バイオスーパーコンピューティング東北2014
２０１４年６月２日

予測医療を目指して
ーマルチモダリティと血流シミュレーションの融合ー

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Outline

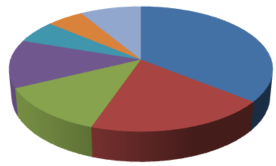
- *Introduction*
- *Patient-specific modeling of vascular geometry*
- *Numerical method*
  - *1D-0D Simulation of the entire circulation including the cerebrovascular system*
- *Patient-Specific simulation for Cerebrovascular circulation after carotid stenting*
  - *Measurement data & 3D-1D-0D simulation*
  - *Measurement data & 1D-0D simulation*
- *Summary and Future Work*

Background : the situation of cardiovascular diseases in Japan

Main causes of death in Japan

- Cancer 28.5%
- Heart disease 15.6%
- Cerebrovascular disorder 9.9%

Cardiovascular disease



Statics according to Ministry of Health, Labour and Welfare (2012)

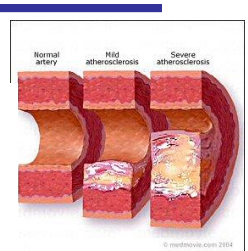
Since Japan is becoming an aging society, the number of patients with cardiovascular diseases would increase.

There is high possibility for a patient to become paralysis or bedridden.

Quality of life of the patient becomes low.
The family experience the burden of long-term care.

Background & Motivation — Atherosclerosis—

It is a main cause of stroke and heart attack

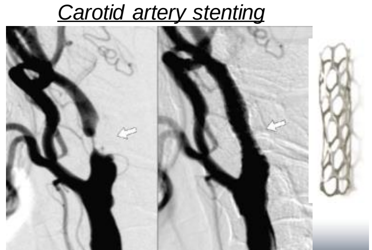


- *Characteristics of atherosclerosis formed at preferential locations such as bifurcation areas with low WSS(wall shear stress)*
- *Treatment :*

Carotid artery stenting is becoming widely used

- *restenosis*
- *intracranial hemorrhage (ICH)*

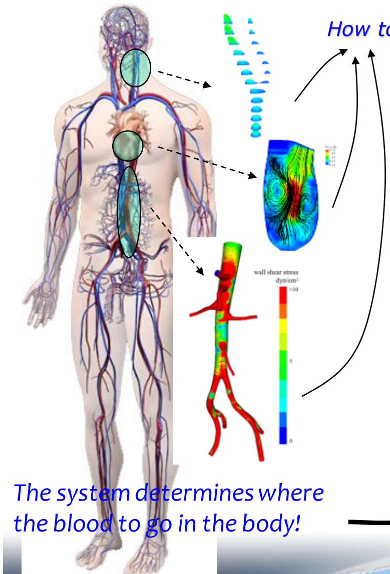
Carotid artery stenting



How can we predict the influences of the surgery on individuals in the preoperative stage ?

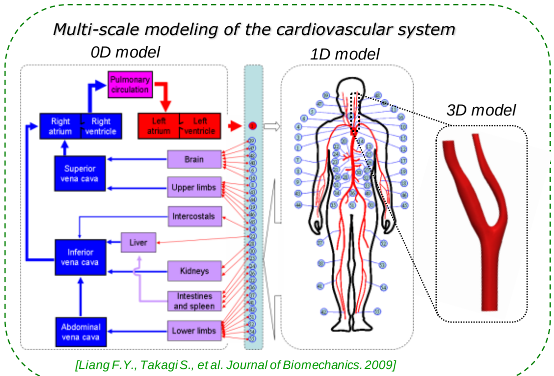
Patient-specific computer simulation

Objectives



How to correctly prescribe boundary conditions?

Place a 3-D model into a model of the entire system

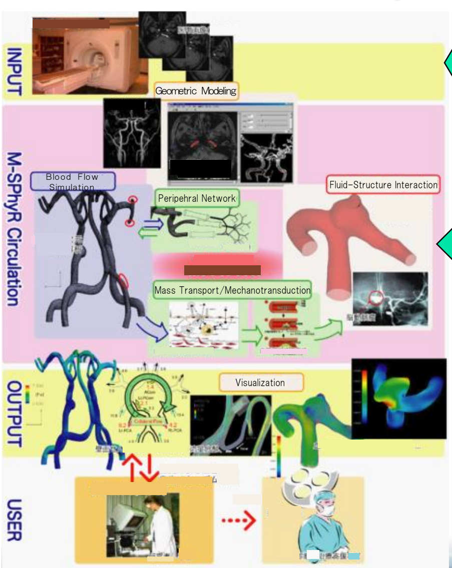


[Liang F.Y., Takagi S., et al. Journal of Biomechanics. 2009]

The system determines where the blood to go in the body!

