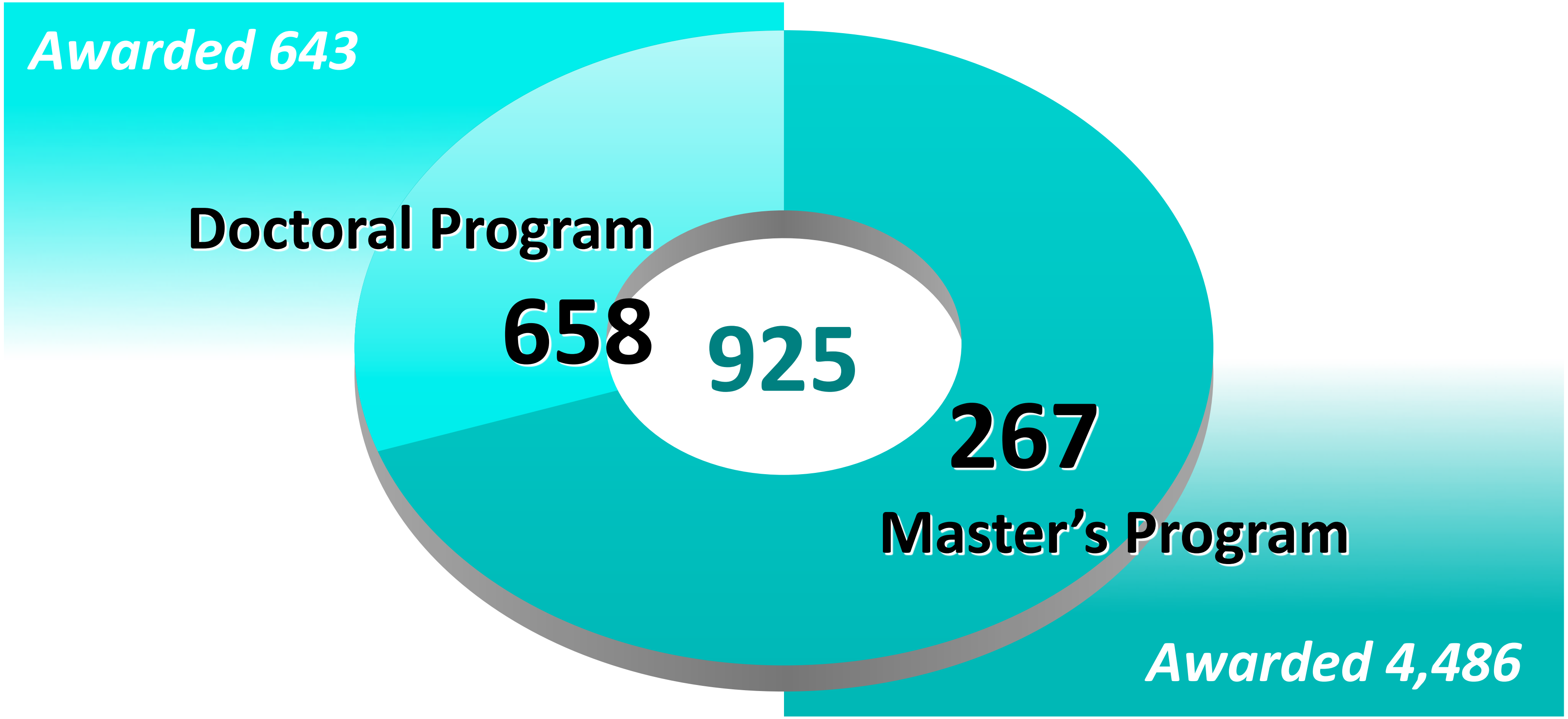
Education in a Bilingual Enviroment

- 25% international students
- 15% non-Japanese faculty

Courses at doctoral level are taught in English !!

A Good Balance of Students

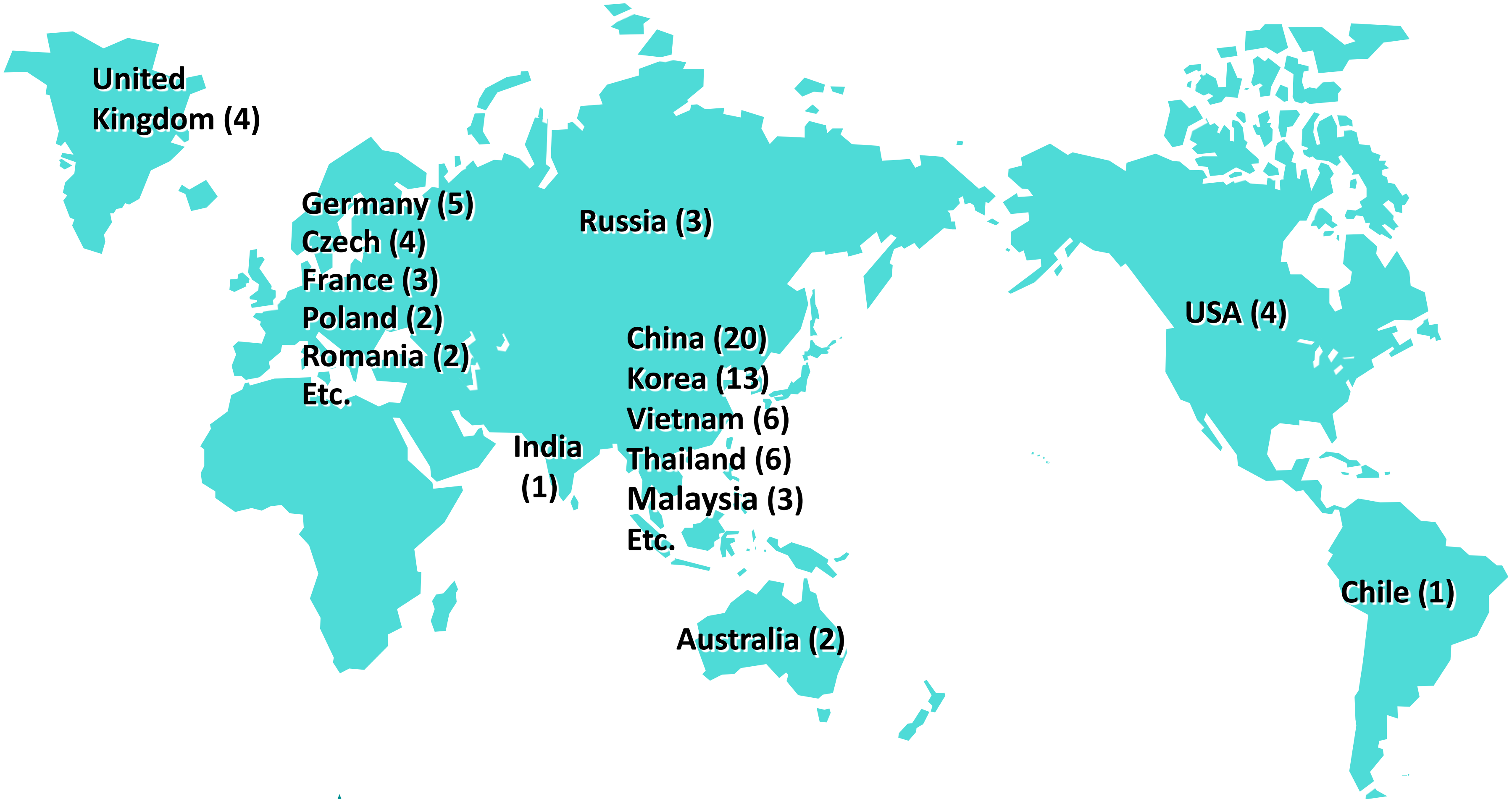
As of April 1, 2011



✸ Students from abroad (26%)

Academic Exchanges

As of April 1, 2011



91 institutions in 26 foreign countries

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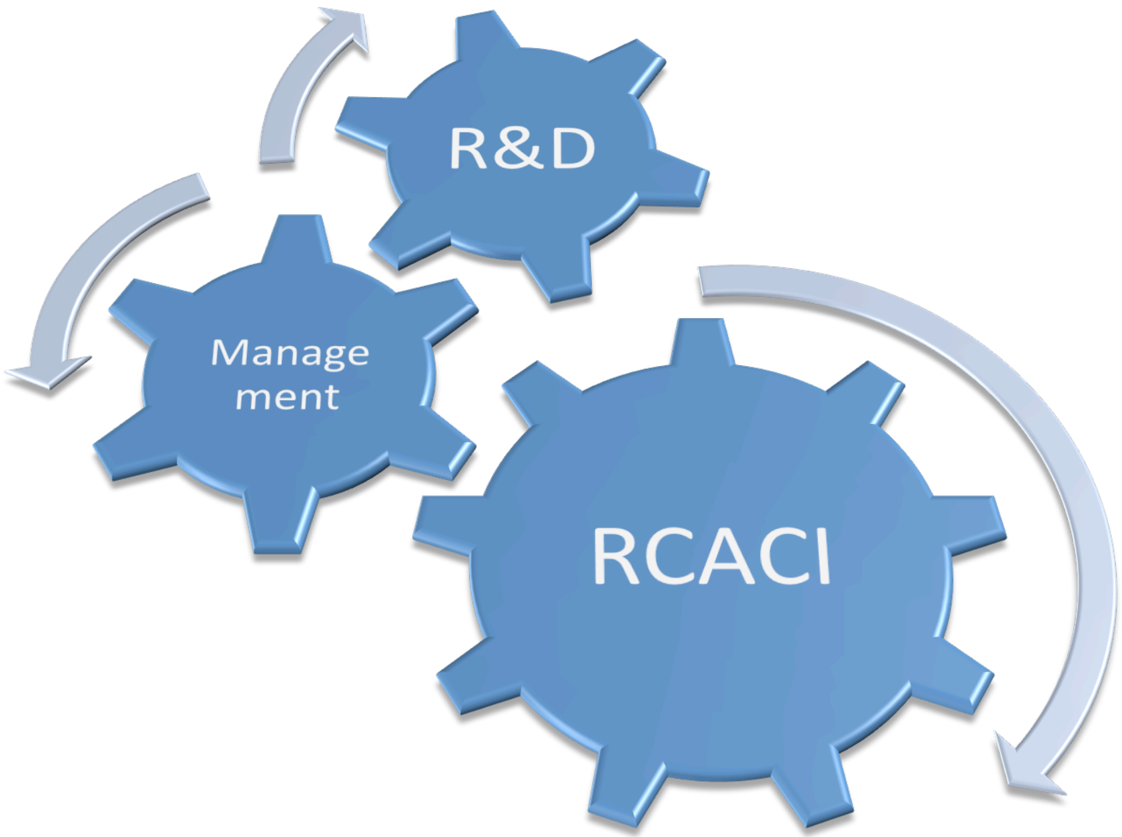
JAIST Research Center for Advanced Computing Infrastructure

Role of RCACI

- Addressing various needs from education and research of advanced science and technology area, we build, manage and provide the world class information and communication environment such as;
  - High speed and highly-available network
  - High performance and large scale storage
  - Large scale & high performance MPC's
  - Highly-secured environment

RCAIC Organization



RCACI Operation Group

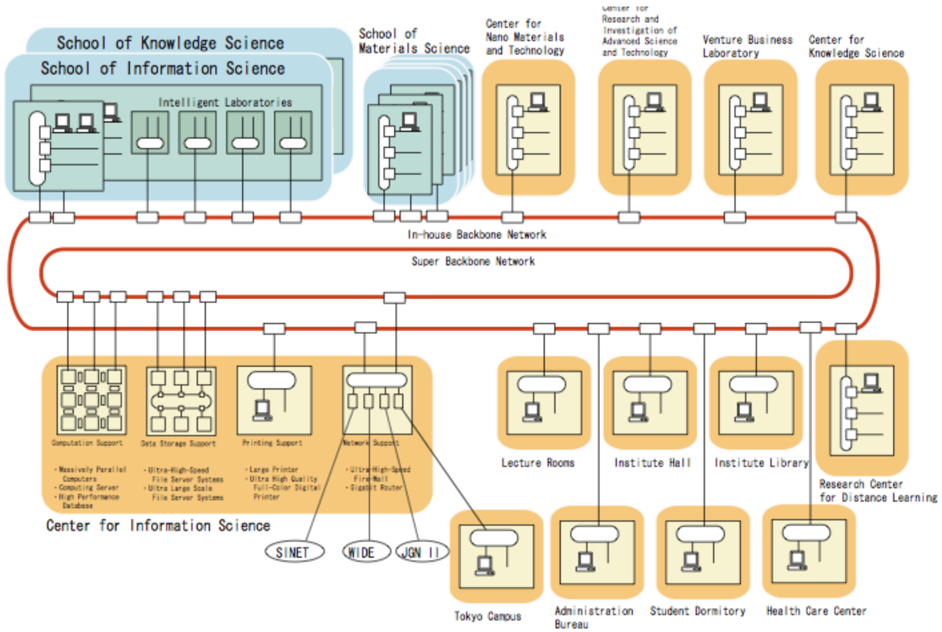
- Providing well balanced and high level ICT service, and ongoing quality enhancement for Knowledge, Material and Information science education/research activities, library and administration sections
- Building and operating ICT system as a leader among ICT centers of Japan
- Contribution to world class network building

RCACI R&D Group

- Develop challenging technology for supporting ICT based society, and provide vast demonstration experiments on technology
  - Next-generation complex ICT system (Cloud)
  - Next-generation network for internet
  - MPC system development for supporting education & research of advanced science and technology
  - Security technology to realize the ease & safe ICT society

Network

Network in Compus	Performance
Campus Backbone	10 Gbps
Floor connection	1 Gbps
Internet connection	Sinet4 10 Gbps and Wide 10Gbps
Wireless connection	All over campus, including dormitory (IEEE801.11 b/g/n)



Storage

Storage System	Capacity
SGI /Onstor	For /user home, 101 TB Total
Dell Equal Logic	For /user home, 159 TB Total
DataDirect Networks	For /projects etc, 881 TB Total
EMC	For administration, Disaster Recovering in remote location

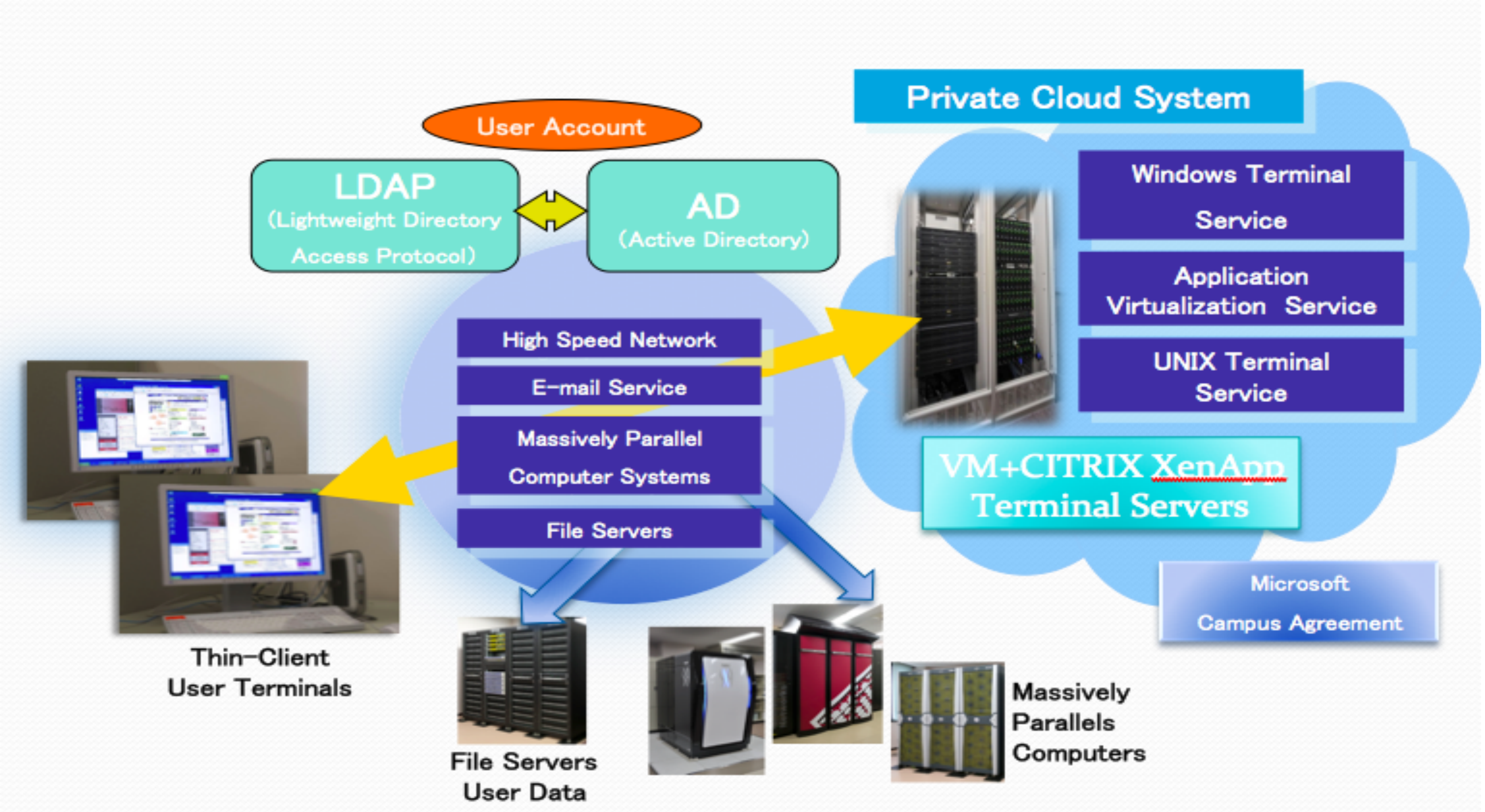


MPC

System	Configuration & Performance
Cray XT5	AMD Opteron 2048-core, 4TB Memory, 19.6 TFLOPS
SGI Altix 4700	Itanium2 192-core, 2.3TB Memory, 1.2 TFLOPS
SGI Altix XE Cluster	Xeon 40-core/5-node, Xeon 8-core & Altea Stratix III x 3/1-node
NEC SX9	4-cpu, 256GB Memory, 409.6 GFLOPS
Appro PC Cluster	Xeon 512-core/64-node/1.5TB & 192-core/8-node/1TB
IBM QS22	PowerX cell 8i 16-cpu/8-node/64 GB Memory



Private Cloud System (2010)



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SC1X since 2007

Year	City, State
SC07	Reno, NV
SC08	Austin, TX
SC09	Portland, OR
SC10	New Orleans, LA
SC11	Seattle, WA

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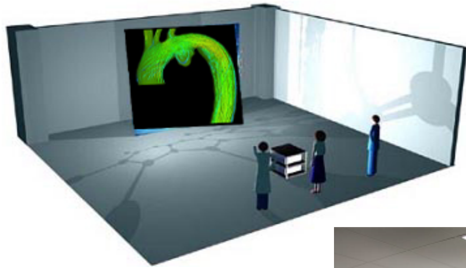
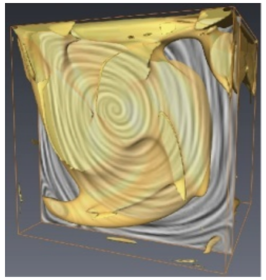
Our Laboratory Activities

- Air-Flow Simulation in Nasal Cavity
- Blood Flow Simulation in Thrombosed Aortic Dissection
- Blood Flow Simulation in Aneurysm with STENT
- Heart Simulation using Medical Images Voxel Based Fluid-Structure-Cell Interaction Analysis

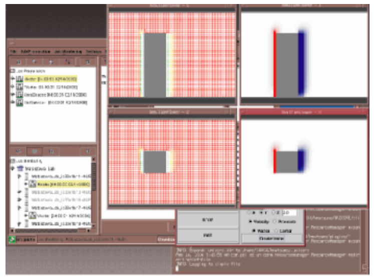
Introduction

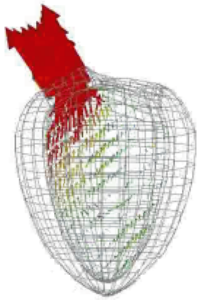
Biomechanics flow simulation activities on JAIST

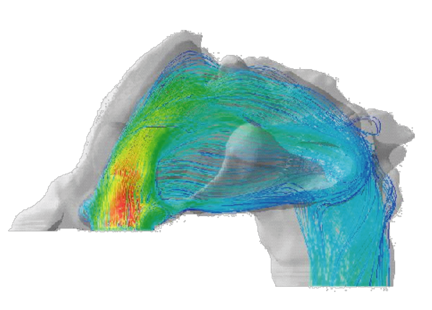


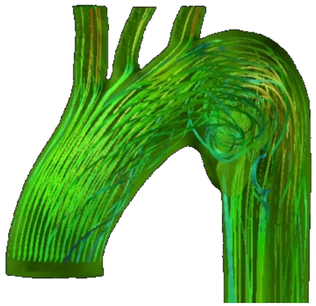


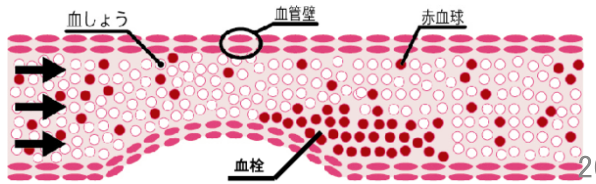
- We have continued to study for the CFD and HPC
- Especially, biomechanics flow are major subject
- Today, I introduce these subjects
  - Air-Flow Simulation in Nasal Cavity
  - Blood Flow Simulation in Thrombosed Aortic Dissection
  - Blood Flow Simulation in Aneurysm with STENT
  - Heart Simulation using Medical Images Voxel Based Fluid-Structure-Cell Interaction Analysis











Air-Flow Simulation in Nasal Cavity

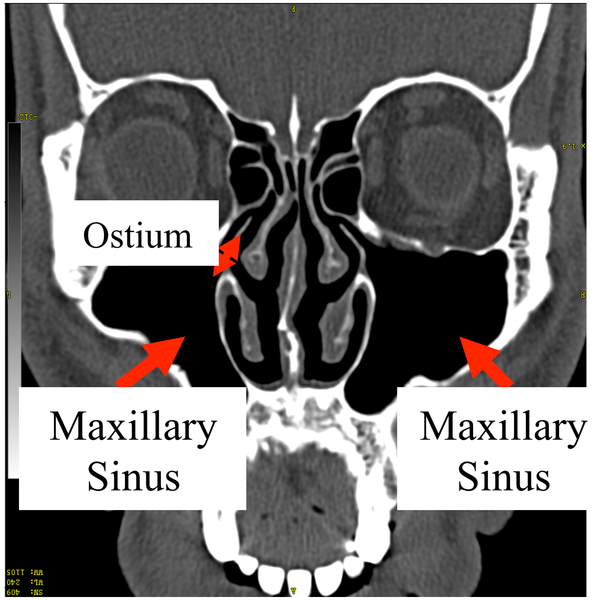
Nasal Cavity

- Nasal cavity is important organ for breathing, and it's anatomy is complex
- Functions of nasal cavity are
  - Breathing
  - Smelling
  - Adjustment humidity of inhaled air
  - Adjustment temperature of inhaled air

- Nasal cavity has paranasal sinus that divides into four parts depend on locations

paranasal sinus

- Paranasal sinus is divided into four parts
  - maxillary sinus (we focus on)
  - frontal sinus
  - ethomidales sinus
  - sphenoidalis sinus
- Physiological functions
  - Support of controlling temperature and Humidity
  - Vocal resonance apparatus
  - Lightening of Skull



CT image of Nasal cavity

Physiological functions of paranasal sinus have not understood sufficiently

Purpose

- To clarify function of nasal cavity
  - we calculate airflow of nasal cavity using heat and humidity models.

