New approach to find biological adaptation rules using CFD and Genetic Algorism

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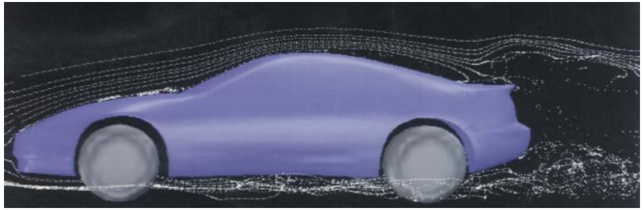
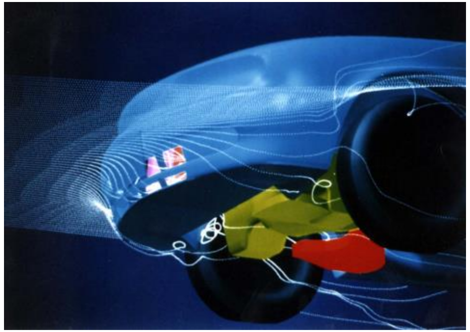
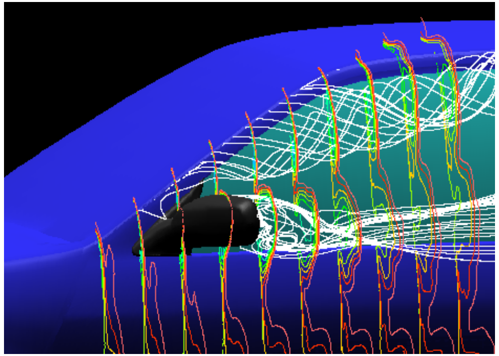
RIKEN

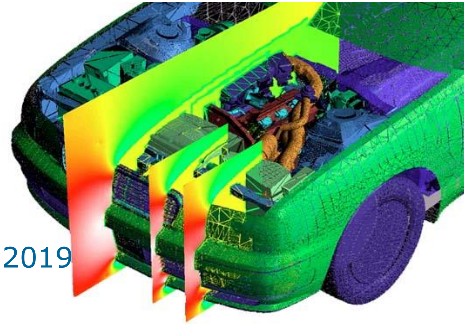
Background(1):Forward Problems

- CFD has been used to solve flow fields under certain initial conditions and boundary conditions.









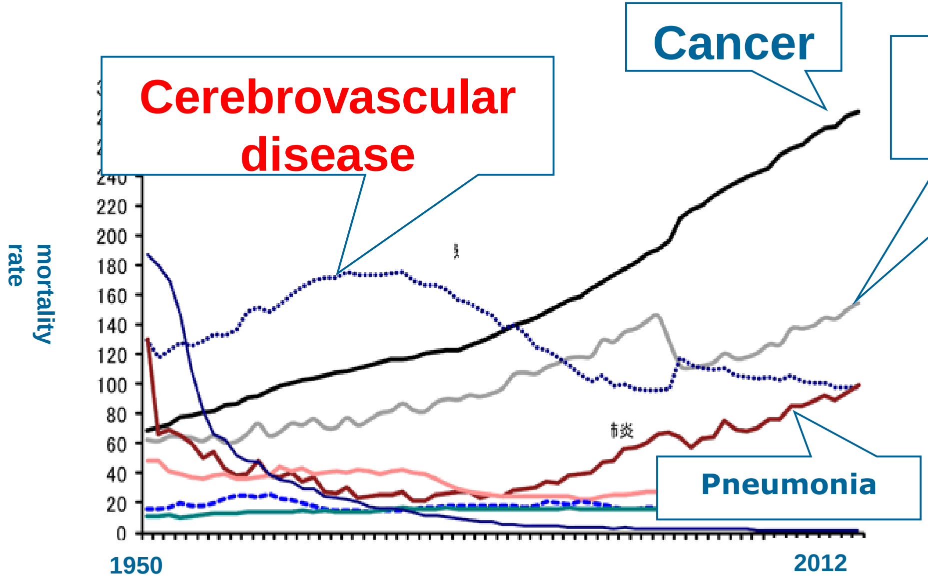
Background(2): Inverse Problems

- Genetic Algorithm gives us optimizing shapes under some conditions.
- Adaptation/growth of organ under some conditions should be solved using GA

-> When optimizing organ shape under several sets of some fluid dynamic factors using GA and compare the shape with real shape, we may know which set of factors gives the most similar shape to real one.