Account for blood distribution over the entire system

Geometrical multi-scale modeling & simulation of the cardiovascular system



[Numerical Issues]

**Patient-Specific Modeling*

**Modeling of Boundary Conditions*

- Even though a simulation is conducted for a local region, it is necessary to consider the rest of circulatory system

- How ?

mutiscale (multi-domain) approach

**Blood Flow–Arterial Wall Interaction*

- It is important to examine wave propagation & influence of hemodynamics on arterial wall

[Blood simulation for cerebral aneurysms & *atherosclerosis]*

- *Shoujima, M. et al., Stroke, (2004,2005)*
- *Meng H, et al., Stroke (2007).*
- *Cebral, J . Et al., Am/, J. Neuroradiol (2005)*
- *Oshima, M., Current Pharmaceutical Biotechnology (2011)*

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Patient-Specific Modeling of Vascular Modeling

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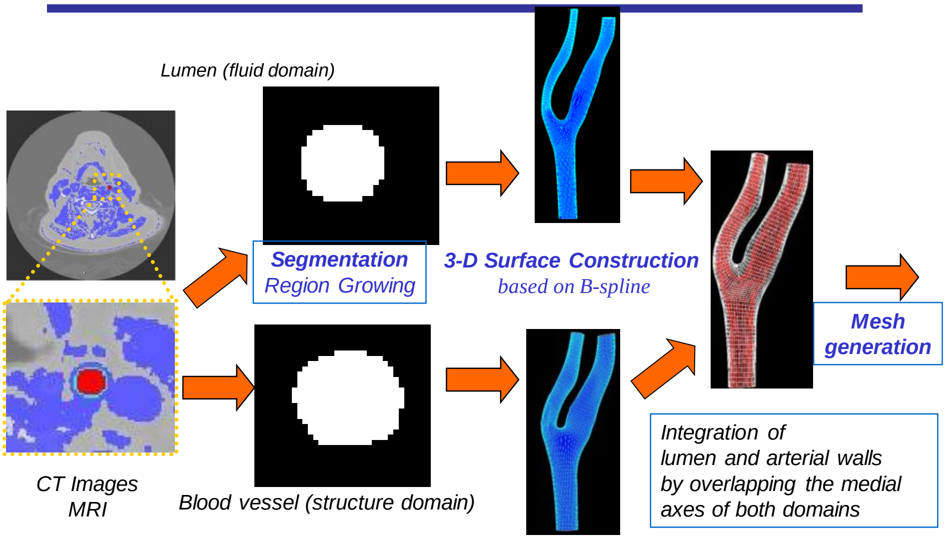
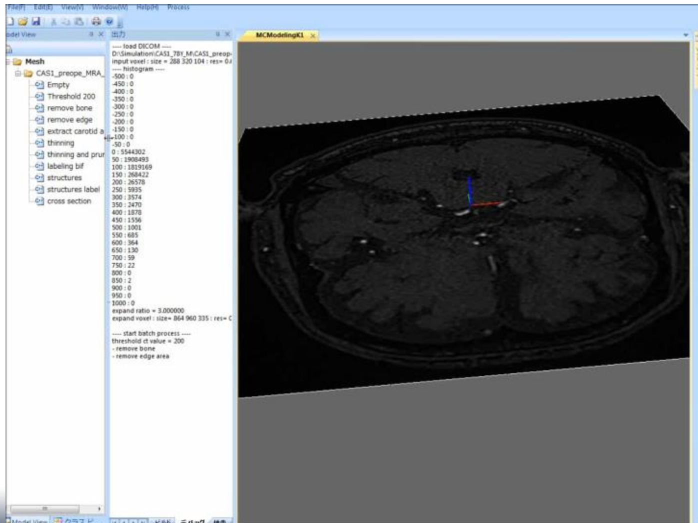
Geometric modeling of lumen and arterial walls



Extraction of a medial axis using the voxel reduction technique,“ Thinning”

V-Modeler – Interactive operation based on GUI

･78 years old, male: The arterial circular of Willis



･Medial axis
･Identify the radius & length
･Categorize a type of artery according to the anatomy