Governing Equation for Thermo-Humid CFD

Flow model
Incompressible, Newtonian viscid, laminar

1. Continuity eq.

$$\nabla \cdot \boldsymbol{u} = 0$$

2. Naiver-Stokes eq.

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \mu \nabla^2 \boldsymbol{u}$$

3. Energy eq.

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\boldsymbol{u}(\rho E + p)) = \nabla \cdot \boldsymbol{Q} + \Phi$$

4. Species (water) transport eq.

$$\frac{\partial \phi}{\partial t} + (\boldsymbol{u} \cdot \nabla)\phi = \nabla \cdot \boldsymbol{W}$$

u Velocity
p Pressure
μ Viscosity
E Energy
Φ Viscous dissipation
φ Mass fraction of water
W Mass flux of water
Q Heat flux
ρMixture density

$$W = D\nabla\phi \qquad \rho = \frac{1}{\dfrac{\phi}{\rho_{water}} + \dfrac{1-\phi}{\rho_{air}}}$$

$$Q = K\nabla T$$

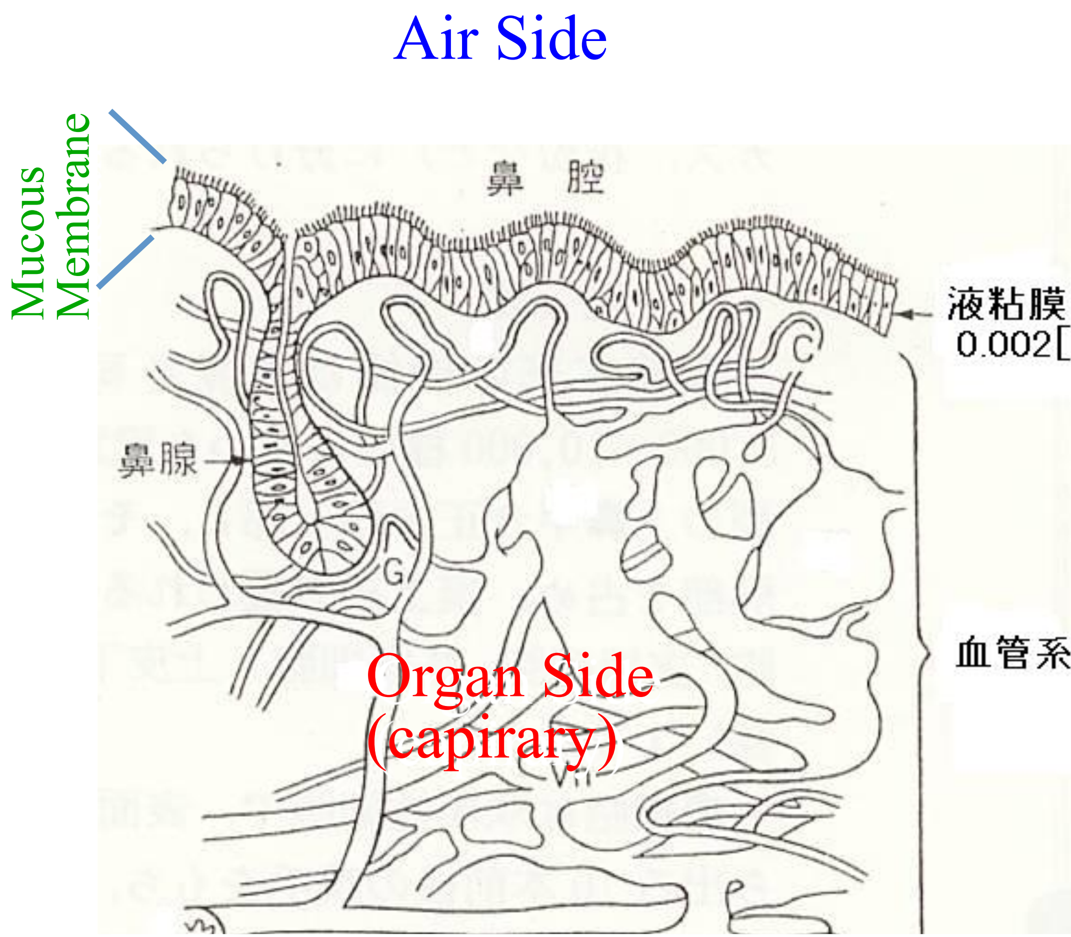
We employ consumer CFD solver Fluent™, FVM method

Thermal and Water Exchange via Mucous Membrane

- Mucous membrane between air and organ
- Thermal and water are exchanged via mucous membrane

- We made models of exchange
  - Thermal
  - Water

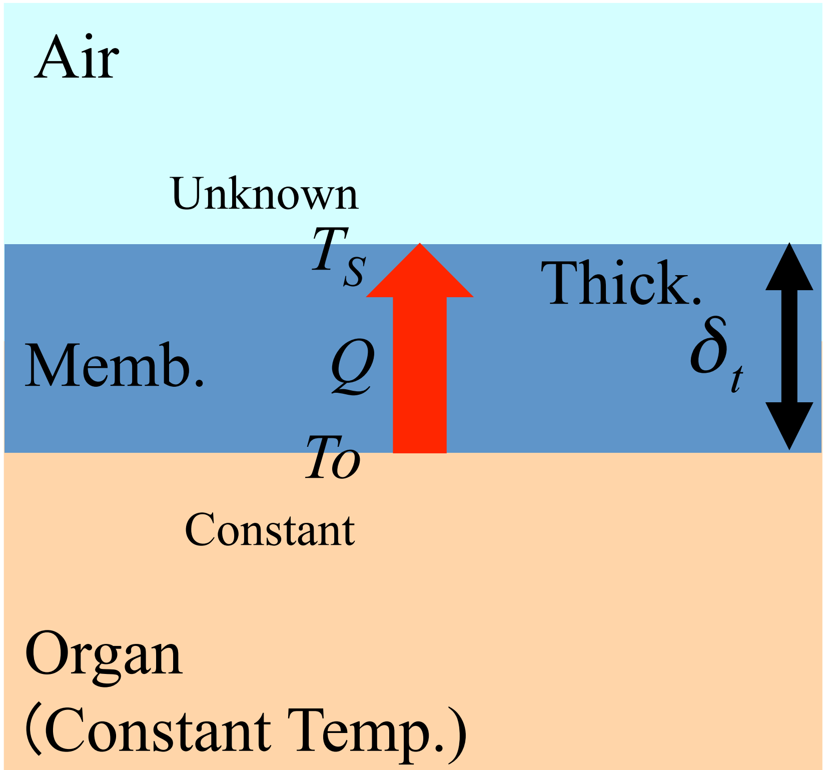
  via membrane



Cross Section of Nasal Cavity

Thermal-Exchange Model on Membrane

Boundary Condition of Convection Heat Transfer Via membrane



δ_t =3mm, K=0.6(W/m･K)

→By Newton's Cooling Law

$$Q = \frac{K}{\delta_t}\left(T_o - T_s\right)$$

K/δ_t Heat Transfer Coef. (W/m^2･K)

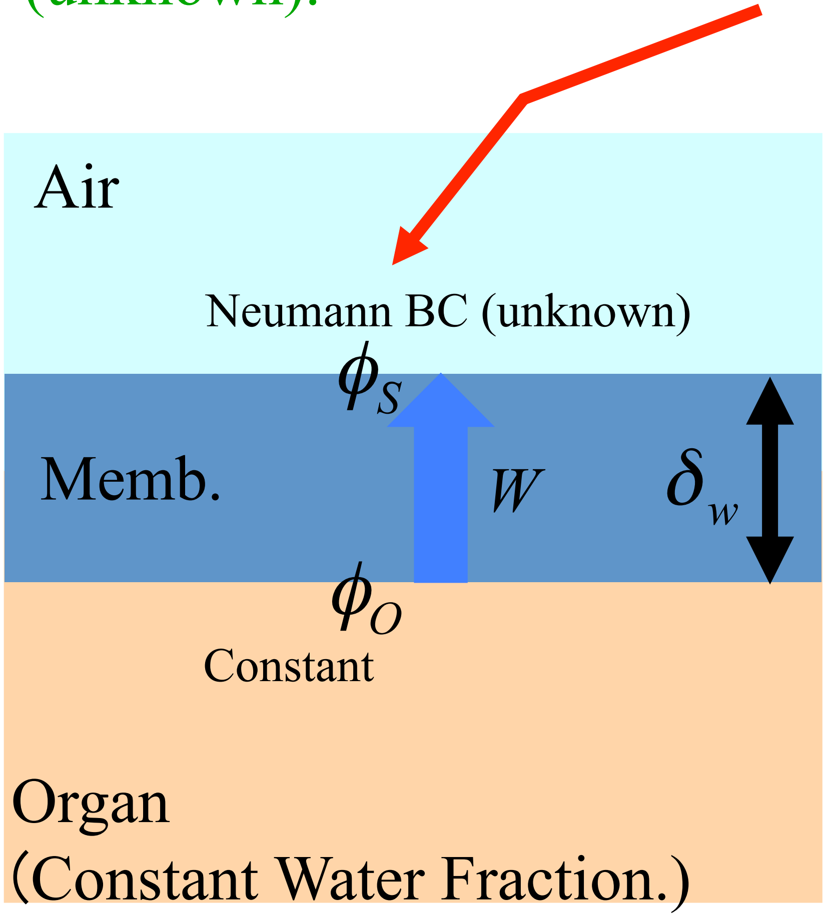
K Thermal Conductivity (W/m･K)

To implement into Energy Eq. as boundary condition

Fluent has this type convection heat transfer BC.

Water-Exchange Model on Membrane

In this time, we have developed the model so that mass fraction of water on surface will be solved. So surface is assigned Neumann BC (unknown).



There is an analogy between heat transfer and mass transfer

$$W = \frac{D}{\delta_w}(\phi_O - \phi_S)$$

D/δ_w Mass Transfer Coef. (m/s)

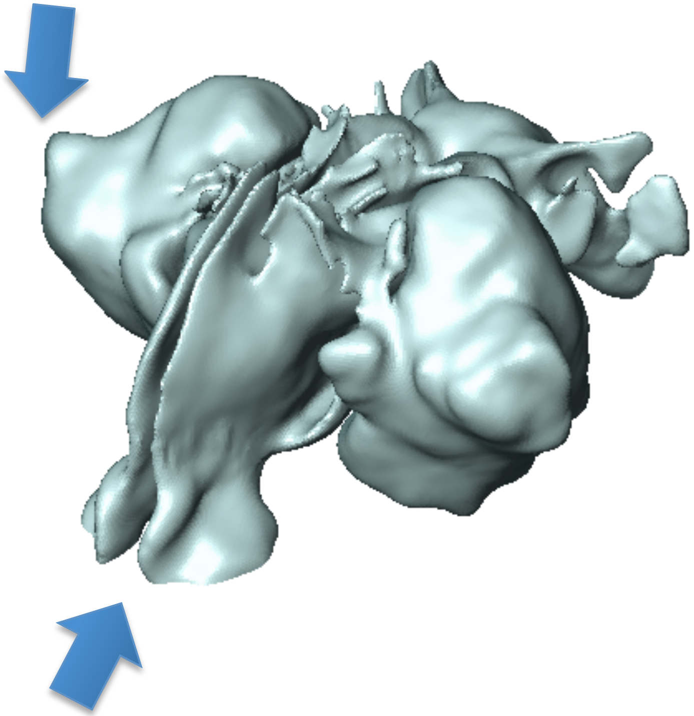
D Mass Diffusivity (m^2/s)

We used "User Defined Function" in Fluent to assign boundary condition of water-transport eq.

Calculation condition

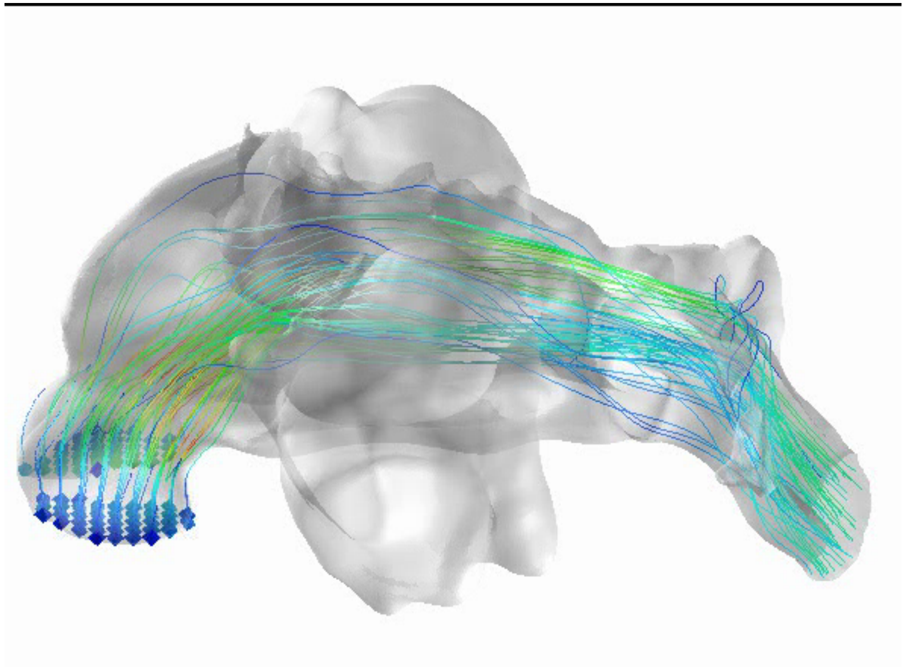
- Geometry of Nasal Cavity
  - Geometric model is reconstructed from CT images

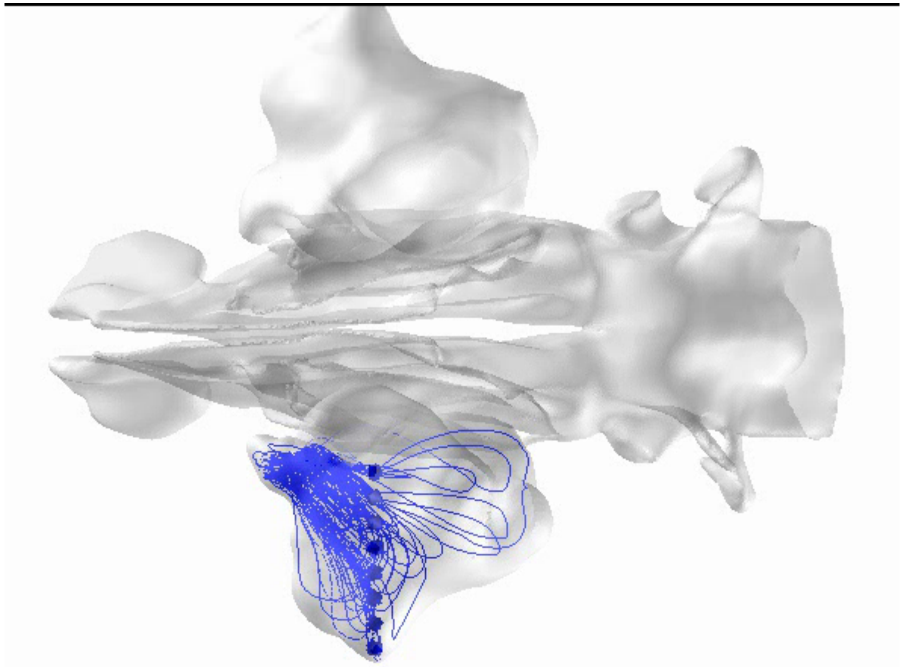
- Boundary Conditions
  - Inspiratory flow : 0.804[m/s]
  - Wall: Temperature 34[ºC]
    : Noslip
- Inhaled air condition
  - Temperature 0, 25[ºC]
  - Humidity 70[%]
- Flow calculation using Heat and Humidity models[1]



[1] K.Kumahata et al. Nasal Flow Simulation Using Heat and Humidity Models, Journal of Biomechanical Science and Engineering, vol5, no 5, 565-577,2010.

Airflow in nasal cavity





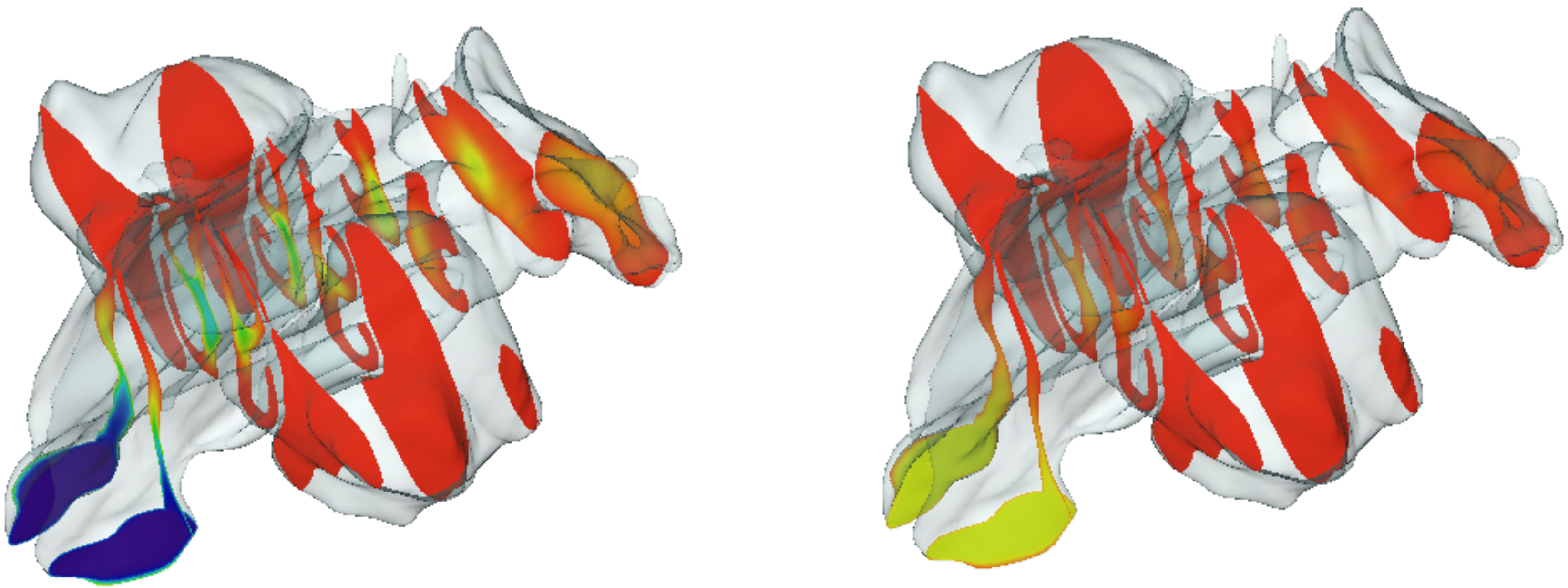
Main flow of nasal cavity

Flow in the maxillary sinus

The high velocity area is middle nasal meatus. And, superior and inferior nasal meatus is low velocity area.