-> this is the way how to find unknown adaptation factors: solving Inverse problem

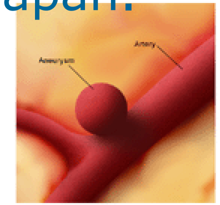
Region we should apply this method



Transition of mortality rate in the major cause of death in Japan

(Population Survey Report: Ministry of Health and Welfare)

Heart diseases and cerebrovascular diseases are major causes of death in Japan.

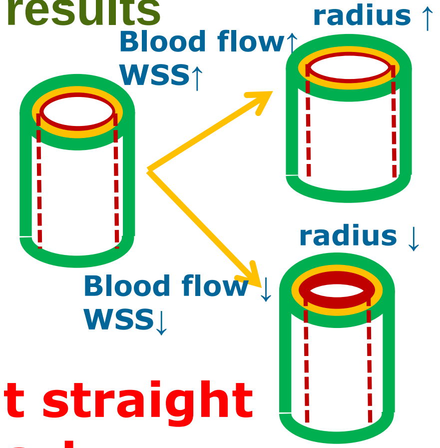


aneurysm

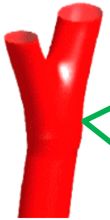
stenosis

We know artery adaptation only at strait part

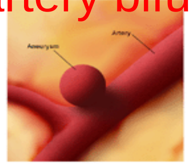
From past experimental results

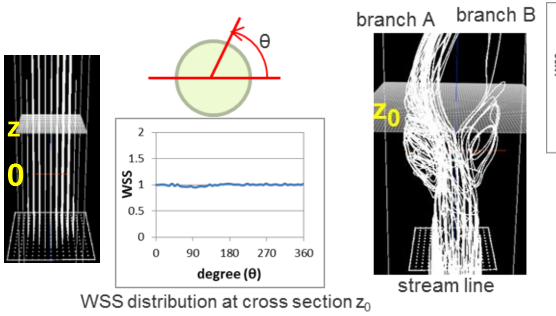


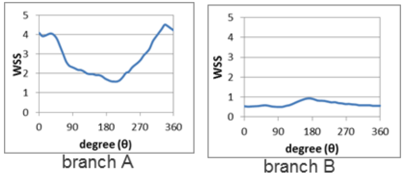
at straight part



Abnormal shapes often occur at artery bifurcation part







Bifurcation area has both high WSS and low WSS

Check how the new approach can work well at the artery development

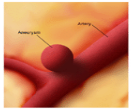
Reported possible factors related with blood flows near bifurcation

·Low WSS ·High WSS

·OSI:large time variation of flow direction
·High WSSG: wall shear stress gradient
·High WSSTG: wall shear time gradient
·WSS harmonic
etc.

- Melec et al. Transactions of the JSME 282(1999)
- Kleinstreuer, et al., Crit Rev Biomed Eng. 29(2001)
- Ojha, Circ. Resarch, 74(1994)
- Himburg et al., Am J Physiol Heart Circ Physiol, 286(2004)


stenosis

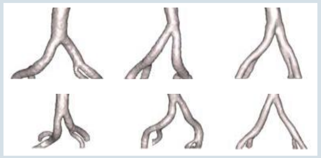

aneurysm

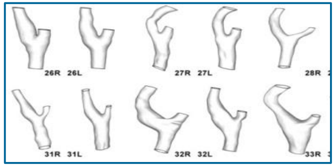
Unknown Relationship with abnormal shape

We do not know normal adaptation of blood tube

Common fluid dynamic factor?

Wide variation at blanch


Abdominal aortic bifurcation



Carotid artery bifurcation

Which factor plays most important role?