･possible to conduct virtual surgery such as stent and bypass surgery

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Multi-Scale Simulation

1D-0D simulation
3D-1D-0D simulation

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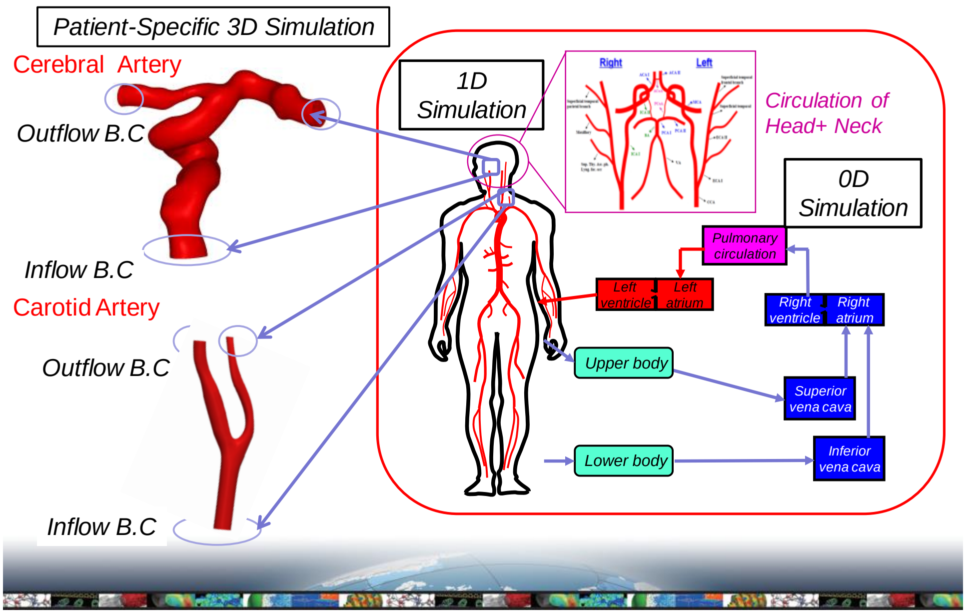
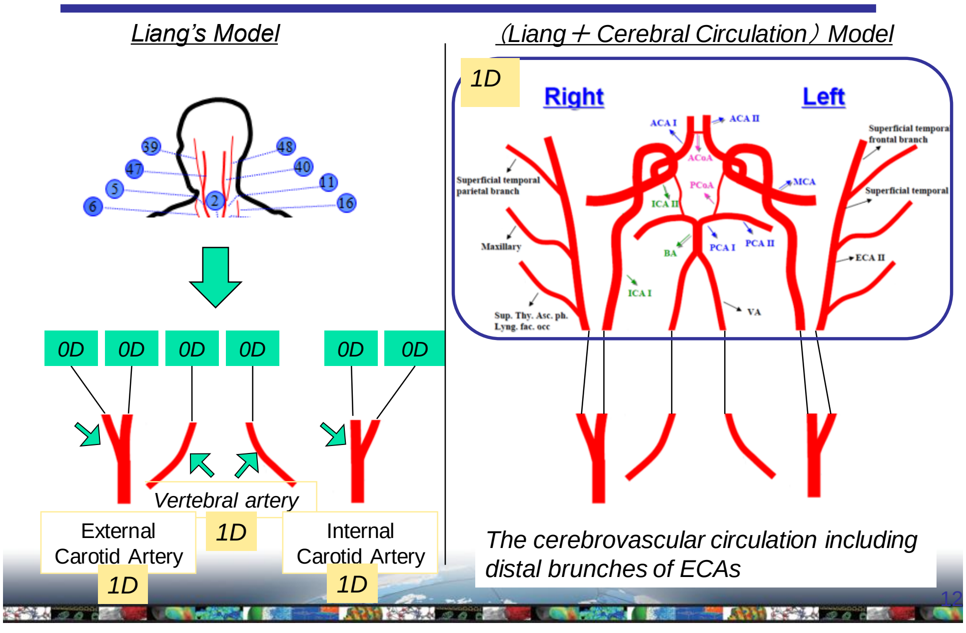
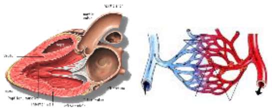
Schematic Illustration of multi-scale simulation of the circulatory system



Cerebrovascular circulation

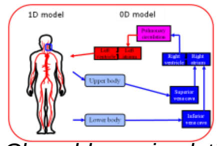


1D-0D modeling of the entire cardiovascular system

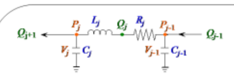


<0D model> +

<1D model> =



Closed-loop circulation model



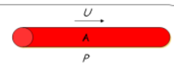
Mass and momentum conservation equations

$$\frac{dV_j}{dt} = Q_j - Q_{j+1}$$

$$L_j \frac{dQ_j}{dt} = P_{j-1} - Q_j R_j - P_j$$

Pressure-volume relationship

$$P_j = V_j / C_j$$



Mass and momentum conservation equations

$$\frac{\partial}{\partial t}\begin{pmatrix} A \\ U \end{pmatrix} + \frac{\partial}{\partial z}\begin{pmatrix} UA \\ \frac{U^2}{2} + \frac{P}{\rho} \end{pmatrix} = \begin{pmatrix} 0 \\ -K_R \frac{U}{A} \end{pmatrix}$$

Pressure-area relationship

$$P - P_0 = \frac{Eh_0}{r_0(1-\sigma^2)}\left(\sqrt{\frac{A}{A_0}} - 1\right)$$

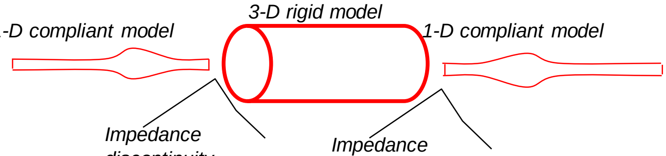
Fourth-order Runge-Kutta method ⇔ Coupling ⇔ Interior points: Two-Step Lax-Wendroff method; Bifurcation conditions: Ghost-point method coupled with the Newton–Raphson method