In the maxillary sinus, airflow is quitely slow in comparison with main flow of nasal cavity.

Temperature distribution



Inhaled air Temp:0[ºC]   Inhaled air Temp:25[ºC]

0[ºC]   25[ºC]   34[ºC]

- Temperature of inhaled air are heated by function of nasal cavity in each case.
- Even if inhaled air temperature is low, inhaled air is heated to suitable temperature until throat.

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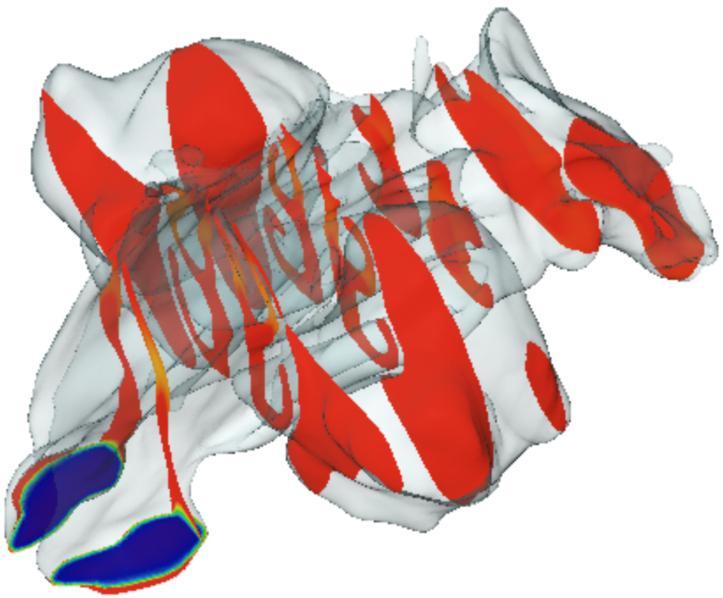
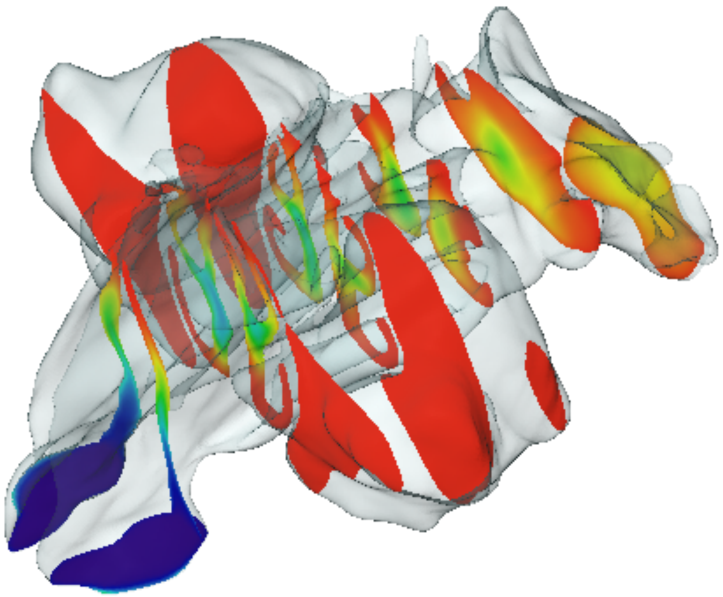
Humidity distribution





Inhaled air Humidity:70[%] (0ºC)

Inhaled air Humidity:70[%] (25ºC)

70[%]

100[%]

- Humidity of inhaled air are humidified by function of nasal cavity each case.
- Case of inhaled air Temp:0 is humidified quickly in comparison with Temp:25 Case. Because, we represent relative humidity distribution (Temp:0 case is low temperature).

Conclusion

- Temperature and Humidity of inhaled air were adapted to suitable condition by function of nasal cavity.

- In the maxillary sinus Airflow is slow, and Temperature and Humidity are maintained high.

Blood Flow Simulation in Thrombosed Aortic Dissection

Aortic Dissection

- The thoracic aortic dissection is a pathogenesis of an intimal tear or damage of the aorta wall
- Divide the true lumen and false lumen
- Classification in state of blood flow
  - Communicating aortic dissection
  - thrombosed dissected thoracic aorta

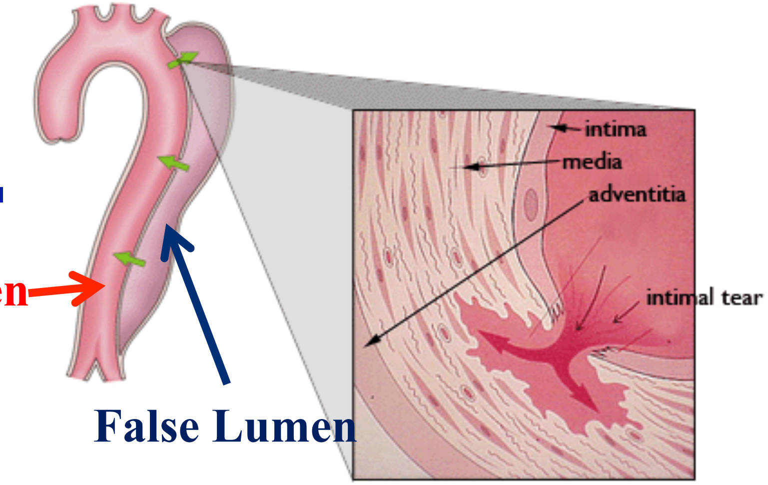


Fig. Aortic Dissection

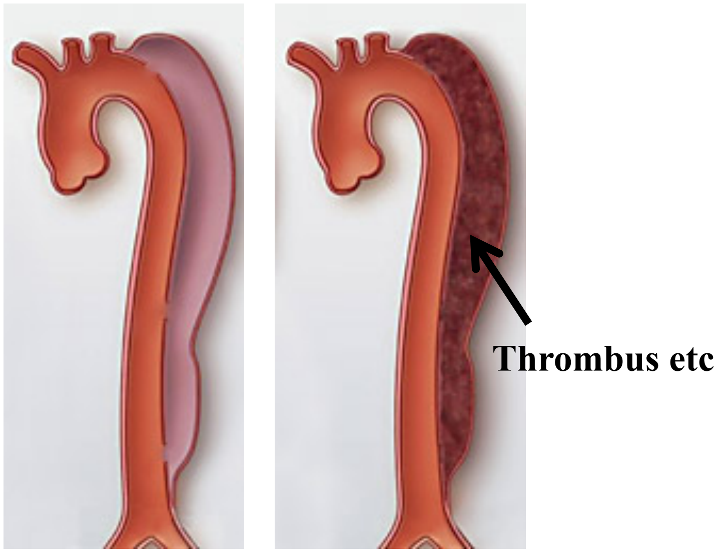


Fig. Classification of blood state in false lumen at Aorta Dissection of type B*

*Thomas T. Tsai et al., NEJM, Volume 357, No. 4, pp. 349-359(2007)

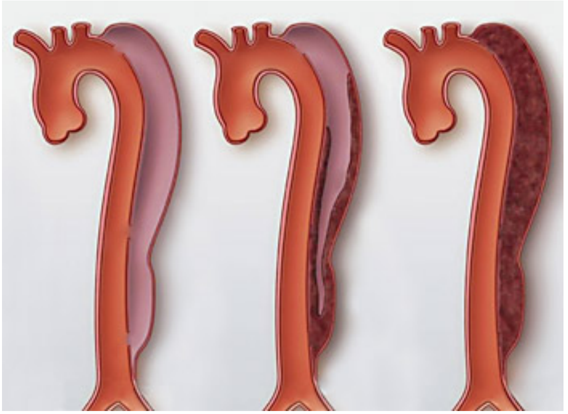
Aortic Dissection (Cont.)

- Mortality in Stanford Type B Aortic Dissection*
  - 201 patient breakout
    - Patent Type :114(56.7%)
    - Partial Thrombosis Type :68(33.8%)
    - Complete Thrombosis Type :19(9.5%)
  - Mortality for 3 years in each tyepes
    - Patent Type : 13.7%
    - Partial Thrombosis Type : 31.6%
    - Complete Thrombosis Type : 22.6%

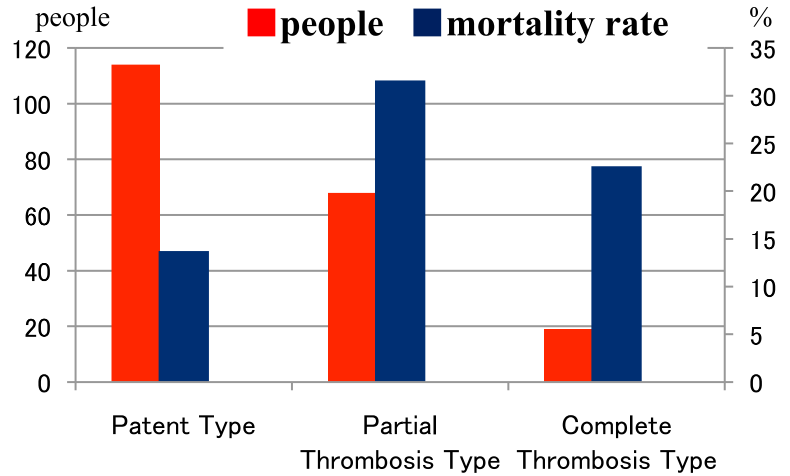
Cause of Mortality-rupture of aneurysm, cardiac tamponade etc

The medical management is selected in complete thrombosis type . However, the mortality is high in complete thrombosis type

The aneurysm and re-dissection are seen from Ulcer-Like Projection (ULP)



Patent Type **Partial Thrombosis Type** **Complete Thrombosis Type**

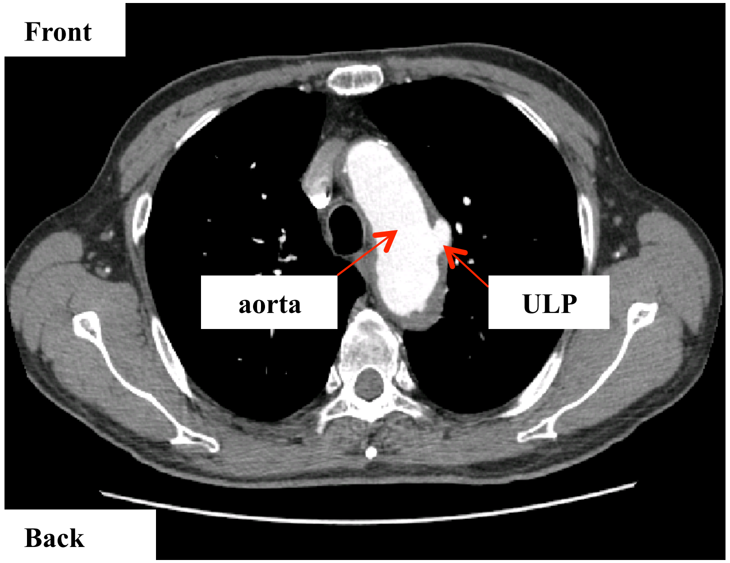


Mortality rate in each type

*Thomas T. Tsai et al., NEJM, Volume 357, No. 4, pp. 349-359(2007)

Ulcer-Like Projection (ULP)

- Ulcer Like Projection (ULP) as process to aneurysm in complete thrombosis type
- What ULP？
  - an ulcer part from intimal to false lumen
  - suggests entry part
  - **Not know whether expand it**
  - Frequency is high



ULP in thoracic aorta of complete thrombosis type

Time dependent change of ULP is important in diagnosis of complete thrombosis type

Purpose

- To clarify predict factor of expansion ULP in hemodynamic
  - We was reconstructed ULP shape due to complete thrombosis type using time-series medical data and was analyzed

Valuable information can be obtained by combining a clinical diagnosis and with the CFD results

Patient Information

- Targeted patients (Age:70±6, Sex：Male) are occurred complete thrombosis type
- Position of ULP are aortic arch and descending aorta

	Case1	Case2	Case3
Age	75	64	70
Sex	Male	Male	Male
Position of ULP	Descending Aorta	Aortic Arch	Descending Aorta

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Reconstruction Shape

Case1-A **Case1-B**

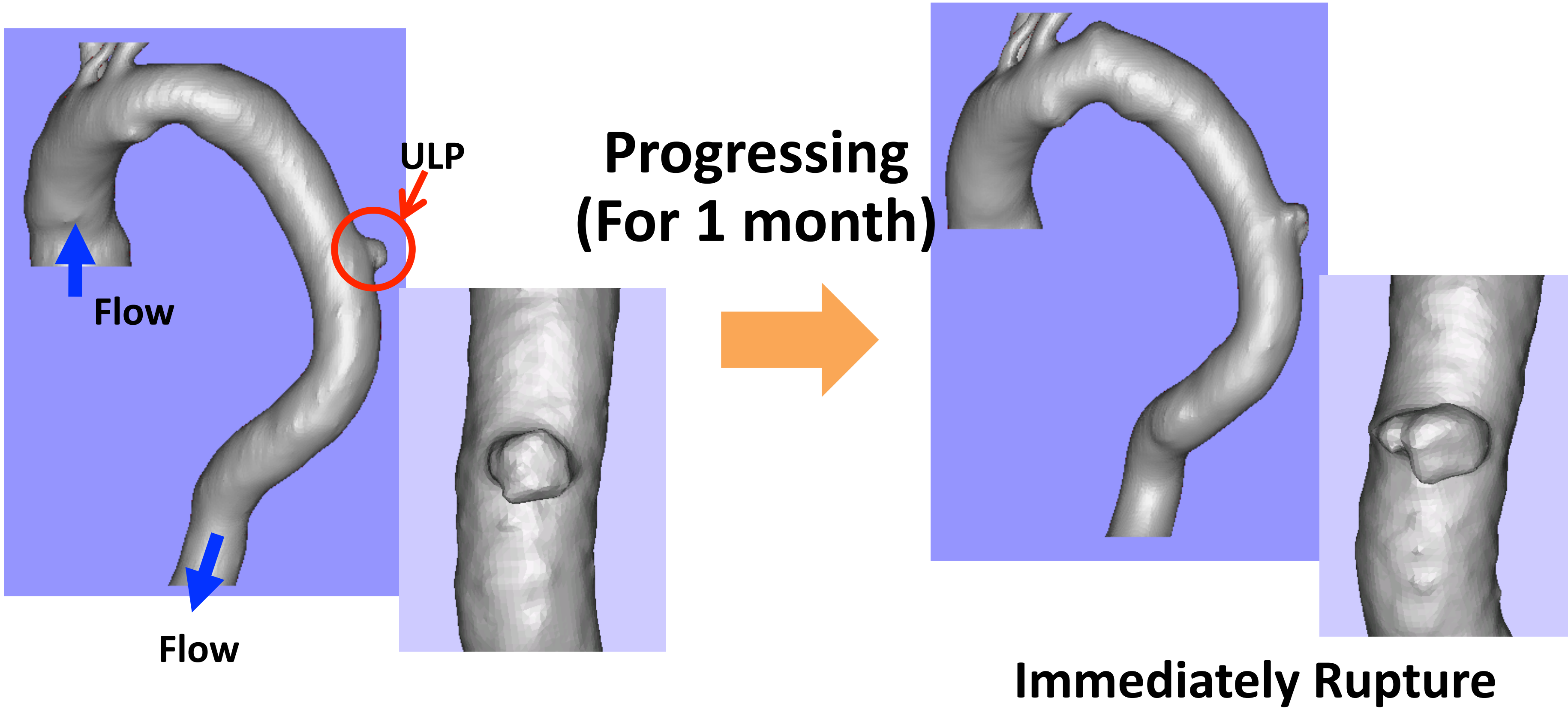


Fig. time-series reconstruction shape

This patient treated within two weeks after taken a picture of case1-B and is recovering now.

Calculation Conditions

Steady Condition
Assumption : Blood
Density ρ=1050kg/cm^3
Viscosity μ=0.0035kg/m·s

Calculation Condition
Inlet: Uniform flow (u=0.6 m/s)
Outlet: Pressure corresponding to the distance from the inlet
Wall : no-slip, rigid
No. elements :2,000,000 (Tetrahedron mesh)
Reynolds number : Re=6500
Turbulence model: k-εmodel

Solver
Fluent Inc., Fluent 6.3.26

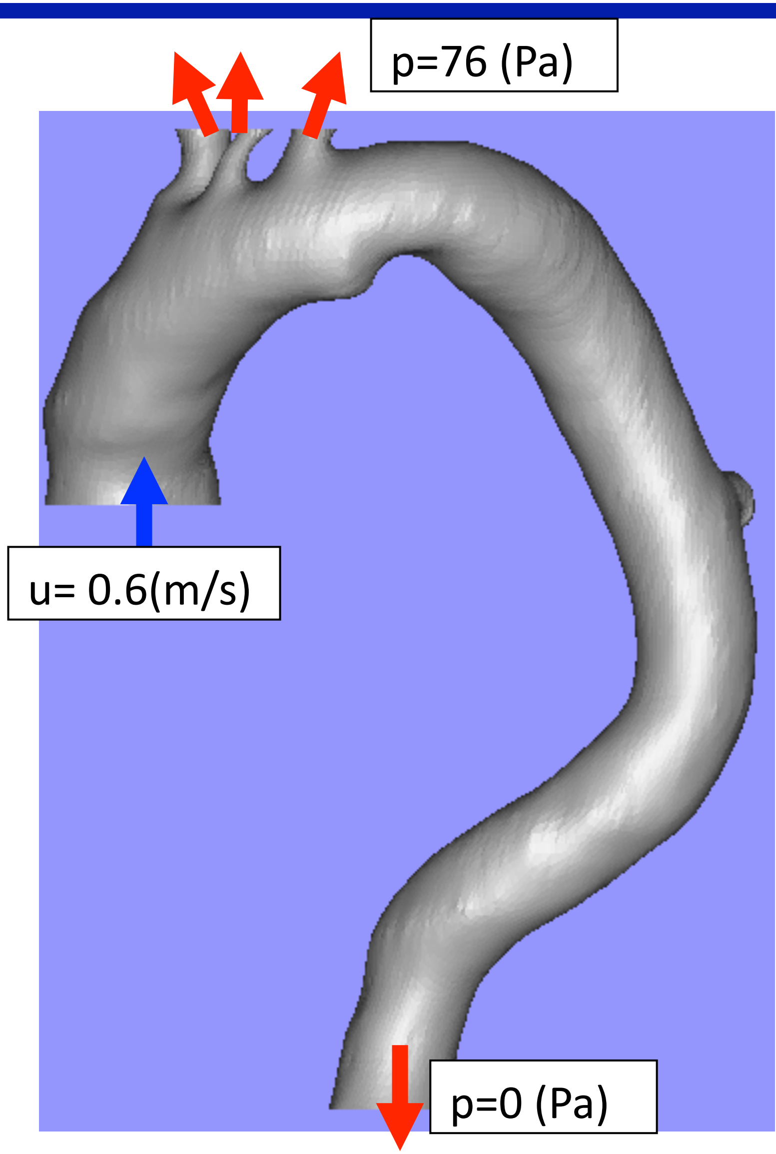
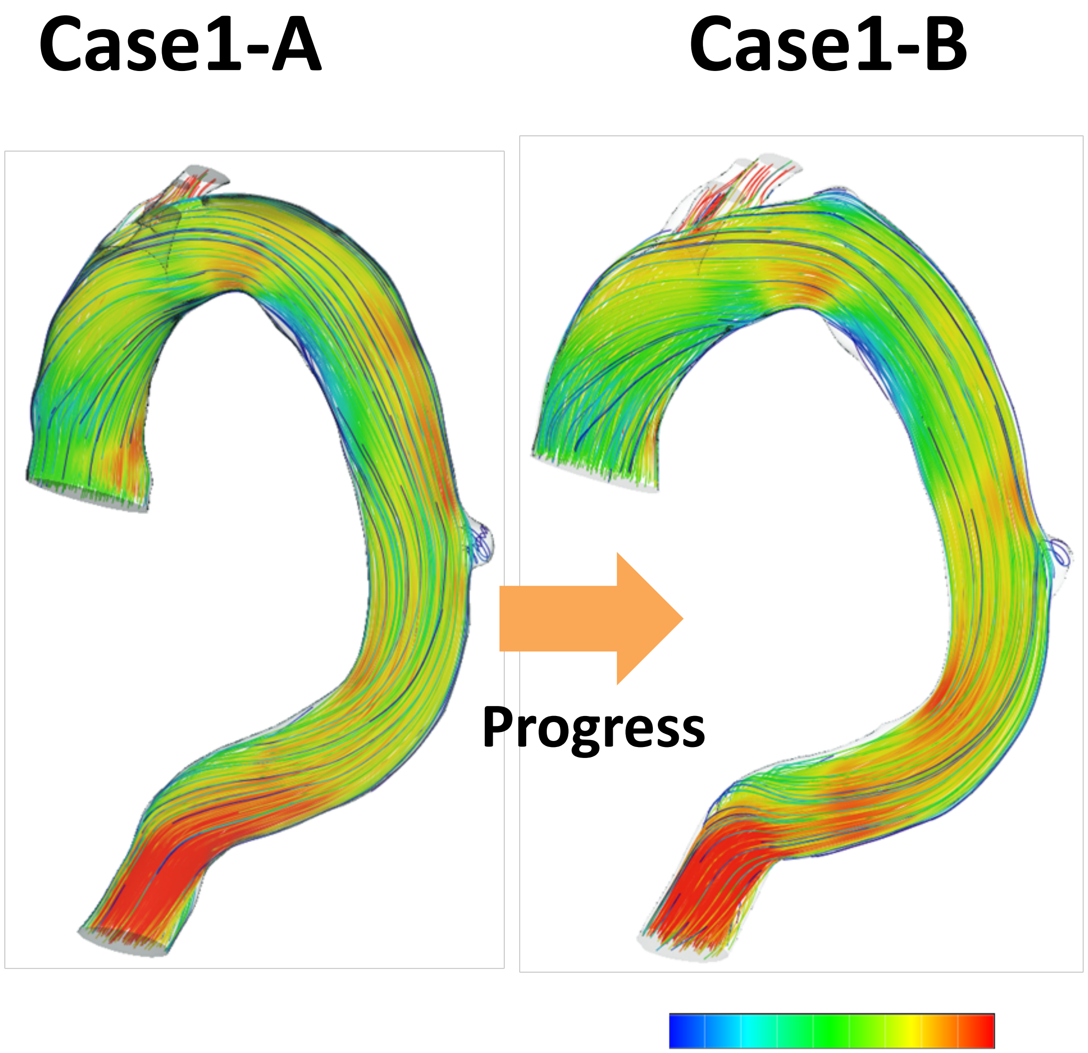


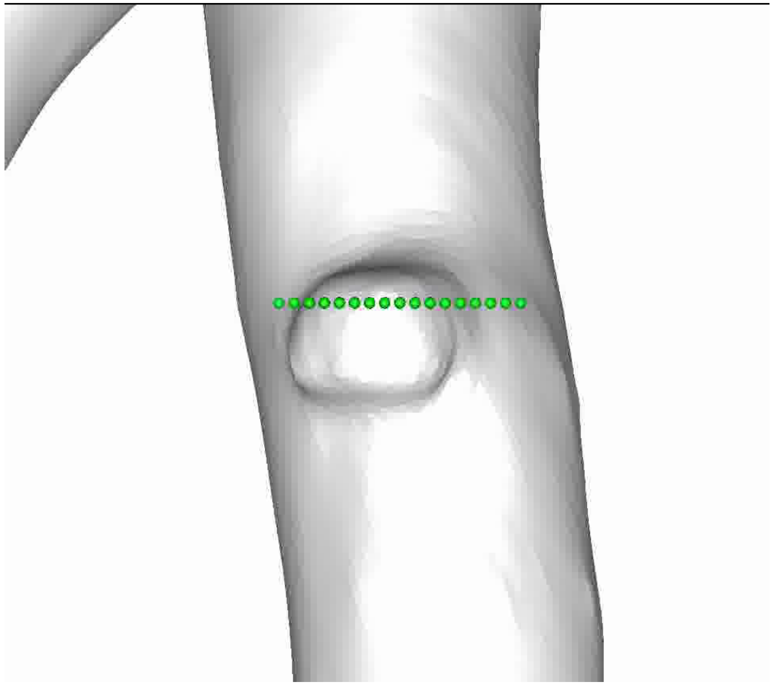
Fig. Boundary Conditions

Flow –Case1

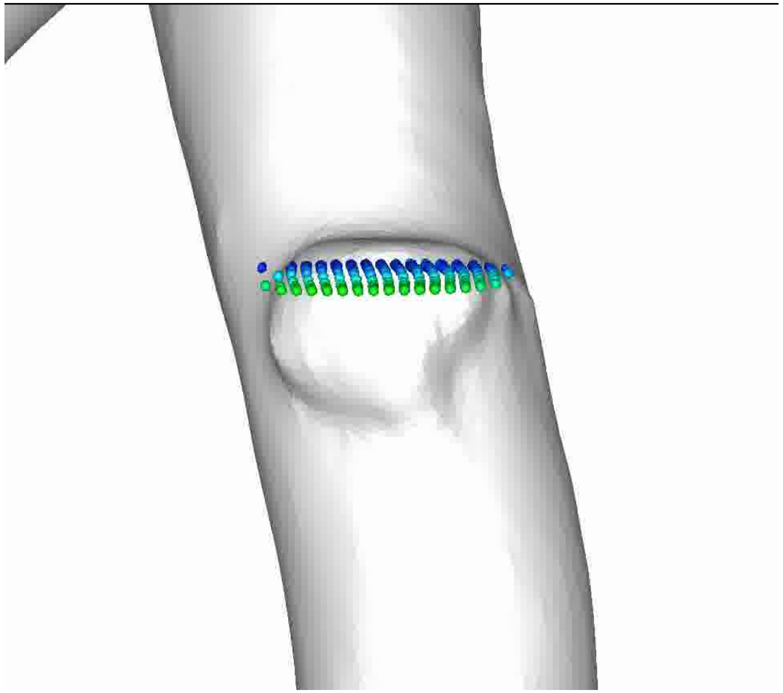
- The high flow is seen in back, and the slow flow is seen in inside.
- the vortex was observed at ULP.
- Inflow to ULP flows along the wall.



Flow in ULP

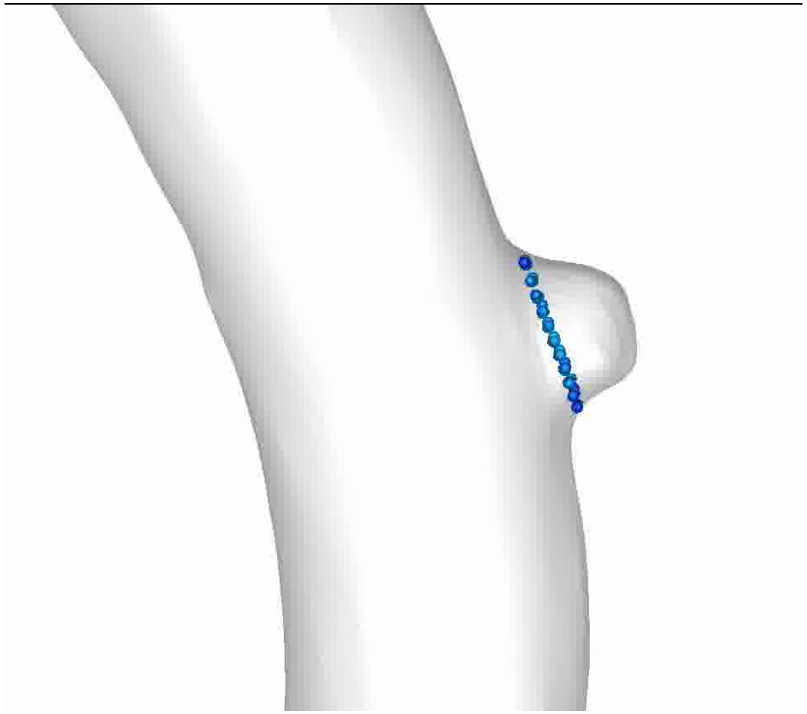


Case1-A

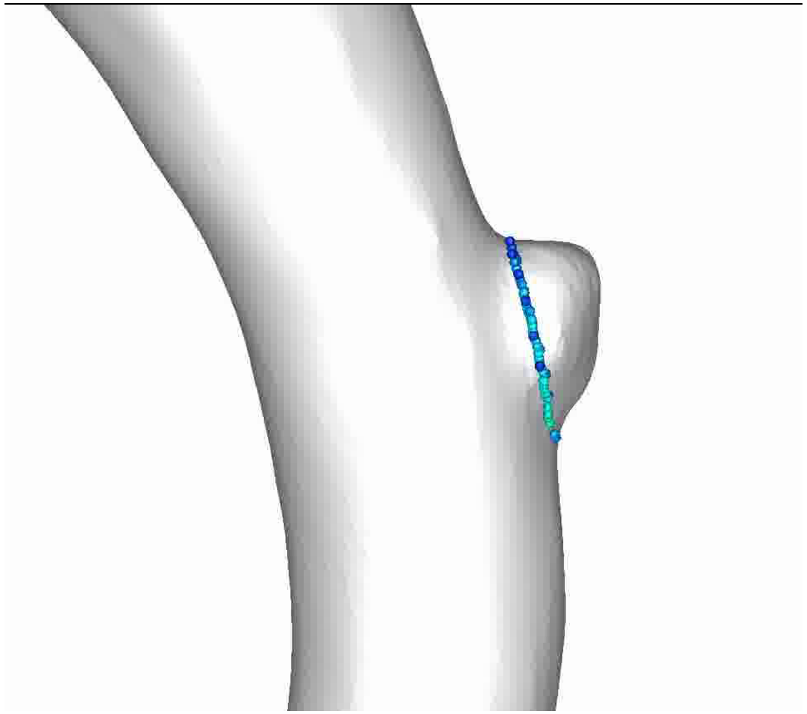


Case1-B

Flow in ULP (cont.)



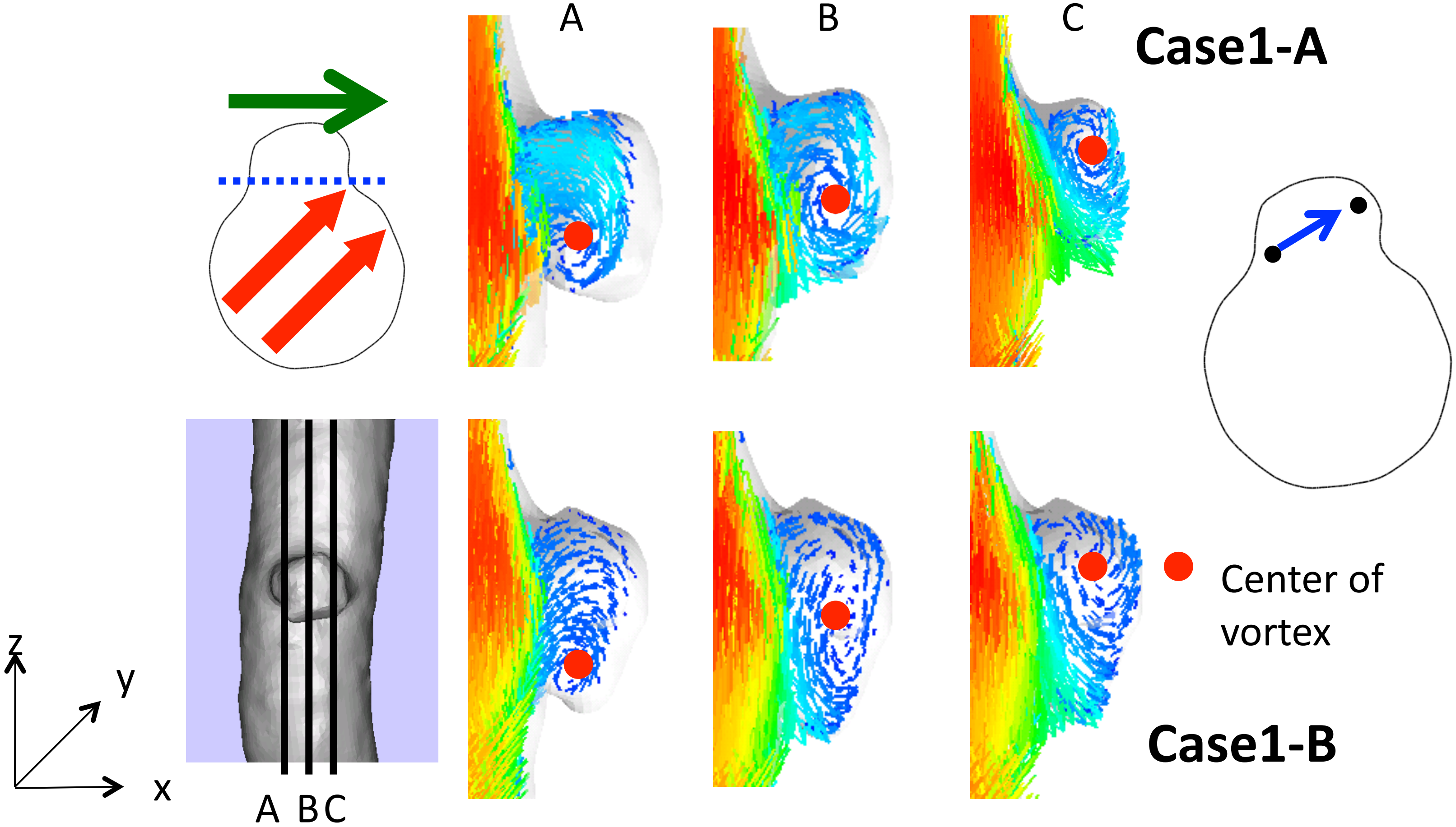
Case1-A



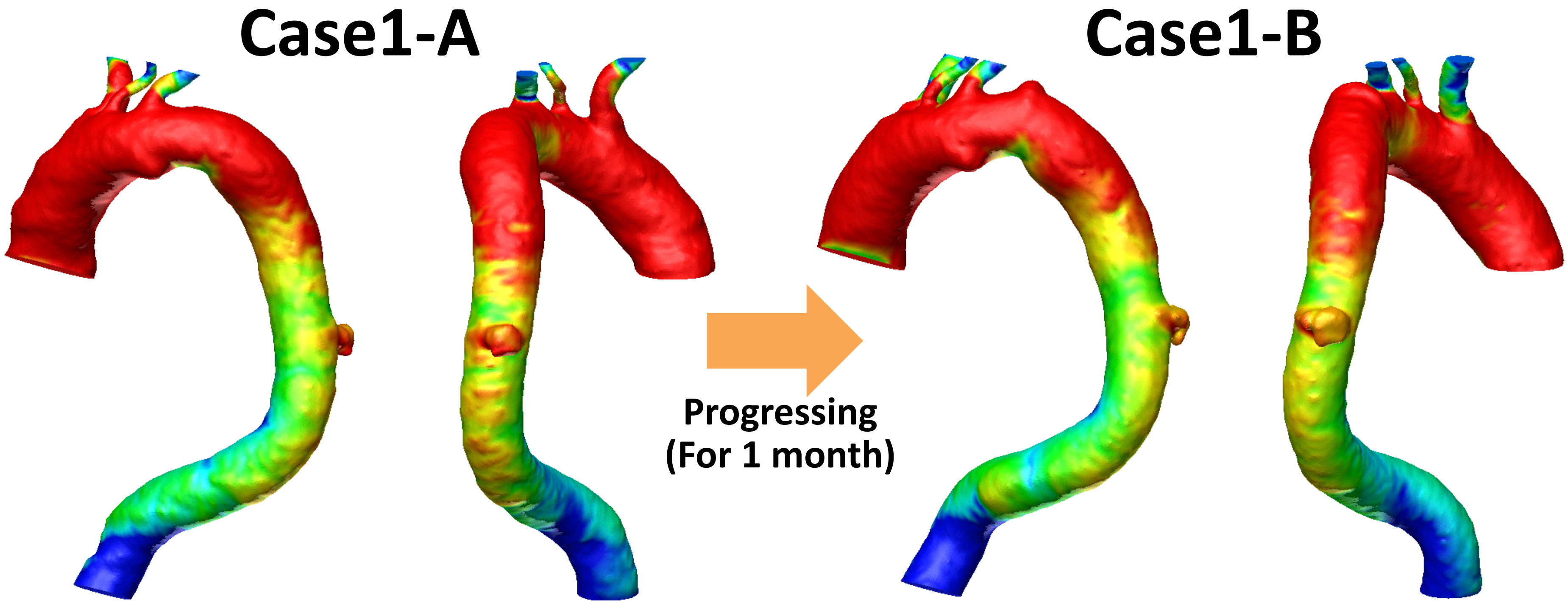
Case1-B

Flow – Secondary Flow

- The horizontal section slice decides an on the left, right, top and bottom based on the direction of the secondary flow in vertical section

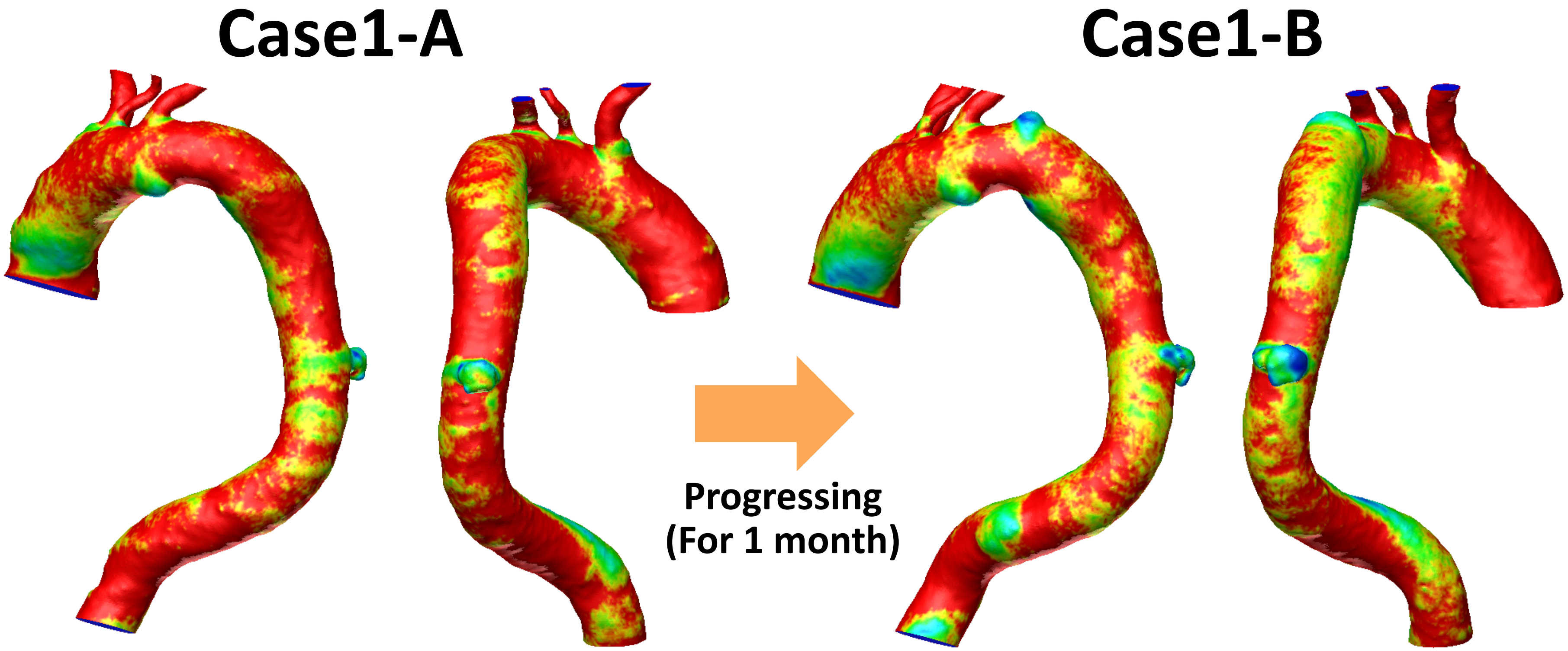


Pressure distribution



- Progression of ULP
  - In high pressure around aneurysm, the aneurysm is progressing
- Rupture of ULP
  - the pressure distribution of aneurysm in situation Case 1-B is higher than that of each situations

Wall Shear Stress distribution



- Progression after Development ULP
  - The aneurysm occurs in the low WSS distribution regions

Conclusion

- Low wall shear stress distribution tends to be seen in the direction where the vortex was moved
  - It is reported progress part where is a vortex and low pressure distribution*

* Wada, S et al., *The Japan Society of Mechanical Engineers A, Vol. 69 (2003), pp. 62-69*

- In high pressure distribution of ULP, ULP can predict to expansion

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Blood Flow Simulation in Aneurysm with STENT

Background

- The stent treatment for cerebral aneurysm is paid attention around the world
  - health costs is high
  - a low invasive therapy

Objective of stent treatment

To shield the aneurismal wall and reduce the blood flow into aneurysm

⇒ progressively inducing aneurismal flow stasis, thrombus formation and aneurysm occlusion

Study of Stent Treatment

What is **role of STENT**?