[F.Y. Liang et al. Medical & Biological Engineering & Computing. 2009]

Roles of model

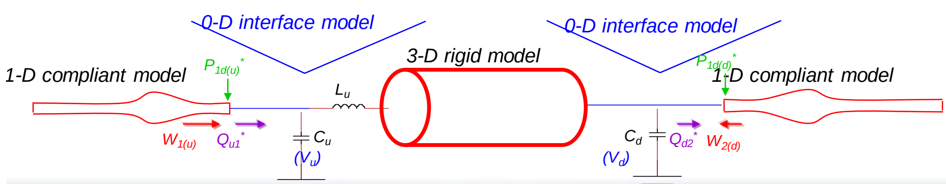
- 1D model describes pulse wave propagation in the arterial system
- 0D model closes the 1D model to account for systemic hemodynamic behaviors.

Coupling of a 1-D compliant model and a 3-D rigid model

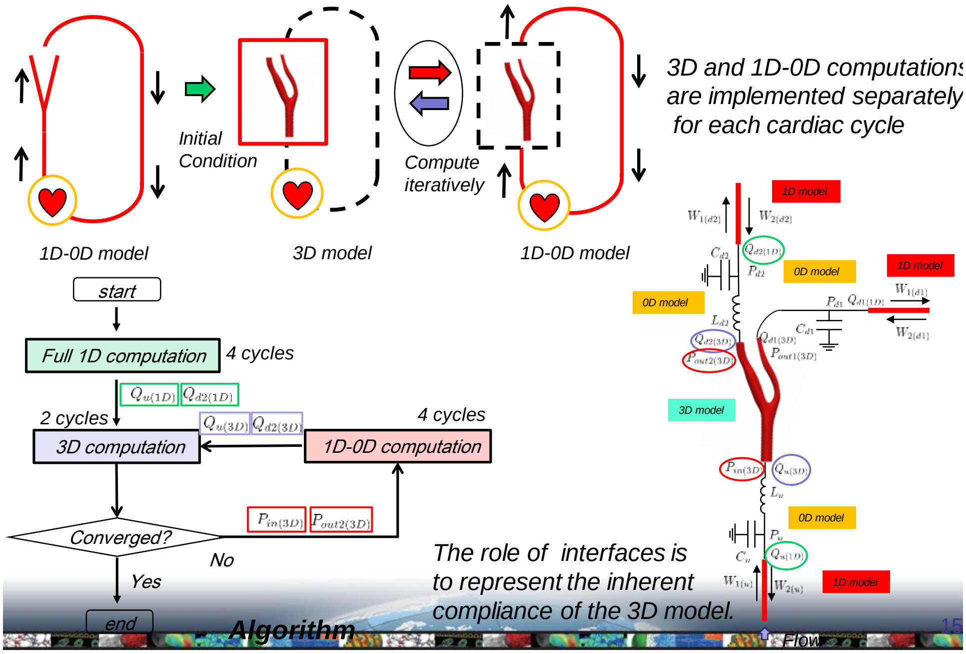


A direct coupling results in unrealistic wave reflection

(Passerini et al. Journal of Engineering Mathematics. 2009)



How to couple 3D-1D-0D model



Patient-Specific Modeling & Simulation

＊ Measurement data & 3D-1D-0D (MRI & PC-MRI)

＊ Measurement data&1D-0D (MRI, PC-MRI,SPECT)

Clinical record of a patient undergoing *carotid surgery*

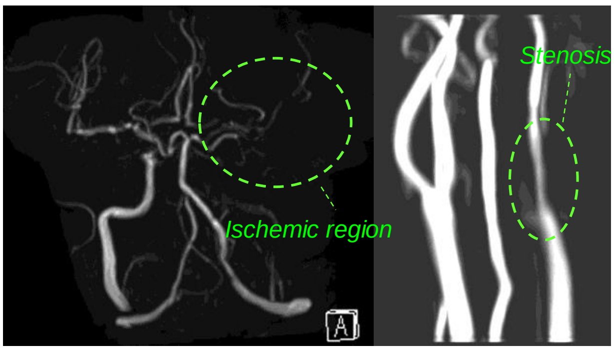
Patient: 78 years old male

Preoperative symptoms: Stroke induced by a severe stenosis present in the left internal carotid artery (ICA).