- to prevent blood flow into the aneurysm and to decrease the risk of rupture

- the blood flow into aneurysm can be reduced by only stent placement for reported by experimental and CFD simulation
  - Study of STENT
    Ex)Design, Position   etc…
- When treat using stent, the diameter of stent is larger than that of blood vessel diameter
  - the blood vessel has been slightly expanded by stent placement

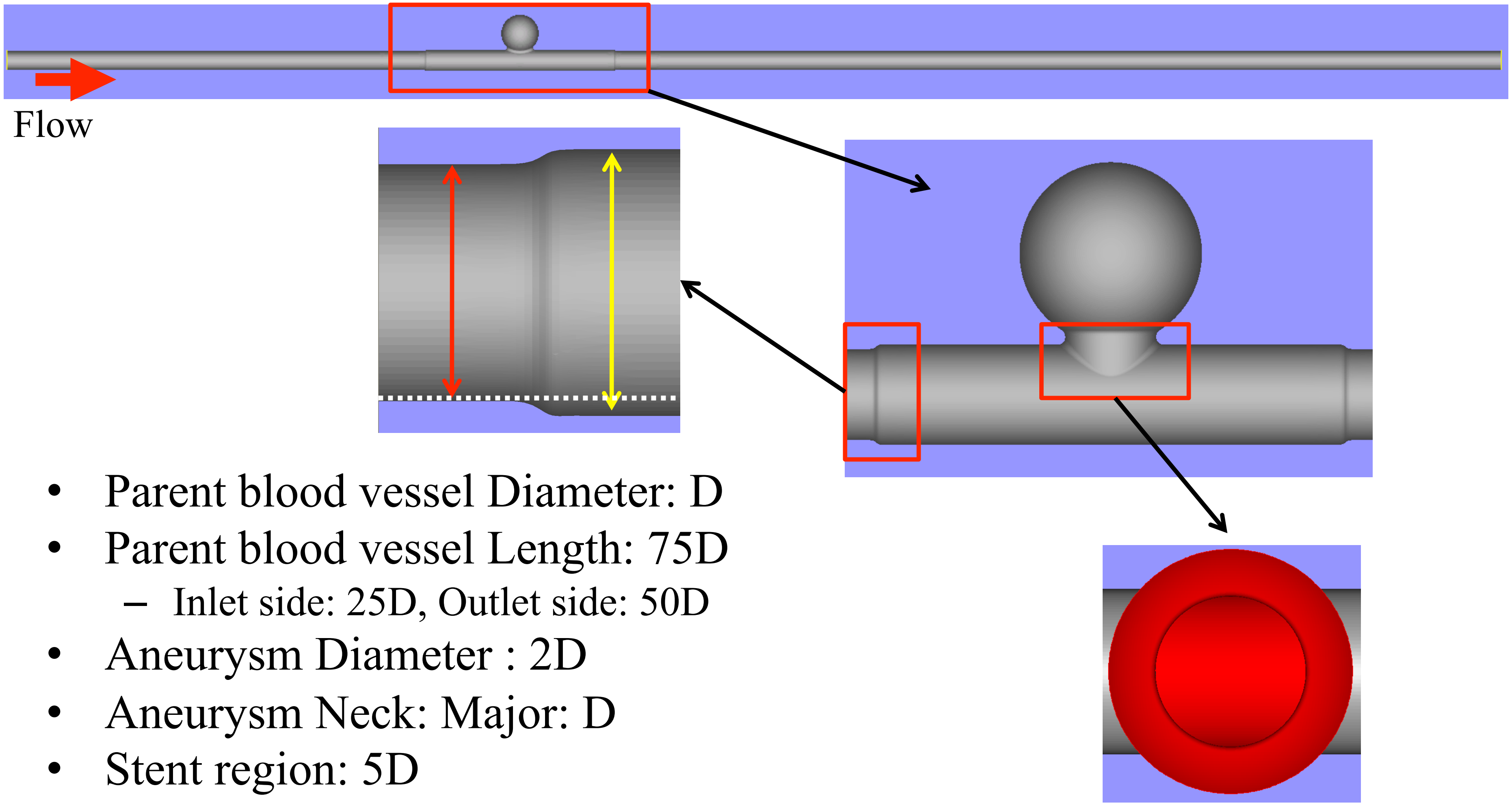
Not consider the expansion blood vessel by stent placement

Purpose

- To clarify effect of blood vessel expansion for stent treatment
  - Examine that Compare to consider the expansion blood vessel by stent placement and not consider it, **which more effective**
  - We consider the expansion of blood vessel by stent placement and analyze using idealized shape

Method –Idealized blood vessel Shape

Idealized expansion blood vessel by stent placement with aneurysm *



- Parent blood vessel Diameter: D
- Parent blood vessel Length: 75D
  - Inlet side: 25D, Outlet side: 50D
- Aneurysm Diameter : 2D
- Aneurysm Neck: Major: D
- Stent region: 5D
- BV Expansion Rate :5%, 10%

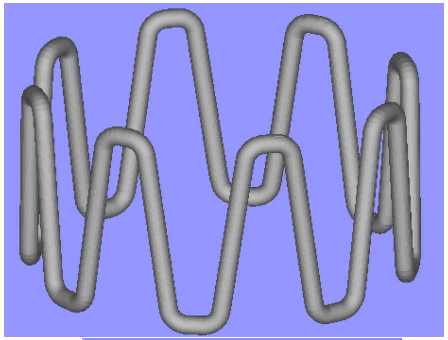
[*]Ohta.M et al., Three Dimensional Geometry Measurement of Cerebral Aneurysms and Vessel Size for Analytical Geometry

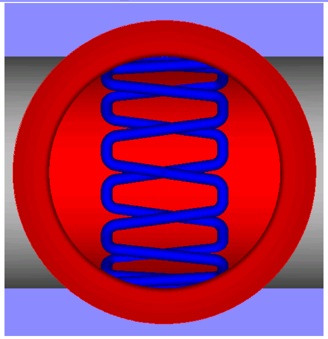
Method –Idealized stent shape

- Stent Shape

  Idealized Zigzag stent

  – Cross-section of strut
    - Circle
- Stent Position
  – Cover completely the orifice





Construct three situations

- Not blood vessel Expansion (BVE) with stent: Not BVE
- blood vessel Expansion (BVE) with stent: **% BVE (ex) 5%BVE, 10%BVE

Calculation Conditions

Calculation Conditions

- Distribution of inlet : Uniform flow
- Inlet condition: 0.2 m/s
  - Reynolds number : Re=240
- Outlet condition :Pressure 0 Pa
- Wall & Stent Surface : no-slip
- No. elements
  - WithStent:8,000,000 (Tetrahedron mesh)
  - Without Stent: 4,000,000 (Tetrahedron mesh)

Basic Equation

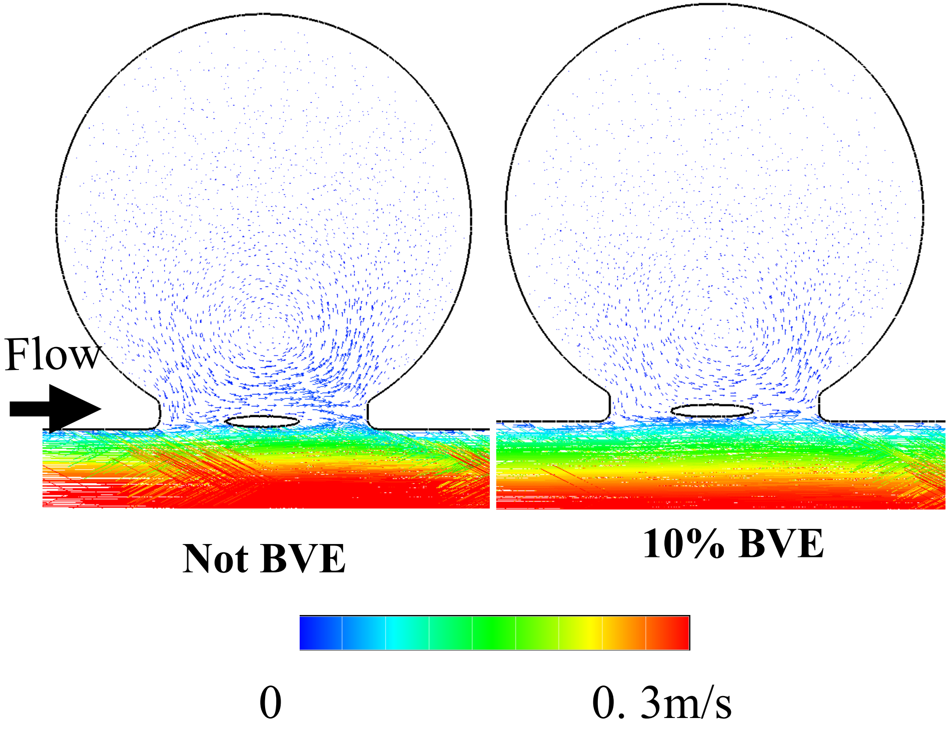
- Assumption: Steady & incompressible viscous fluid
- Equation of Continuity
- Navier-Stokes Equations

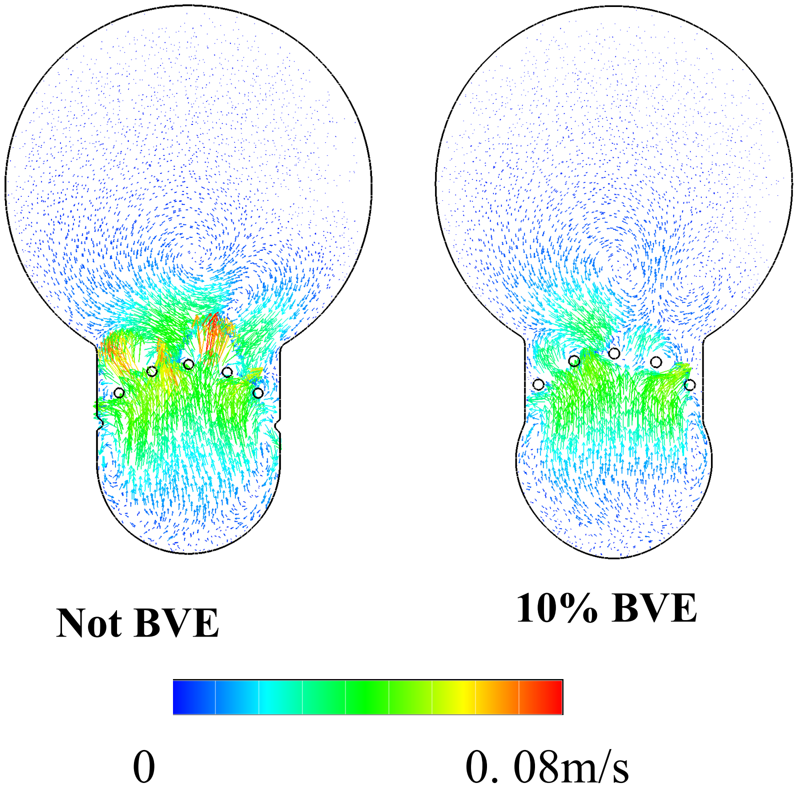
Solver

- Finite Volume Method, ANSYS Inc. Fluent 6.3

Flow pattern of center section and vertical section

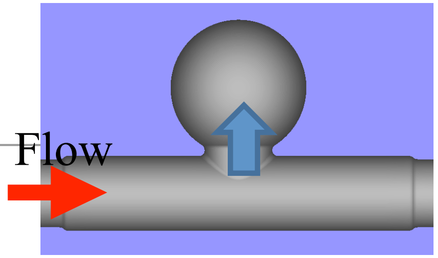
- The flow that stepped over stent and along the artery wall was seen
- When compare not BVE and 10%BVE, the inflow to aneurysm of 10%BVE has more decrease than that of not BVE.
- The flow velocity has decreased more than not BVE.





In-flow rate to Aneurysm

- Compare not BVE to 5 and 10% BVE, inflow to aneurysm has been decrease by 3 to 14%



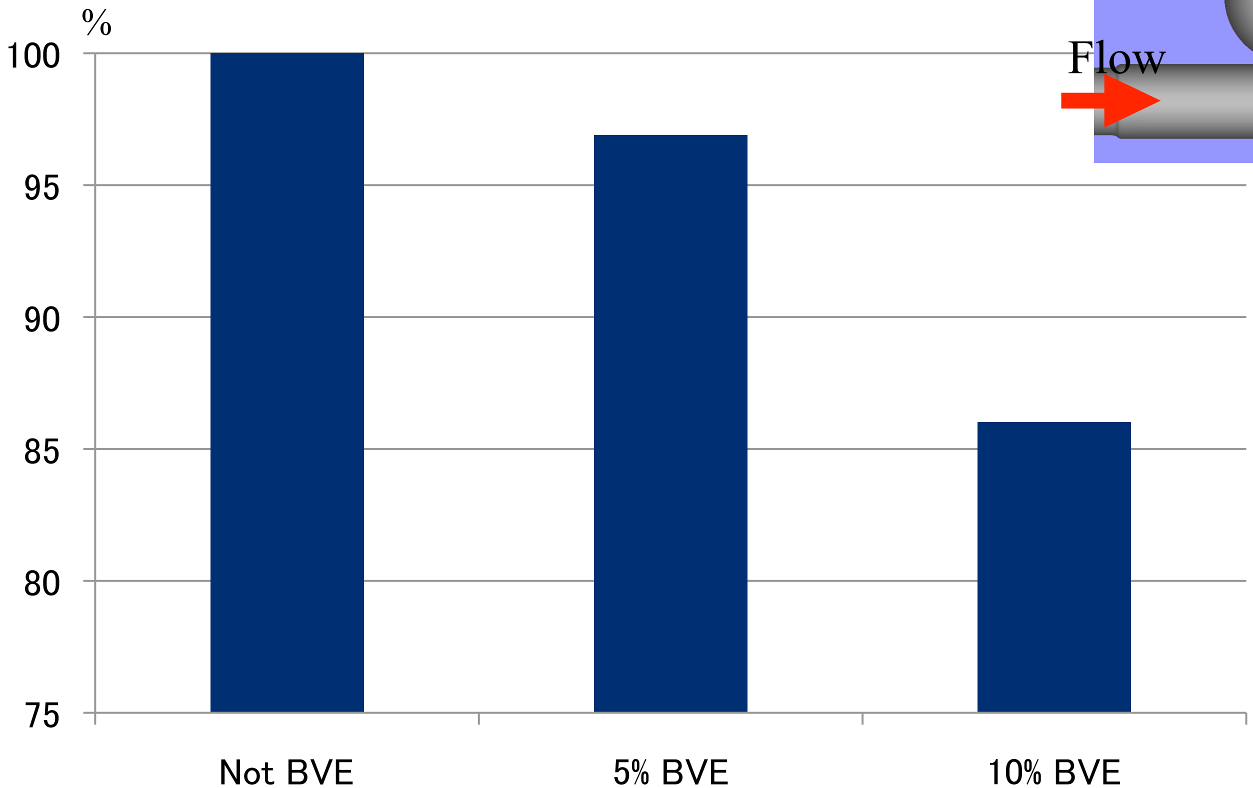
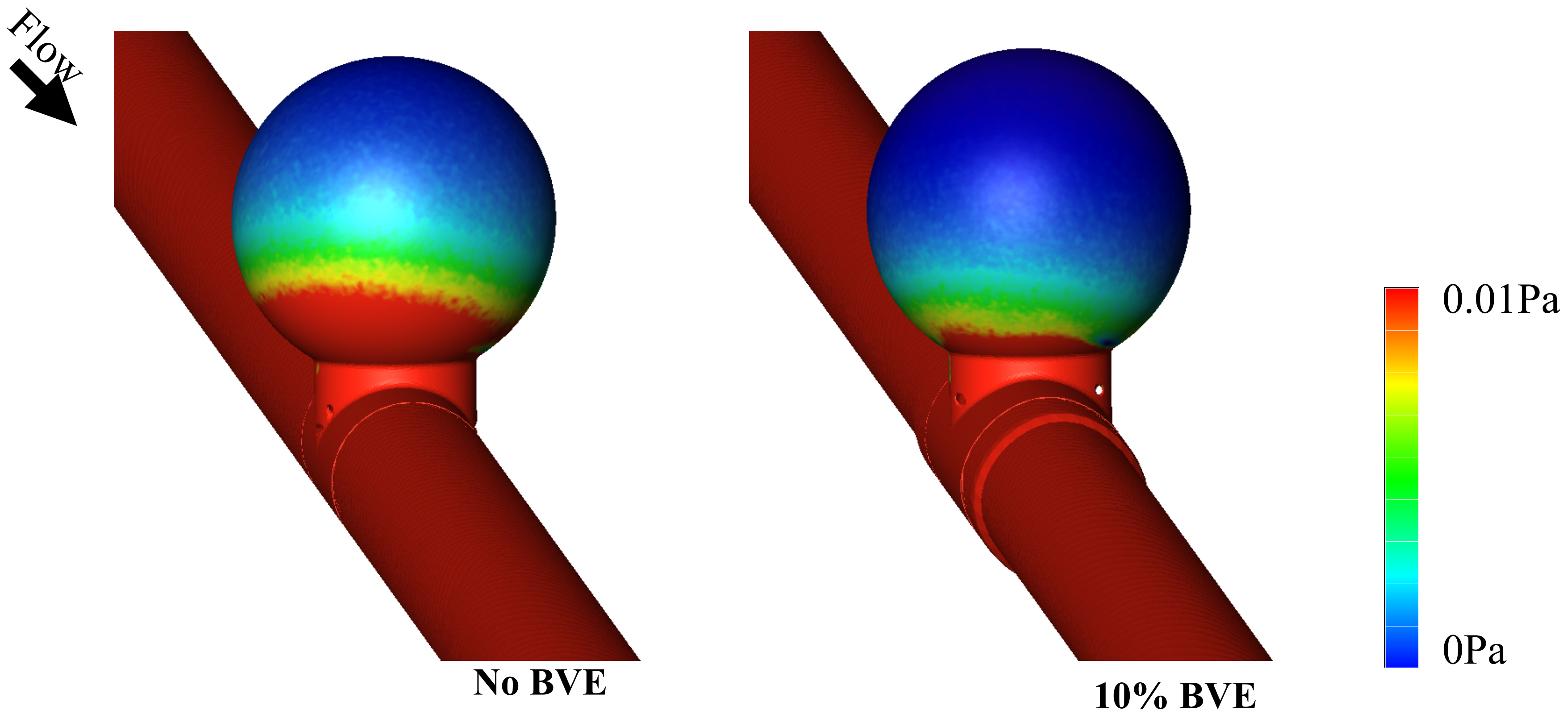


Fig. In-flow rate to Aneurysms in each cases

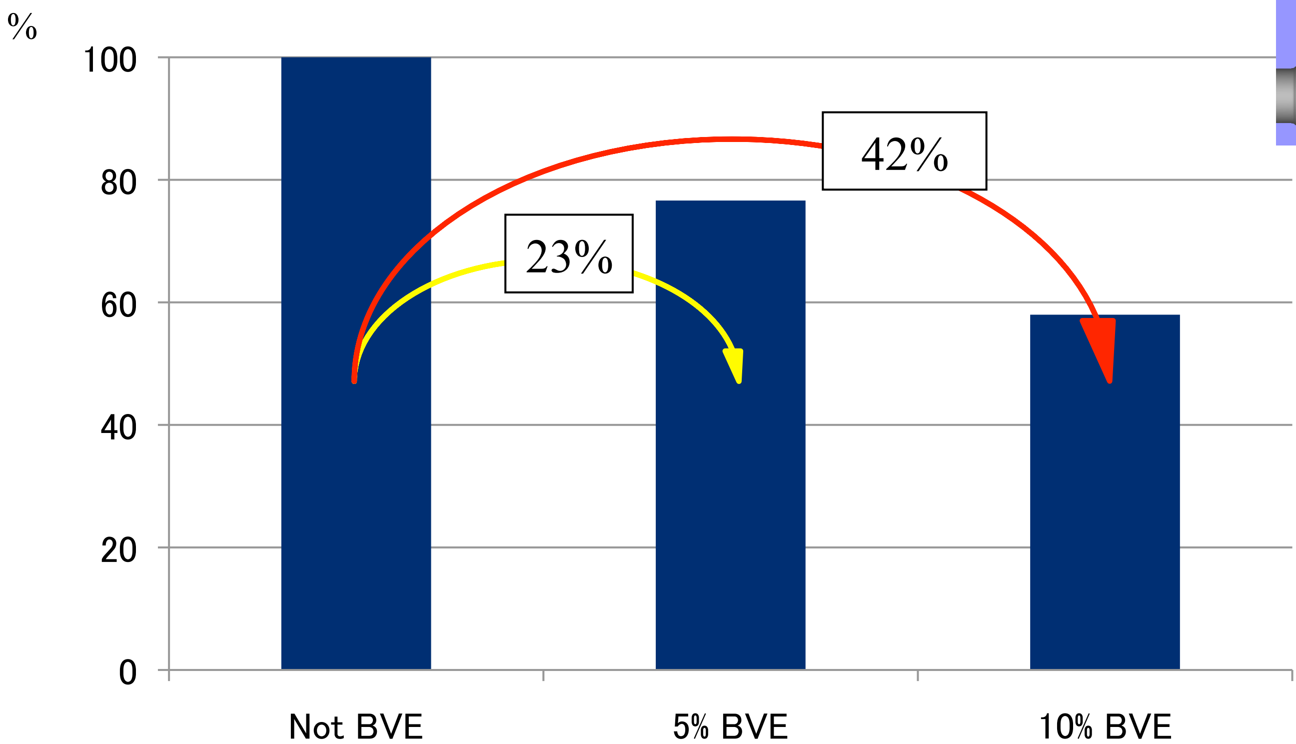
Wall Shear Stress Distribution

- WSS distribution has been decreased by stent placement in aneurysm part
- The expansion BVE is more decrease than that of not BVE



Mean Wall Shear Stress of Aneurysm

- Compare not BVE to 5 and 10% BVE, mean wall shear stress of aneurysm has been decrease by 23 to 42%



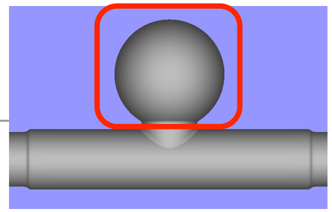


Fig. Mean WSS distribution Value of Aneurysm

Conclusion

- We examine the effect of stent to compare not expansion blood vessel and expansion blood vessel

- By consider the expansion blood vessel by stent placement, the velocity and WSS distribution has decrease than not expansion.

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Heart Simulation using Medical Images Voxel Based Fluid-Structure-Cell Interaction Analysis

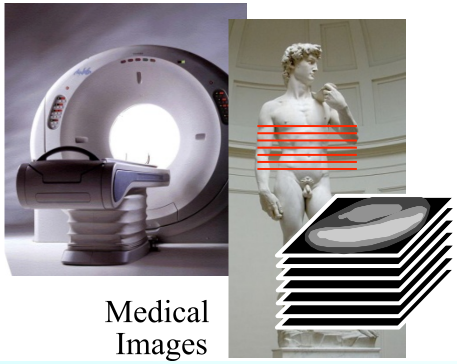
Background

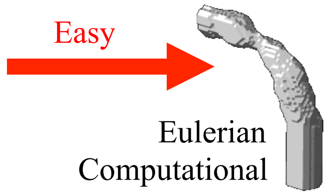
- **Many blood flow simulation using realistic blood vessel shape are performed**
- **Because blood flow is driven by heart deformation, considering of heart deformation is preferable to blood flow simulation**
- **Therefore, blood flow simulation need fluid-structure interaction between flow and heart deformation essentially**
- **In addition, heat deformation have closely relationship with cardiomyocyte behavior**
- **Accordingly, realistic blood flow simulation need heart simulation involving with heart deformation and cardiomyocyte behavior**

Our Aim

To help daily medical for each patients, obtaining computational grid should be easy

- Blood vessel and heart shape are obtained from medical images as Voxel data →Easy to obtain grid





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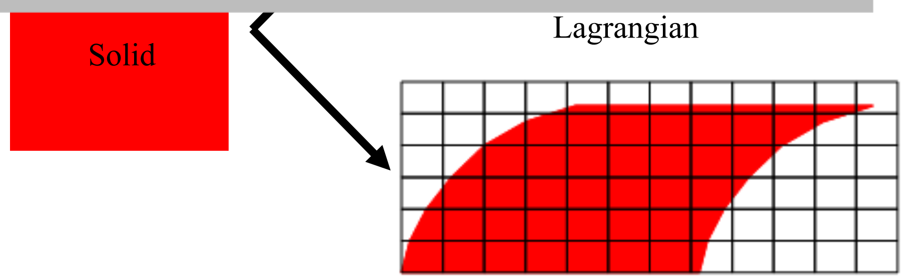
Our Aim:
Development of fluid-structure-cardiomyocyte interactive simulation system on Eulerian frame

This presentation introduces basic idea and introductive current experiment

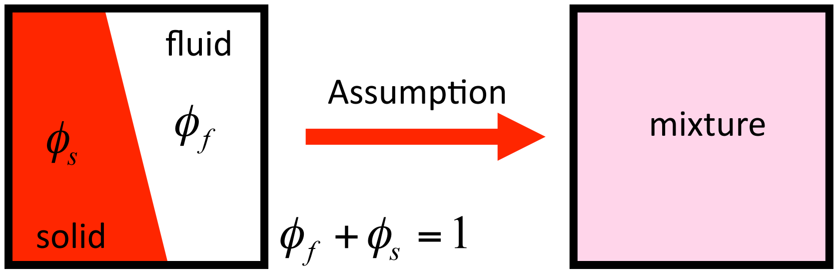
In terms of easiness of performing fluid-structure interaction simulation, it is desirable to simulate deformation in Eulerian frame by same way to fluid analysis



Governing Equation

Assumption

We assumed heart wall and blood are "Incompressible continuous" and considered mixture medium



Governing equation

- **Mass conservation law of incompressible continuous mixture medium**

$$\nabla \cdot \boldsymbol{v}_{mix} = 0 \quad (1)$$

- **Momentum conservation law (Navier-Stokes Eq.)**

$$\rho_{mix}\left\{\frac{\partial \boldsymbol{v}_{mix}}{\partial \boldsymbol{t}} + (\boldsymbol{v}_{mix}\cdot\nabla)\cdot\boldsymbol{v}_{mix}\right\} = -\nabla p + \nabla\cdot\left(\phi_f \boldsymbol{\sigma}'_f + \phi_s \boldsymbol{\sigma}'_s\right) \quad (2)$$

Deviatoric stress term

Fluid (Newtonian)

$$\boldsymbol{\sigma}'_f = 2\mu \boldsymbol{D} - p\boldsymbol{I}$$

Solid

$$\boldsymbol{\sigma}'_s = \left\langle \begin{array}{ll} 2GA & \text{Liner Elastic} \\ G\left\{\boldsymbol{B} - \frac{1}{3}\mathrm{tr}(\boldsymbol{B})\boldsymbol{I}\right\} & \text{Hyper Elastic (Neo Hook)} \end{array} \right.$$

Dev. Stress defined with velocity by these formula

$$\frac{\partial \boldsymbol{B}}{\partial t} + (\boldsymbol{v}_{mix}\cdot\nabla)\cdot\boldsymbol{B} = \boldsymbol{L}\cdot\boldsymbol{B} + \boldsymbol{B}\cdot\boldsymbol{L}^T$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + (\boldsymbol{v}_{mix}\cdot\nabla)\cdot\boldsymbol{A} = \boldsymbol{D} - \boldsymbol{L}^T\cdot\boldsymbol{A} - \boldsymbol{A}\cdot\boldsymbol{L}$$

$$\boldsymbol{D} \equiv \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\boldsymbol{e}_i\otimes\boldsymbol{e}_j \qquad \boldsymbol{L} \equiv \frac{\partial v_i}{\partial x_j}\,\boldsymbol{e}_i\otimes\boldsymbol{e}_j$$

Mixture motion can solved by CFD scheme

ϕ_f	Volumetric ratio of fluid	P	Pressure	D	Stretching tensor	B	Left CG deform. tensor
ϕ_s	Volumetric ratio of solid	σ'_f	Fluid stress	I	Unit tensor	L	Velocity gradient tensor
v_{mix}	Mixtured Velocity	σ'_s	Solid stress	A	Almansi strain	D	Stretching tensor
ρ_{mix}	Mixtured Density	ν	Viscosity	G	Shear modules		

Implement Cardiomyocyte Contractile Effect

- **Previously introduced solid stress term is caused by deformation →Passive Stress**
- **To treat self-contraction of heart wall, we added new stress term →Active Stress**

Re-Define Solid Stress

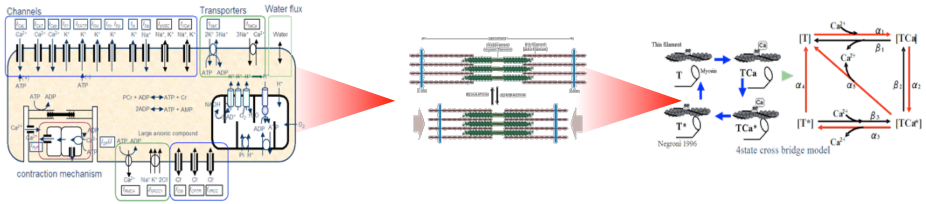
$$\boldsymbol{\sigma}'_s = \boldsymbol{\sigma}_s^{Active} + \boldsymbol{\sigma}_s^{Passive}$$

$\boldsymbol{\sigma}_s^{Active} =$ Active stress Calculated by cardio-myocyte simulator

$$\boldsymbol{\sigma}_s^{Passive} = G\left\{\boldsymbol{B} - \frac{1}{3}\mathrm{tr}(\boldsymbol{B})\boldsymbol{I}\right\}$$

Passive

Cardiomyocyte contractile simulation model by Kyoto Model



Entire cell model

Contractile model of cardiomyocyte fiber

simBio, KyotoModel, http://www.biosim.med.kyoto-u.ac.jp/, Sarai, 2006

Deformation Treatment

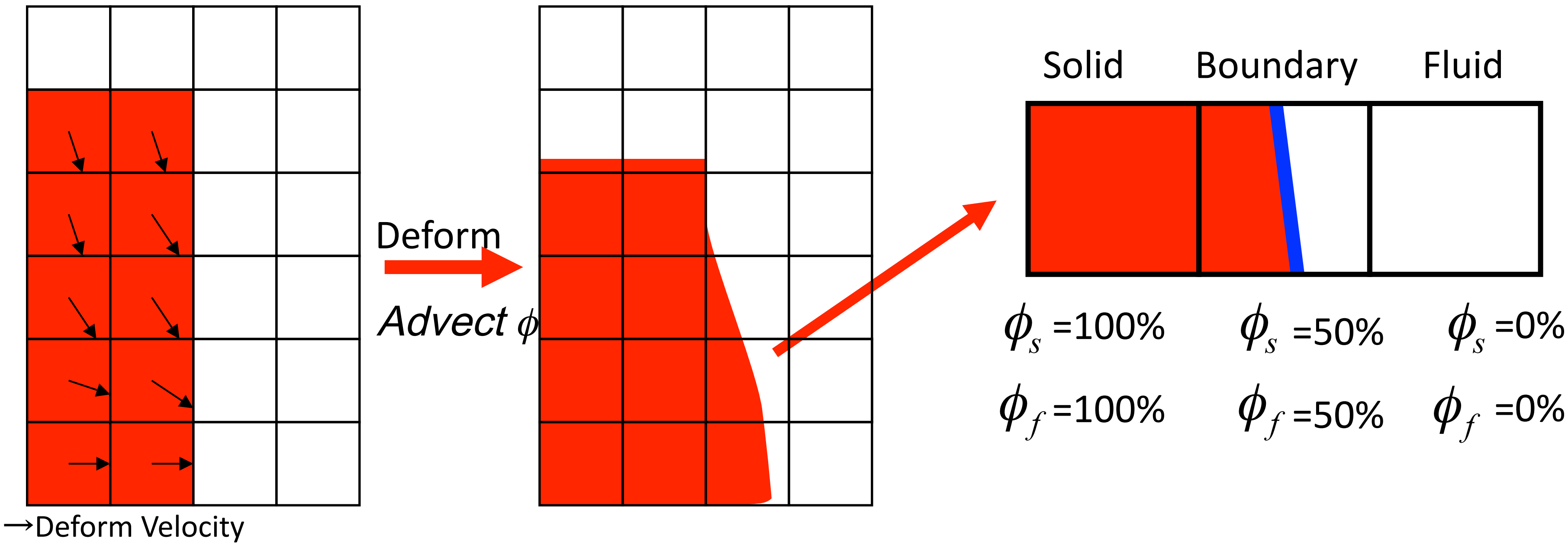
- **Deformation simulation should treat object boundary moving**

  VOF method

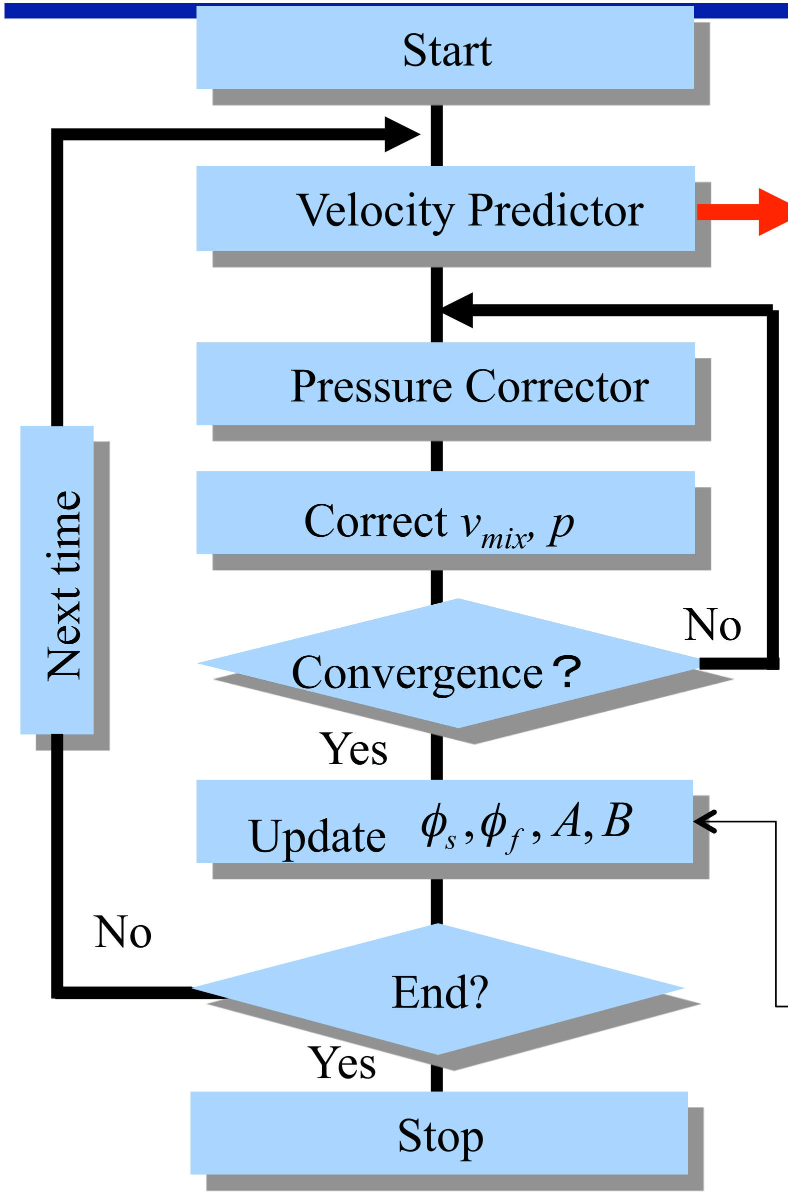
  - Each Control Volume(CV) has volumetric ratio ϕ of the considering elastic solid to each CV volume
  - Surface moving described by volumetric ratio ϕ change by solving ϕ transport equation

$$\frac{\partial \phi_s}{\partial t} + (\boldsymbol{v}_{mix} \cdot \nabla)\phi_s = 0$$

$$\frac{\partial \phi_f}{\partial t} + (\boldsymbol{v}_{mix} \cdot \nabla)\phi_f = 0$$



Computational Algorithm



Conventional CFD scheme SMAC

Using mixture stress instead of fluid stress

$$\boldsymbol{v}^* = \boldsymbol{v}^n_{mix} + \Delta t\left\{-\left(\boldsymbol{v}^n_{mix}\cdot\nabla\right)\boldsymbol{v}^n_{mix} + \frac{1}{\rho}\left(\nabla\cdot\boldsymbol{\sigma}'_{mix}\right)\right\}$$

$$\boldsymbol{\sigma}'_{mix} = \phi_f \boldsymbol{\sigma}'_f + \phi_s\left(\boldsymbol{\sigma}_s^{Passive} + \boldsymbol{\sigma}_s^{Active}\right)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \left(\boldsymbol{v}_{mix}\cdot\nabla\right)\cdot\boldsymbol{B} = \boldsymbol{L}\cdot\boldsymbol{B} + \boldsymbol{B}\cdot\boldsymbol{L}^T$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + \left(\boldsymbol{v}_{mix}\cdot\nabla\right)\cdot\boldsymbol{A} = \boldsymbol{D} - \boldsymbol{L}^T\cdot\boldsymbol{A} - \boldsymbol{A}\cdot\boldsymbol{L}$$

$$\frac{\partial \phi_s}{\partial t} + \left(\boldsymbol{v}_{mix}\cdot\nabla\right)\phi_s = 0$$

Comparing Solid Materials

- **Comparing solid materials（Linear and N.H.) behavior when self shrinkage by active stress**

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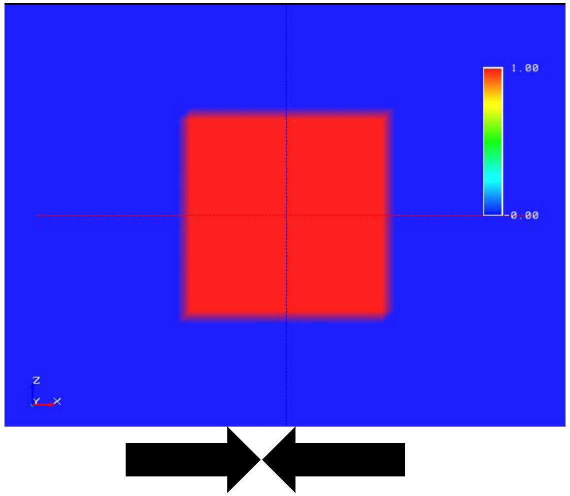
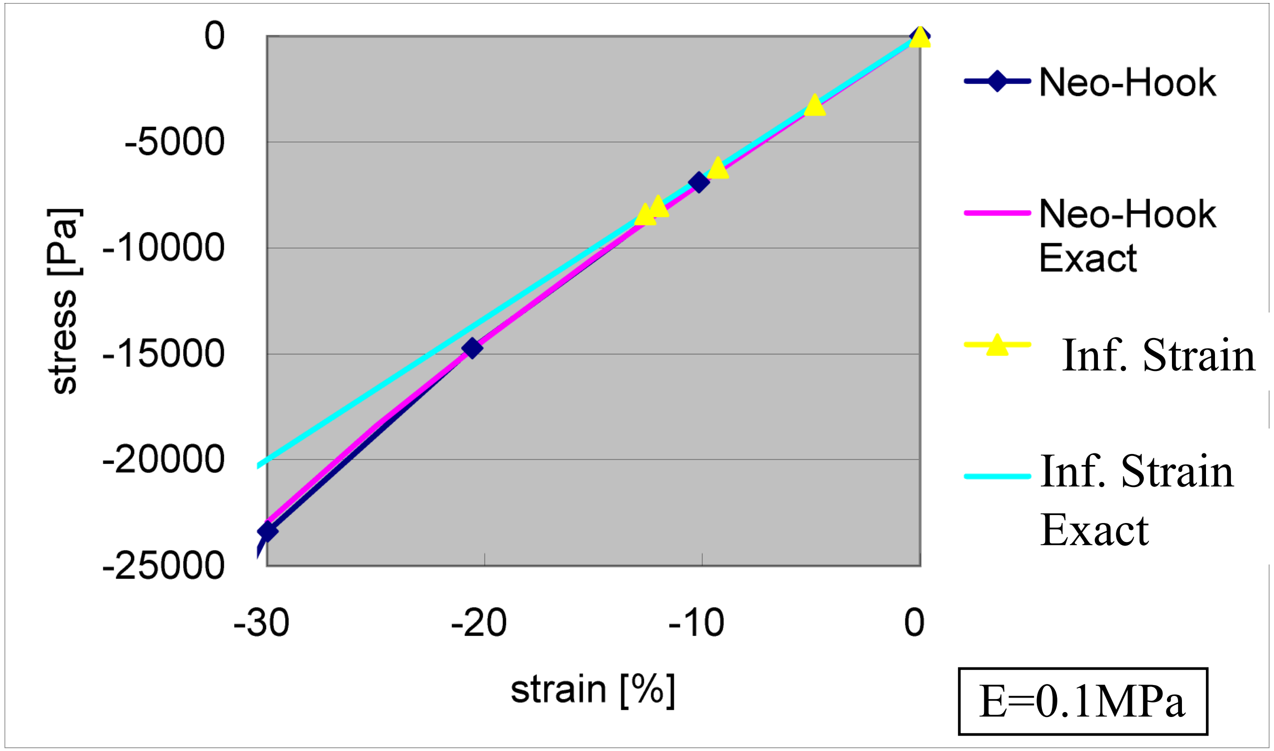


Shrink horizontal
by active stress



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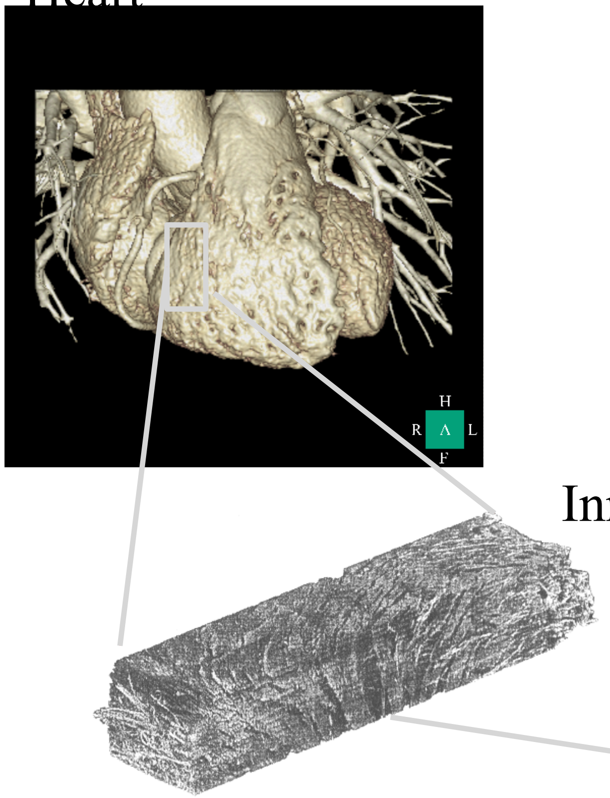
Large difference when large strain

Since heart is active tissue and large deform, it is suitable for employing Hyper elastic model