Surgery: Carotid artery stenting (CAS)

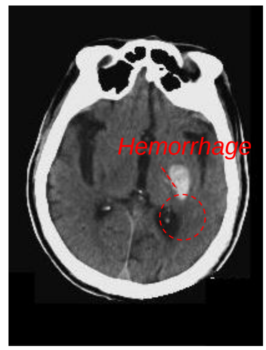
Postoperative syndrome: Intracranial hemorrhage due to hyperperfusion

Pre-operative MRA



Cerebral arteries *Carotid bifurcation*

Post-operative CT



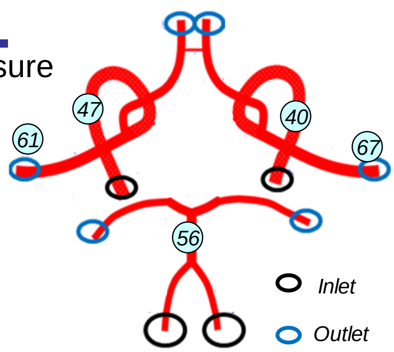
Brain scanning

Patient clinical data

1. Flow rate by PC-MRI & Blood Pressure

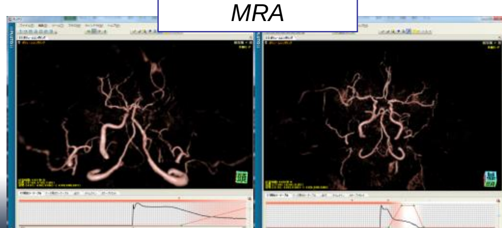
Averaged FR(ml/min)		Pre	Post
Rt. ICA	47	251.1	231.8
Lt. ICA	40	76.4	186.9
BA	56	154.9	142.0
Rt. MCA	61	71.2	50.3
Lt. MCA	67	23.1	59.3
		Max.	Min
Averaged BL (mmHg)		100.0	95.0

Circle of Wills

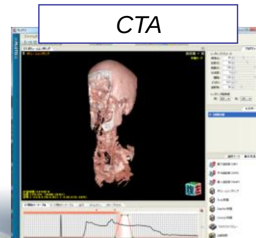


2. Medical Images

MRA

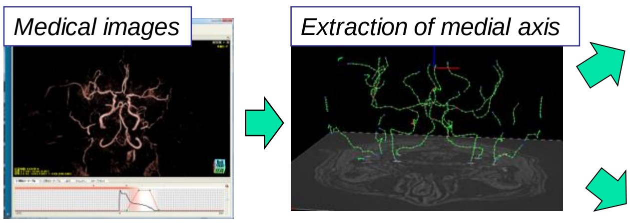


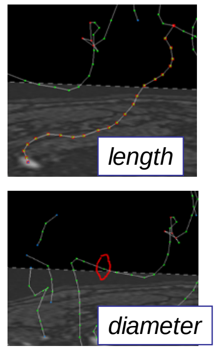
CTA



Optimization of parameters

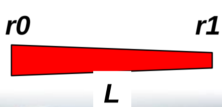
➢Step 1 : Measurement of diameter & length of artery





➢Step 2 : Application of measurement data to simulation
➢Step 3 : Optimization of peripheral resistance
➢Step 4 : Estimation of occlusion (in case of pre-operation)

	L.ICA
Post_data	L:84.4
	r0:1.05 r1:1.02



Application of measurement data and optimization of Parameters

➢Step 1 : Measurement of diameter & length of artery
➢Step 2 : Application of measurement data to simulation
➢Step 3 : Optimization of peripheral resistance

Resistance in 0D model of cerebrovascular circulation

$$R^{n+1} = R^{n} * \left(1.0 - \alpha * \frac{\overline{Q}^{T} - \overline{Q}^{n}}{\overline{Q}^{T}}\right)$$

α=1.2

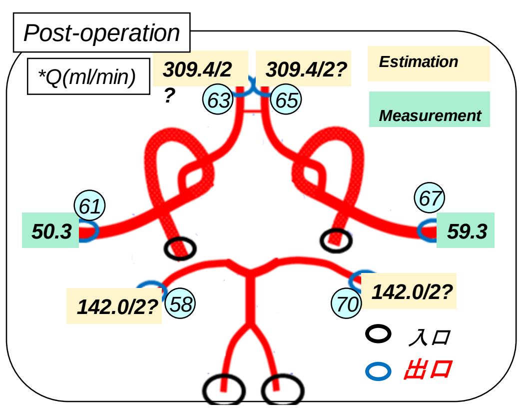
$\overline{Q}^{T}$:measurement data

$\overline{Q}^{n}$: simulated value in the nth step

The rest of parameters are optimized using BP in the arm

$$R^{n+1} = R^{n} * \left(1.0 - \alpha * \frac{\overline{P}^{T} - \overline{P}^{n}}{\overline{P}^{T}}\right)$$

α=0.9



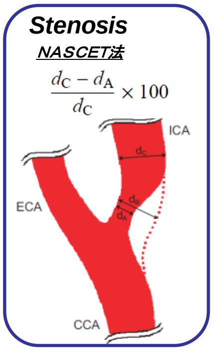
$\overline{P}$:Measurement data
$\overline{P}$: simulated value in the nth step