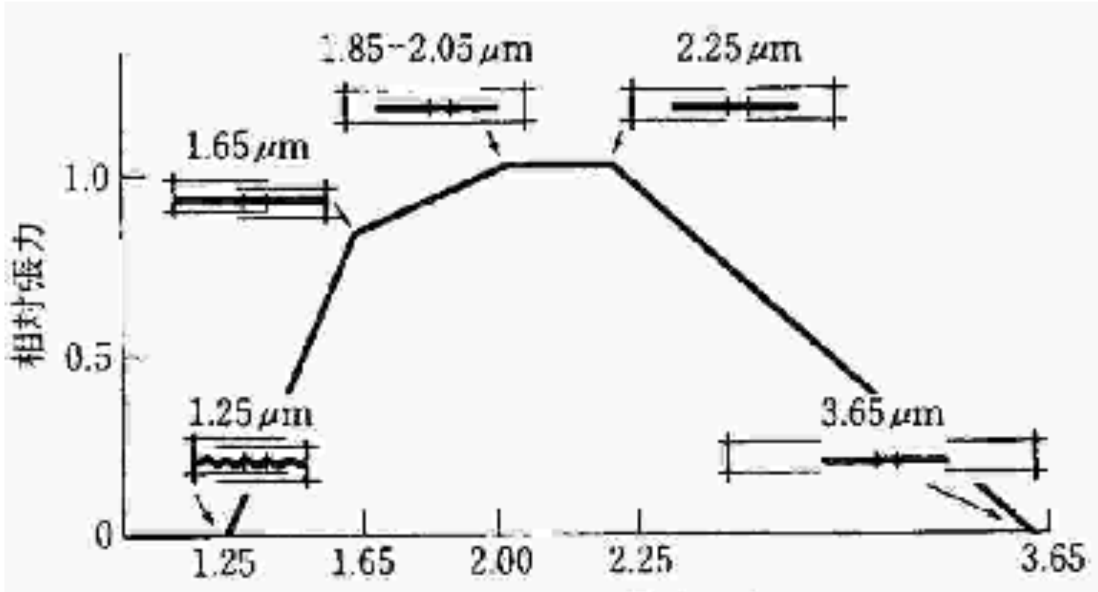
Treatment for Cardiomyocyte Orientation and Length

Heart



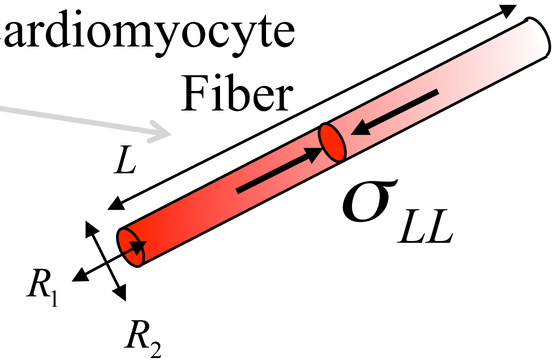
Inner

Outer



Contractile force is proportional to its length

Cardiomyocyte Fiber

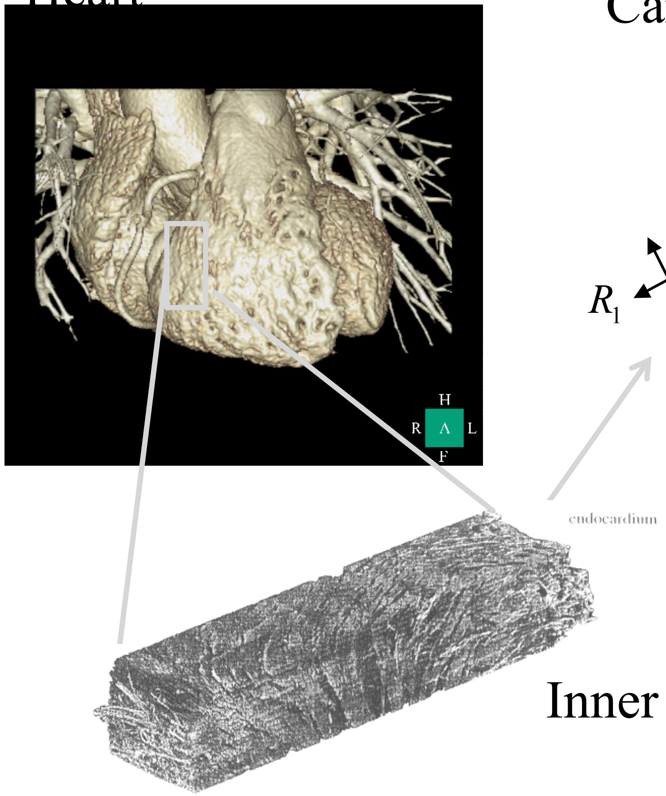


Cardiomyocyte Local Contractile Stress Tensor

$$\sigma_{Local} = \begin{pmatrix} \sigma_{LL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Implement Cardiomyocyte Orientation

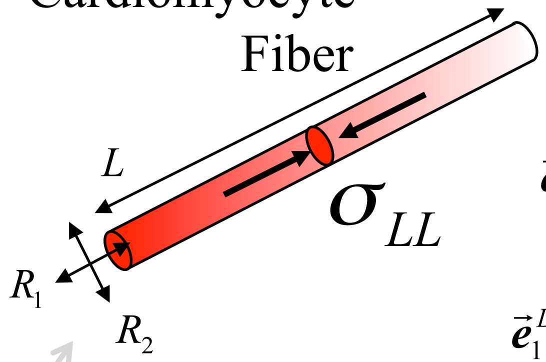
Heart

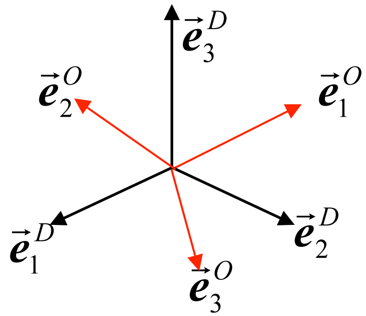


Inner

Outer

Cardiomyocyte Fiber





$\vec{e}_i^{\,D}$

Global Coordinate Basis Vector

$\vec{e}_i^{\,O}$

Cardiomyocyte Coordinate Basis Vector

Cardiomyocyte Local Contractile Stress Tensor

$$\sigma_{Local} = \begin{pmatrix} \sigma_{LL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

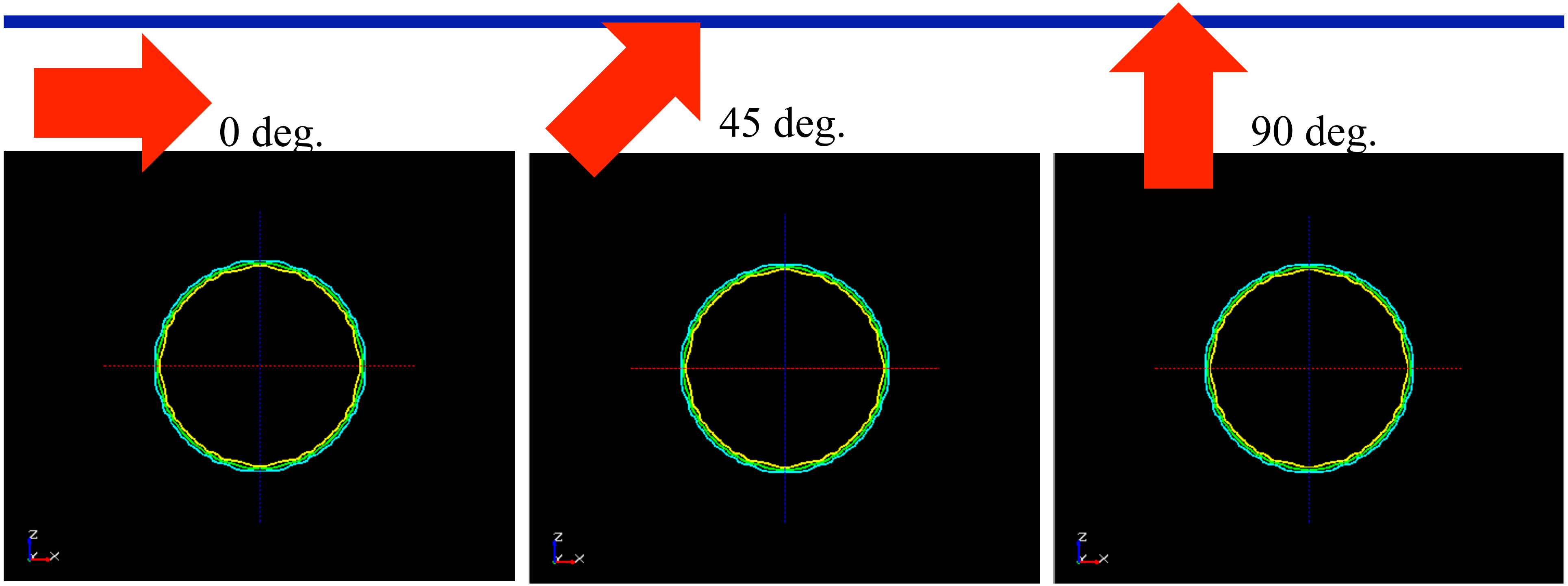
Rotation tensor

$$\boldsymbol{R} = \vec{e}_j^{\,O} \otimes \boldsymbol{e}_j^{D}$$

Rotated contractile stress tensor

$$\sigma_s^{Active} = R \cdot \sigma_{Local} \cdot R^T$$

Sample of Active Stress Rotation



Horizontal Diagonal Vertical

These figures shows the sample of active stress rotation.
Rounds solids have each own orientation, 0-degree, 45-degree, 90-degree.
Solids show different deformation, horizontal, diagonal, vertical contractile

Orientation Tracking

It is need to track the orientation basis vector direction change caused by solid deformation

$$d\boldsymbol{x} = \boldsymbol{F} \cdot d\boldsymbol{X}$$

$$\downarrow$$

$$d\dot{\boldsymbol{x}} = \dot{\boldsymbol{F}} \cdot d\boldsymbol{X}$$

$$= \dot{\boldsymbol{F}} \cdot \left(\boldsymbol{F}^{-1} \cdot d\boldsymbol{x}\right)$$

$$= \boldsymbol{L} \cdot d\boldsymbol{x}$$

Deformation formulation using velocity gradient tensor L, instead of deformation gradient tensor F.

Advection Equation of Orientation Basis Vector

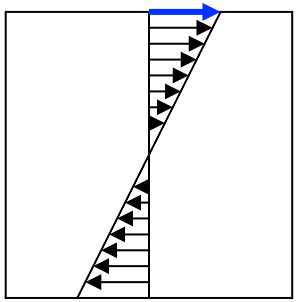
$$\frac{\partial \boldsymbol{e}_i^O}{\partial t} + (\boldsymbol{v}_{mix} \cdot \nabla)\boldsymbol{e}_i^O = \boldsymbol{L} \cdot \boldsymbol{e}_i^O$$

Solving this advection tracks orientation basis vector $\vec{\boldsymbol{e}}_i^O$

F: deformation gradient
dx: deformed vector
dX: original vector

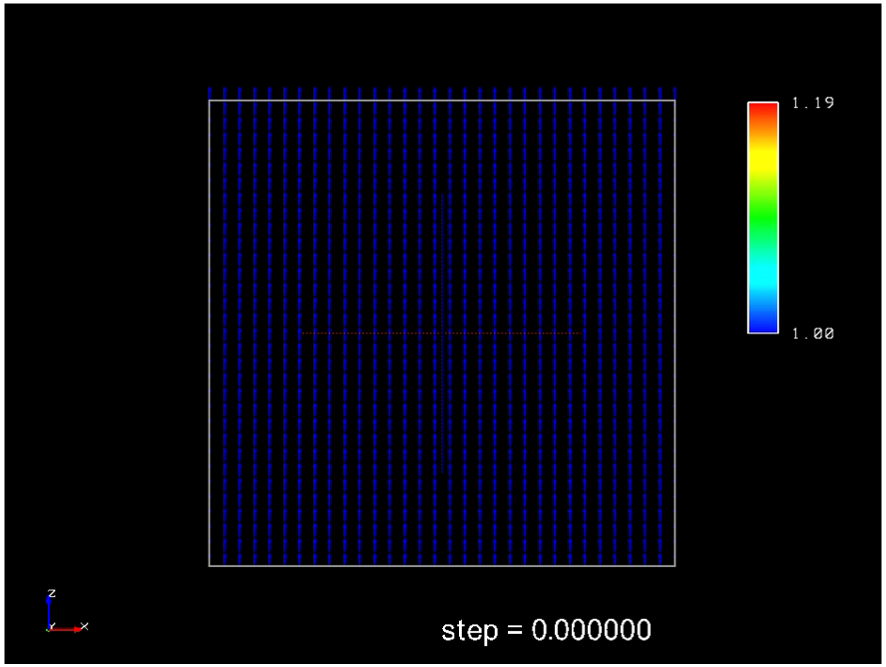
Sample of Orientation Tracking

$u = \sin(2\pi t)$

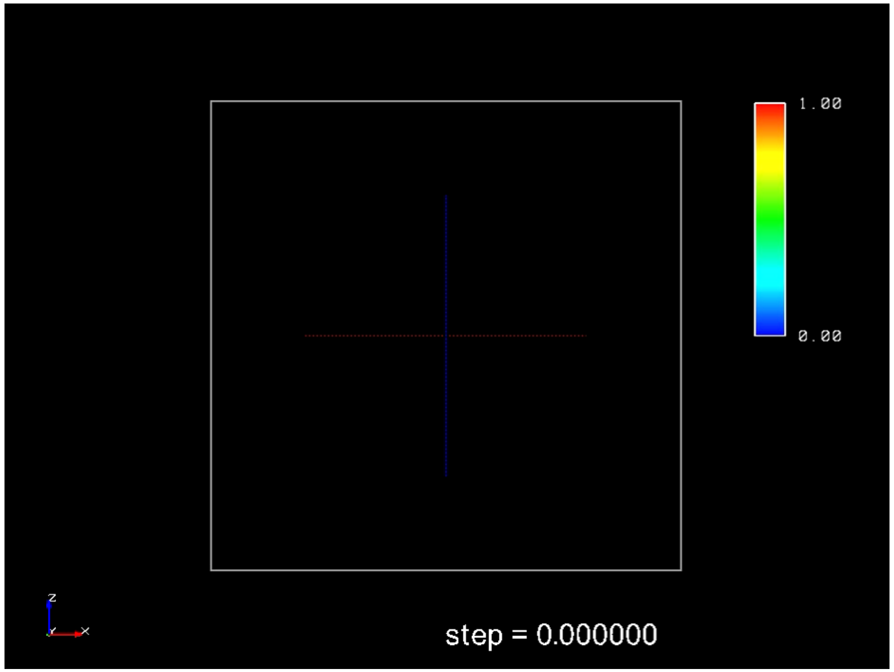


Track orientation vector in case of shearing velocity cycle of 1.0[s]

Initial orientation ⇒ Change by velocity

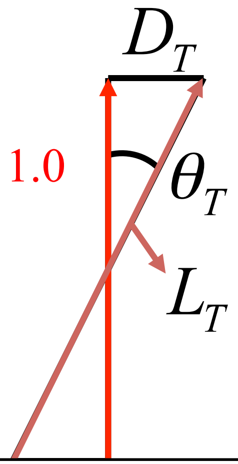


Velocity



Orientation Vector

Tracking Verification by Comparing with Exact solution



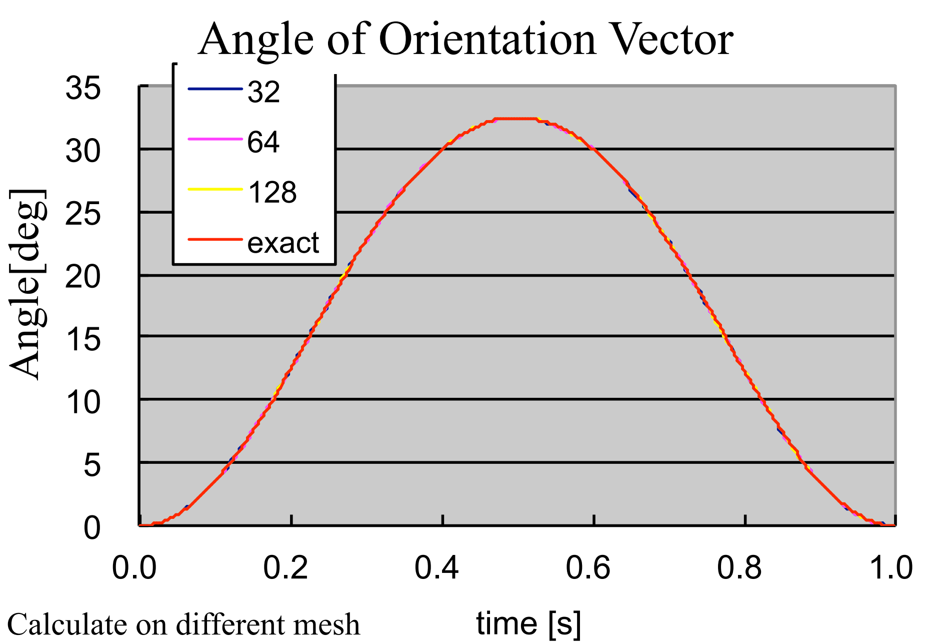
$$D_T = \int_0^T \sin(2\pi t)dt = \frac{1-\cos(2\pi T)}{2\pi}$$

$$\tan\theta|_T = D_T / 0.5$$

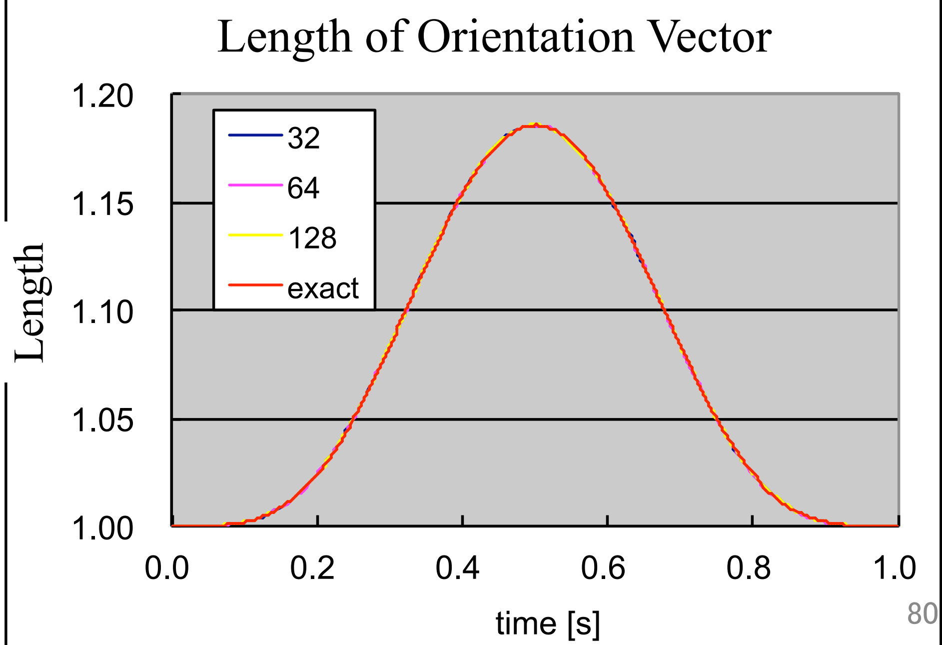
Exact solution at time T

Angle $\theta_T = \mathrm{Tan}^{-1}\left(\frac{1-\cos(2\pi T)}{\pi}\right)$

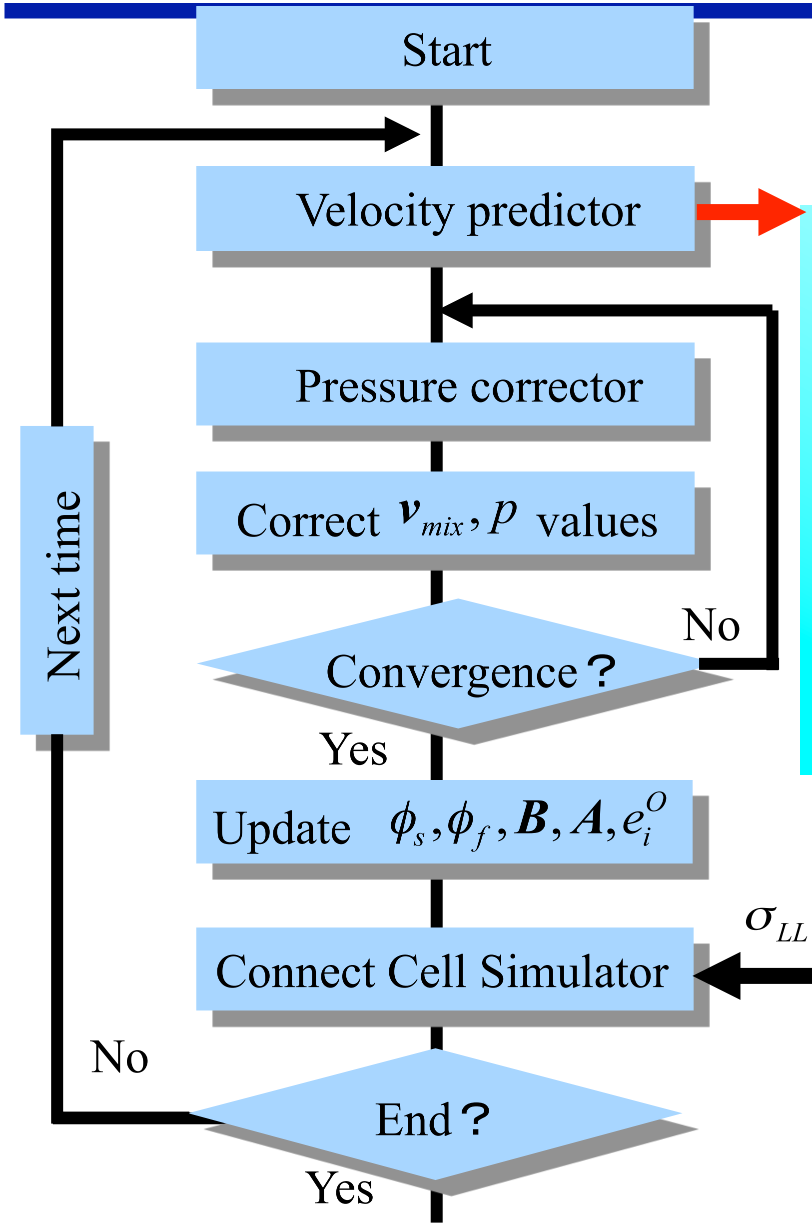
Length $L_T = \frac{1}{\cos(\theta_T)}$



Calculate on different mesh



Final Computational Algorithm



Conventional CFD scheme SMAC

Using mixture stress instead of fluid stress

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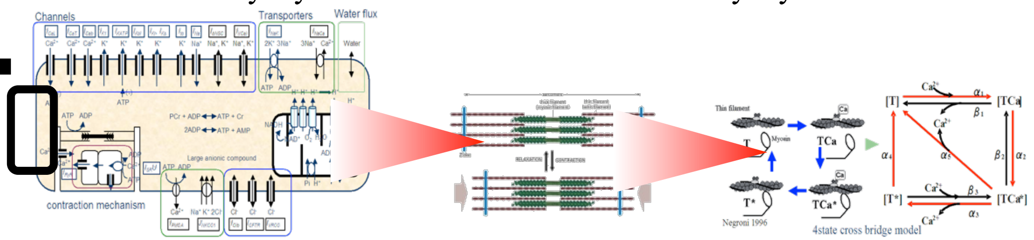
$$\boldsymbol{\sigma}'_{mix} = \phi_f \boldsymbol{\sigma}'_f + \phi_s\left(\boldsymbol{\sigma}_s^{Passive} + \boldsymbol{\sigma}_s^{Active}\right)$$

Cardiomyocyte Simulator SimBIO

Cardiomyocyte contractile simulation model by Kyoto Model



Entire cell model

Contractile model of cardiomyocyte fiber

Numerical Experiment

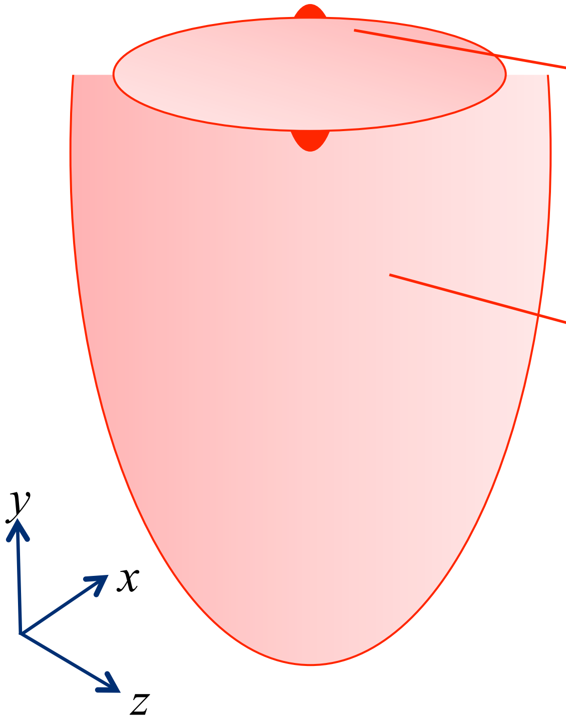
Analysis Simple Left-Ventricle(LV) Model Motion

Model Shape is Ellipsoid

$r_x = r_z$=Short Radius=2.4cm

r_y=Long Radius=3.6cm

Wall Thickness=1.0cm



Inner Fluid

μ=0.0035Pa･s

ρ=1000Kg/m^3

Heart Wall

E=50KPa

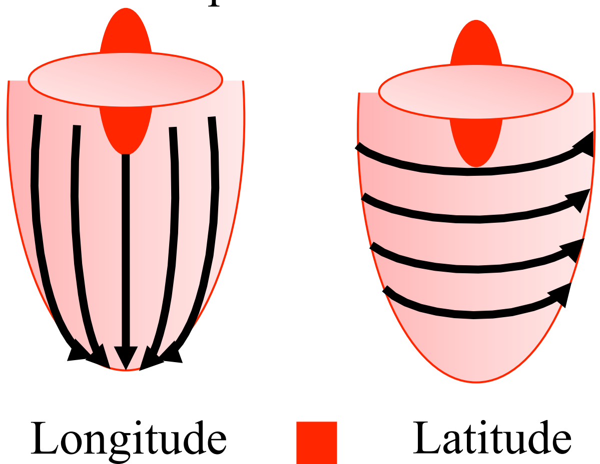
ρ=1050Kg/m^3

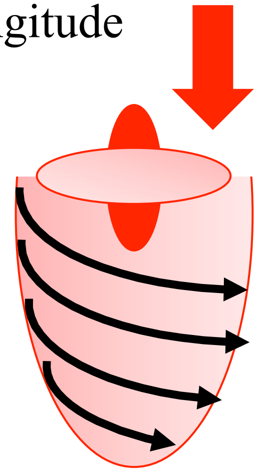
Surrounding Fluid

μ=0.0035Pa･s

ρ=1000Kg/m^3

Orientation vector consist 2 kind of direction component



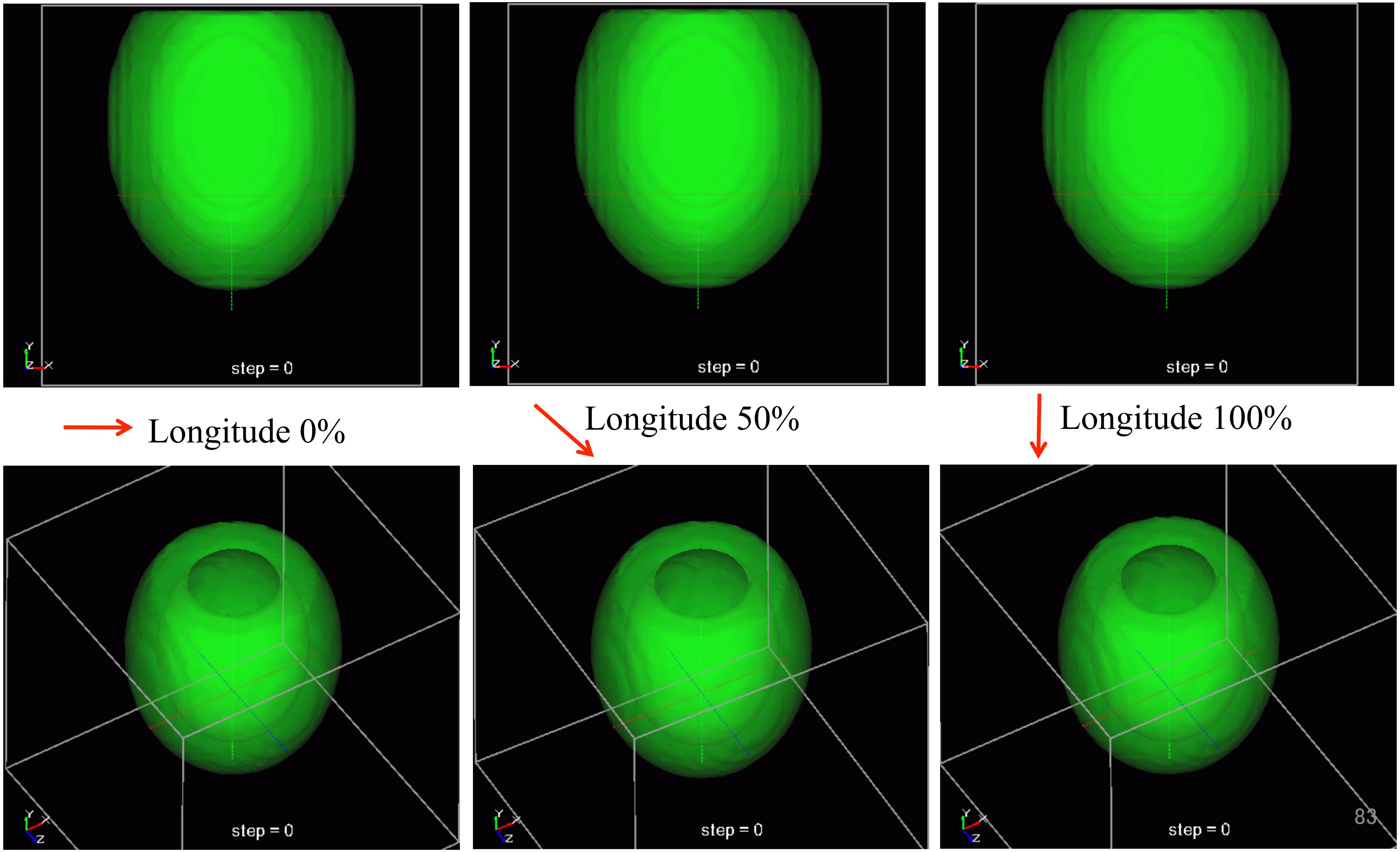


Example

Longitude 30%

Latitude 70%

Aspect of LV Model Deformation

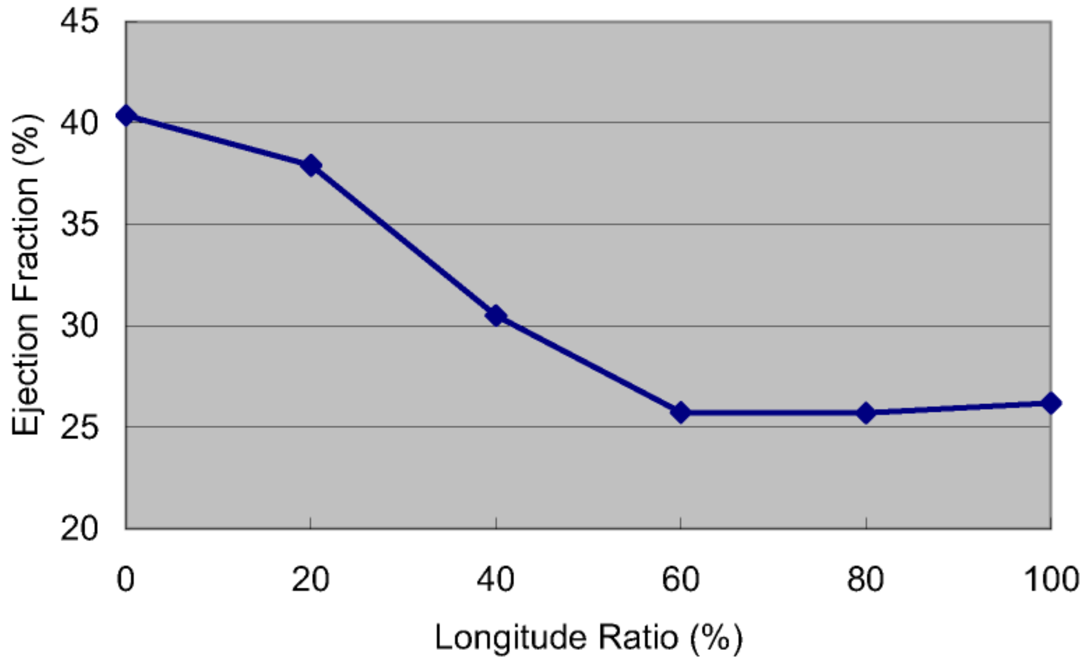


Ejection Fraction

Ejection Fraction:
Index of heart-pump function.
It means how much blood the heart send.

$$E.F = \frac{EDV - ESV}{EDV}$$

EDV: End Diastolic Volume
ESV: End Systolic Volume



Confirmed:

Orientation difference is cause of difference of LV contractile

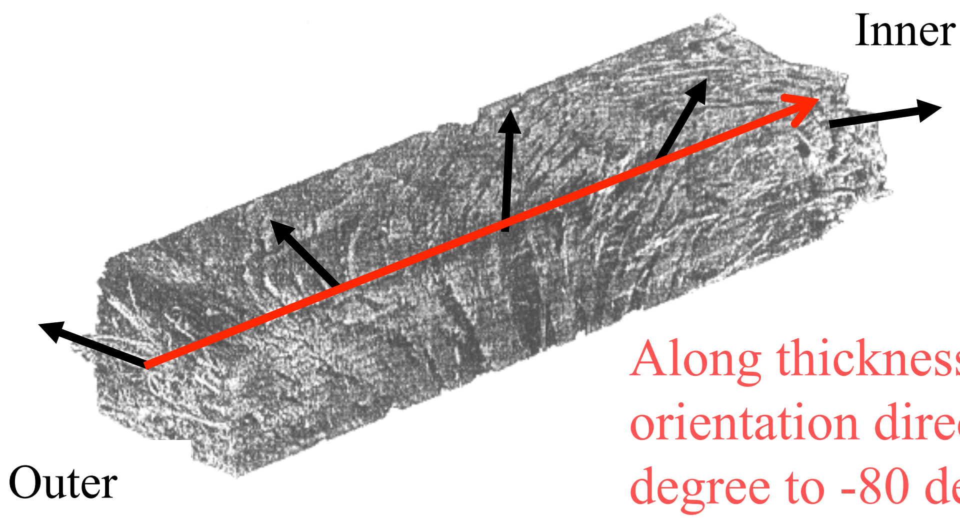
Largest ejection fraction showed in case of the longitude 100%

In actual heart

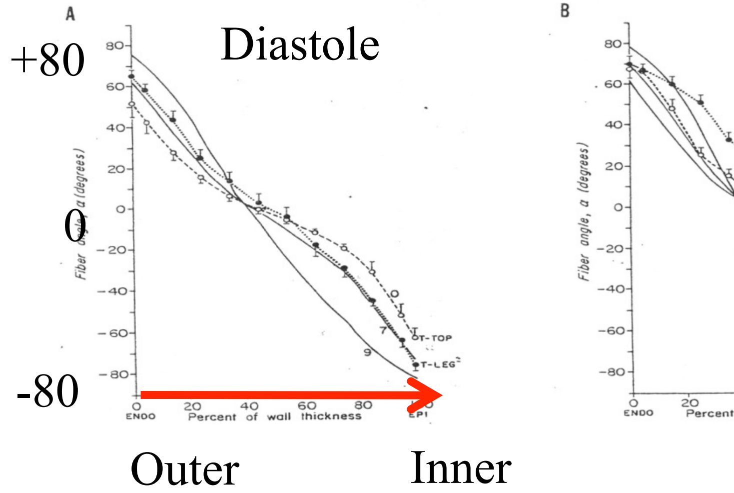
EDV=120ml and ESV=70ml, therefore ejection fraction about 40%

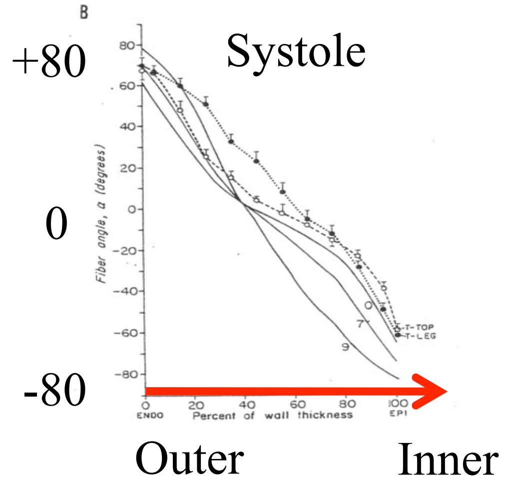
More complicated orientation distribution along thickness direction

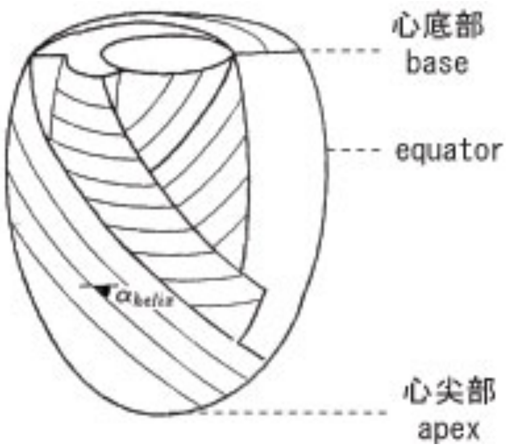
Future Development
More Complicated Orientation Model

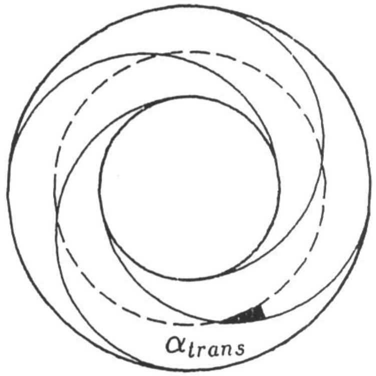


Along thickness direction, orientation direction rotate +80 degree to -80 degree







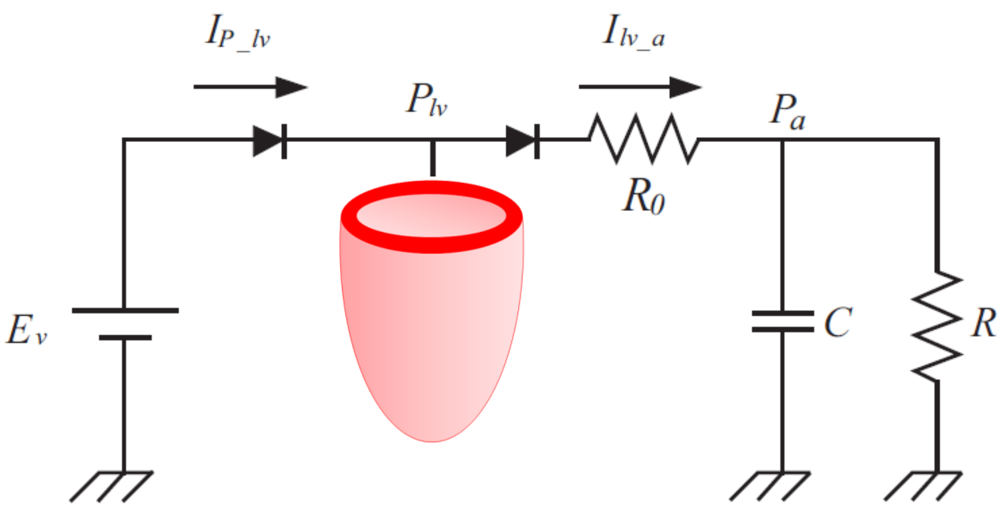


Daniel D. Streeter, et at. al, “Engineering Mechanics for Successive State in Canine Left Ventricular Myocardium:II. Fiber Angle and Sarcomere Length”, Circ.Res.1973;33;656-664.

Future Development
Heart-Valve Model

On opening part of LV model, connect blood vessel model (Windkessel model)

Simulate valve motion by control boundary condition of opening part during each heart phase



I_{p_lv}: Vein→LV flow amount
I_{lv_a} : LV→Aorta flow amount
V_{lv}: LV volume
P_{lv}: LV pressure
P_a : Aorta pressure

E_v: Vein pressure
C: Compliance
R: Peripheral resistance
R_0: Characteristic impedance

Ejection Phase
- Flow to Aorta from LV
- LV pressure > Aorta pressure
- Allow out-flow on opening part

Iso-volumetric Phase
- No Flow
- LV pressure < Aorta Pressure
- LV pressure > Vein Pressure
- Not allow flow on opening part

Filling Phase
- Flow to LV from Vein-side (Atrium)
- LV pressure < Vein pressure
- Allow in-flow on opening part

Conclusion

To simulate heart motion in voxel data from medical image, develop code based on Eulerian frame

- Formulate solid stress term so that it will be determined by velocity field
- Employ VOF method to treat different material boundary
- Employ SMAC method to solve deformation problem in similar way of fluid problem

By using the code

- Solid deformation problem was solve in Eulerian frames
- Fluid flow driven by wall motion was obtained by active stress
- Confirm orientation difference makes contractile difference
- Obtain good agree of ejection fraction to actual heart

In the future

- Implement heart valve model
- Use more realistic orientation model
- Simulate on realistic heart shape from CT/MRI image

Our Research Activities Summary

- We have paid lot attention about the CFD and HPC
- Today We showed some our studies for biomechanics flow
- And we continued to study these other subjects
  - Hybrid parallelization for CFD software on multi-core cluster computer
  - Real-time visualization on distributed computing
  - New visualize scheme to emphasize complicated flow structure
- We hope that the computational biomechanics simulation will be a useful tool to improve medical and quality of life for everyone

Acknowledgement

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END

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