➢Step 4 : Estimation of occlusion (in case of pre-operation)

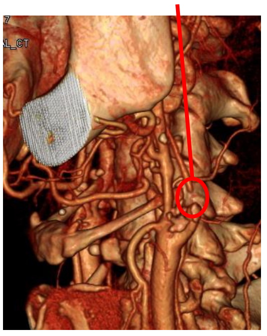
Estimation of parameters for stenosis

- *Step 1 : Measurement of diameter & length of artery*
- *Step 2 : Application of measurement data to simulation*
- *Step 3 : Optimization of peripheral resistance*
- *Step 4 : Estimation of occlusion (in case of pre-operation)*

Less than 1 pixel
da: 0.297mm < 1 pixel of CT image
Dc: 1.56mm
Stenosis : 0.81~1.00



Due to sever stenosis, L. ICA is not shown



Results

◆ *Resistance (mmHg・s・ml(-1))*

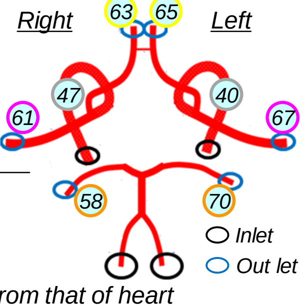
血管番号	58	70	61	67	63	65
No.1(pre)	43.8	37.7	49.4	143.1	24.5	13.9
No.2(post)	14.5	19.4	71.4	59.6	10.6	12.6

◆ *Stenosis*

0.85（*0.81～1.00*）

◆ *Flowrate(ml/min)*

血管番号	58	70	61	67	63	65	47	40
No.1(pre)	77.5	77.5	71.2	23.1	116.6	116.6	251.1	76.4
Measusment(pre)	*77.5*	*77.5*	*71.2*	*23.1*	*116.6*	*116.6*	*253.7*	*75.2*
No.2(post)	71.0	71.0	50.0	59.3	154.7	154.7	233.9	187.0
Measurement（post）	*71.0*	*71.0*	*50.3*	*59.3*	*154.7*	*154.7*	*231.8*	*186.9*



◆*Averaged B P (mmHg)*

No.1	99.7（*100*）
No.2	95.0（*95.0*）

◆*Intracranial flow rate (ml/s) from that of heart*

No.1(pre)	8.05ml/s	11.2%
No.2(Post)	9.35ml/s	12.7%

Estimation of flow distribution from pre-operative data

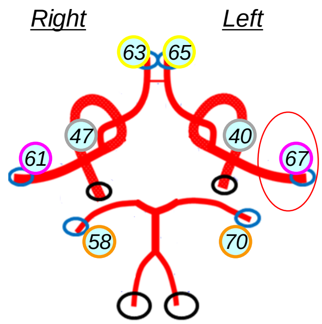
☐Simulation has been conducted using the pre-operative data

◆ Resistance (mmHg･s･ml(-1))

血管番号	58	70	61	67	63	65
Measurement(post)	-	-	-	-	-	-
No.1(**pre**)	**43.8**	**37.7**	**49.4**	**143.1**	**24.5**	**13.9**
No.2(**post**)	14.5	19.4	71.4	59.6	10.6	12.6

◆ Flowrate(ml/min)

血管番号	58	70	61	67	63	65	47	40
	71.0	*71.0*	*50.3*	*59.3*	*154.7*	*154.7*	*231.8*	*186.9*
No.1	**96.4**	**93.7**	**60.5**	**32.2**	**96.2**	**107.8**	**142.0**	**157.1**
No.2	71.0	71.0	50.0	59.3	154.7	154.7	233.9	187.0

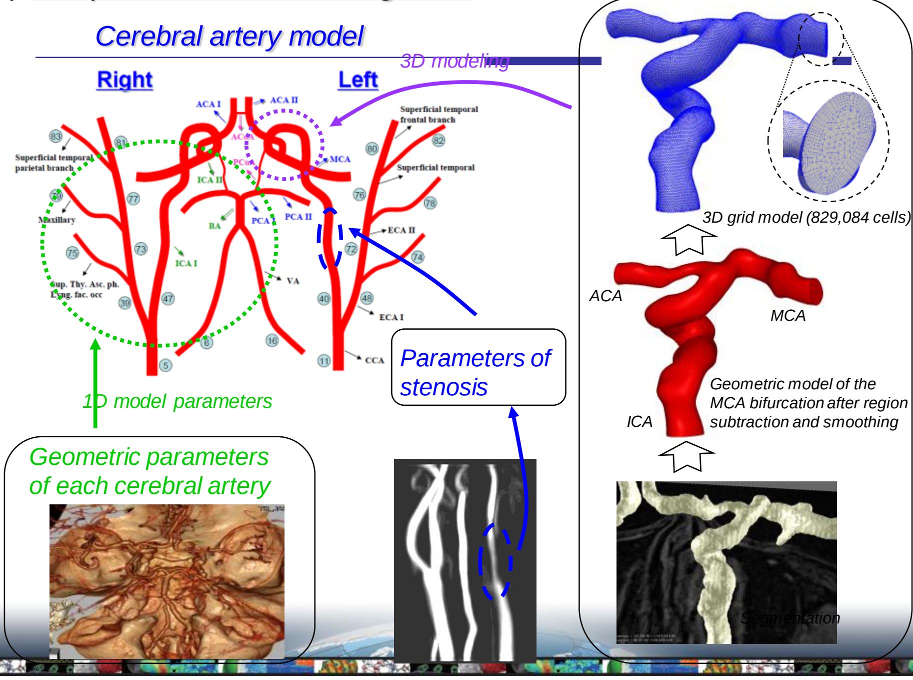


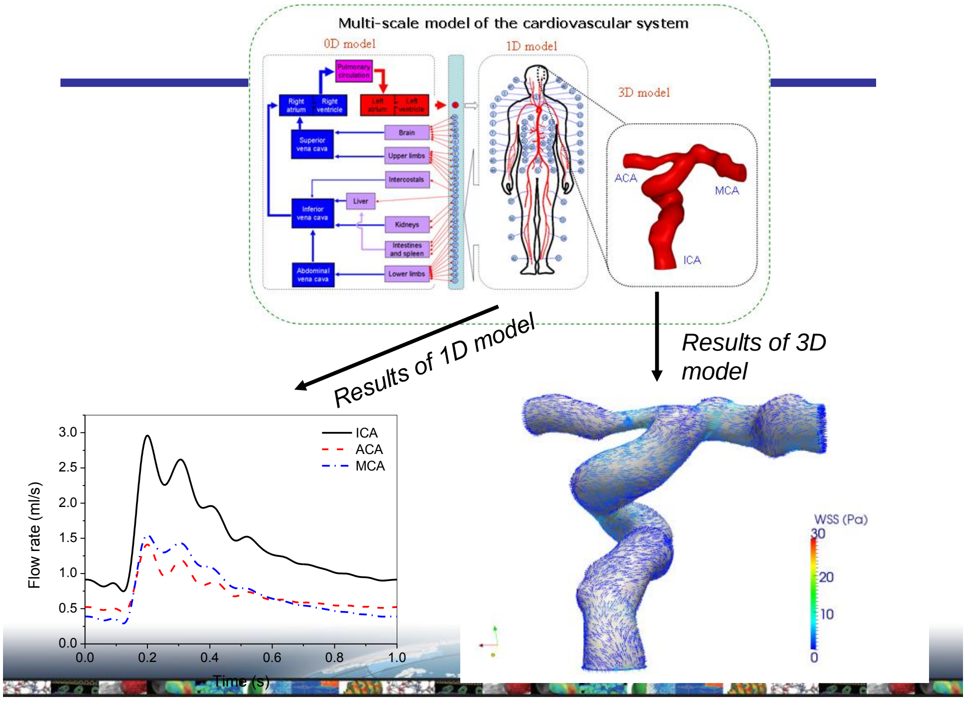
Due to low flow rate, some arteries can not be measured from the images

☐Discussion

It is necessary to use more realistic vascular geometry

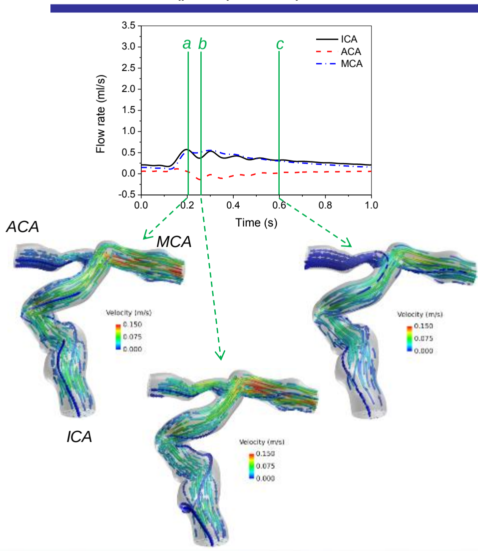
(1) Incorporation of medical image data



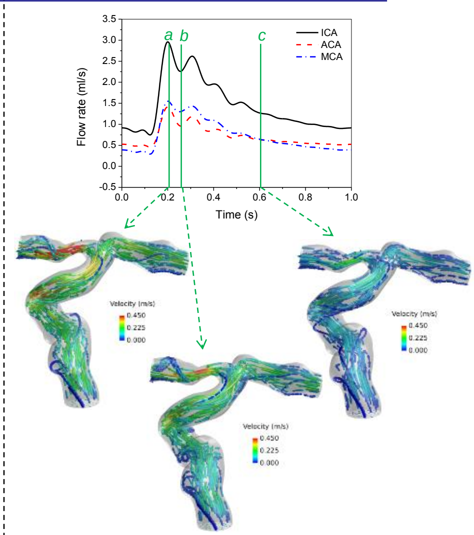


Flow waveforms and streamlines

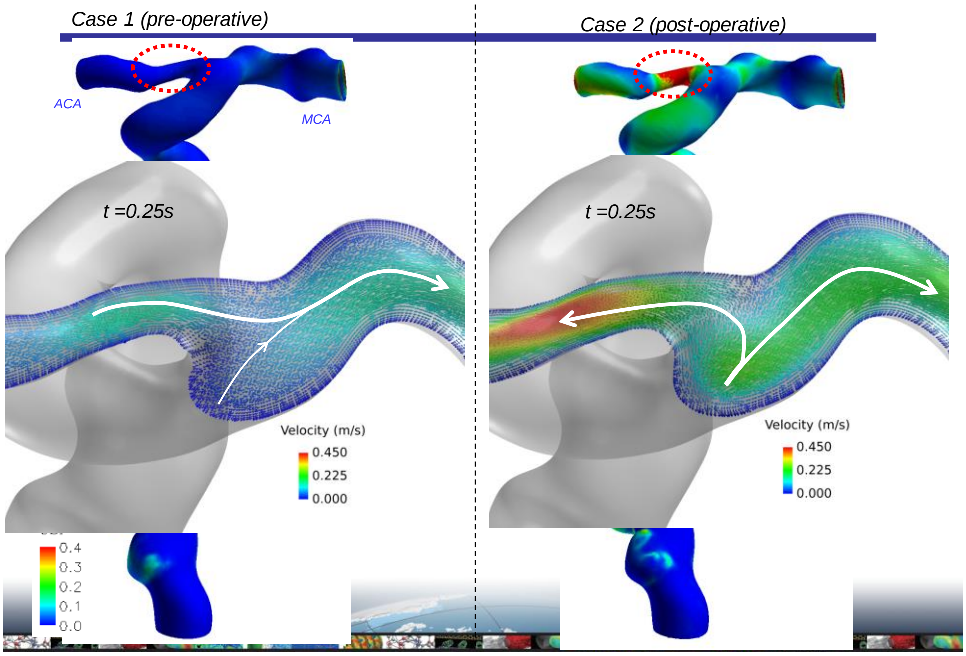
Case 1 (pre-operative)



Case 2 (post-operative)



Mean wall shear stress (MWSS) and Oscillatory shear index (OSI)



Challenges of 3D-1D-0D multi-scale simulation

- What can we do for medical doctors to use simulations in the clinical study ?
  - Requirement for applying simulation to an individual patient
    - Combination of medical image data
  - Requirement for allotted time
    - How long can they wait to get results ?
  - Requirement for usability
    - Can they handle different types of software for modeling, simulation, and visualization ?
    - PC?

How can we combine patient-specific data & simulation in a practical manner ?

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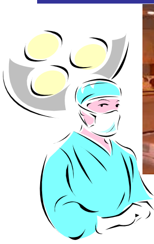
Summary

- *A general cardiovascular model can be personalized to simulate the hemodynamic conditions for a patient.*
  - *The cerebrovascular circulation including distal brunches of ECAs is added on 1D-0D simulation*
  - *Estimation of both pressure & velocity is improved by optimizing the peripheral resistance of the cerebrovascular circulation with the ultrasound data*
  - *Patient-Specific 3D simulation is conducted under the boundary conditions given by 1D-0D simulation of the entire circulatory system*
  - *Patient-specific 1D simulation is incorporated with the entire circulatory system using patient-specific image data such MRI, CT, and SPECT*

A personalized cardiovascular model has the potential to predict the risk of a surgery based on clinical data acquired during preoperative diagnosis.

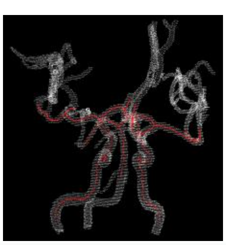
Application of simulation to Clinical Study



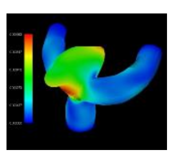
Advancement in Medical images & measurement

Mainly for Visualization use

Simulation + Clinical Data



Prediction of progress on an individual basis



Surgical planning

Contributing to development of medicine and clinical treatment

Acknowledgement

This research is supported by the 'Research and Development of the Next-Generation Integrated Simulation of Living Matter', as a part of the 'Development and Use of the Next-Generation Supercomputer Project' of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

Professor Fuyou Liang: Shanghai Jiao Tong University, Shanghai, China
Professor Shu Takagi: The University of Tokyo, Japan
Dr. Ryutaro Himeno: Riken

Professor Kiyomi Niki: Tokyo City University
Mr. Ryota Abe
Ms. Shiori Yauchi

Professor Motoaki Sugawara: Hemeji Dokyo University
Dr. Shigeki Yamada: Hamamatsu Rosai Hospital

Mr. Masaharu Kobayashi The University of Tokyo

Thank you for your attention