Normal adaptation mechanism may give us hints for abnormal shape

Application: bypass blood tube operation

Proposed method

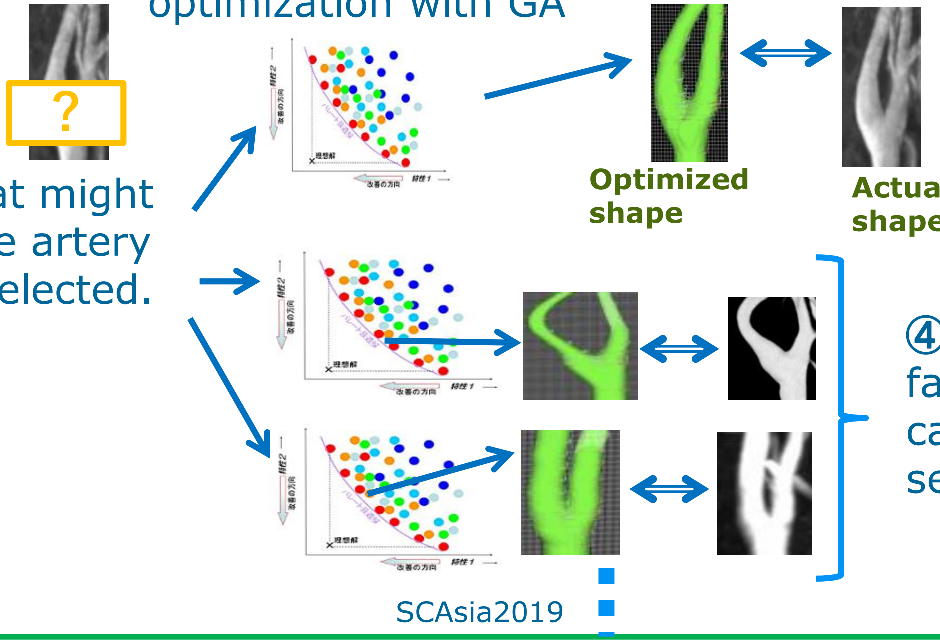
Artery shapes adapt optimally to some kinds of fluid dynamics factors.

This optimization problem is solved using CFD and genetic algorithm(GA).

① Factors that might determine the artery shape were selected.

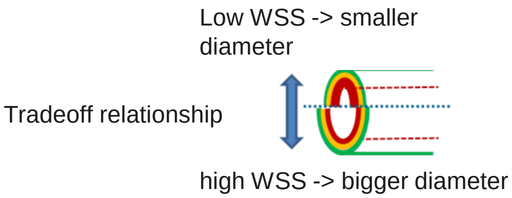
② multi-objective optimization with GA

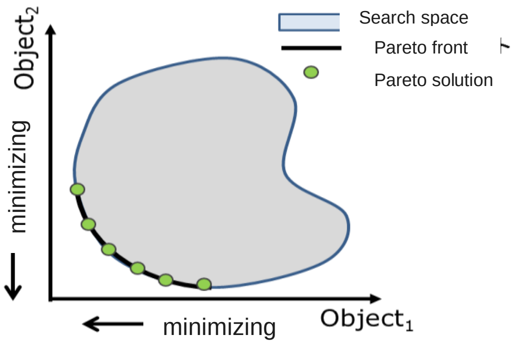
③comparison



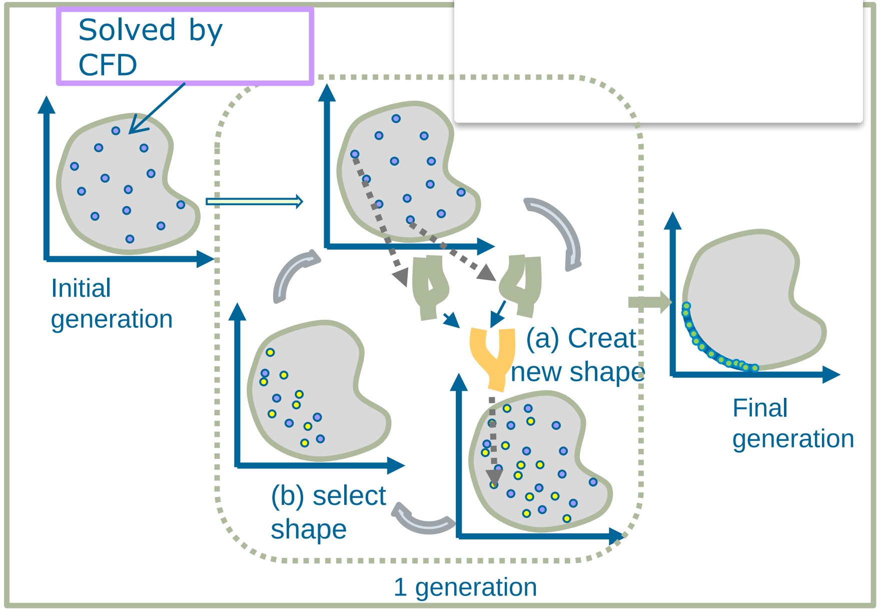
④ Common factors from all cases were selected.

Multi-objective optimization





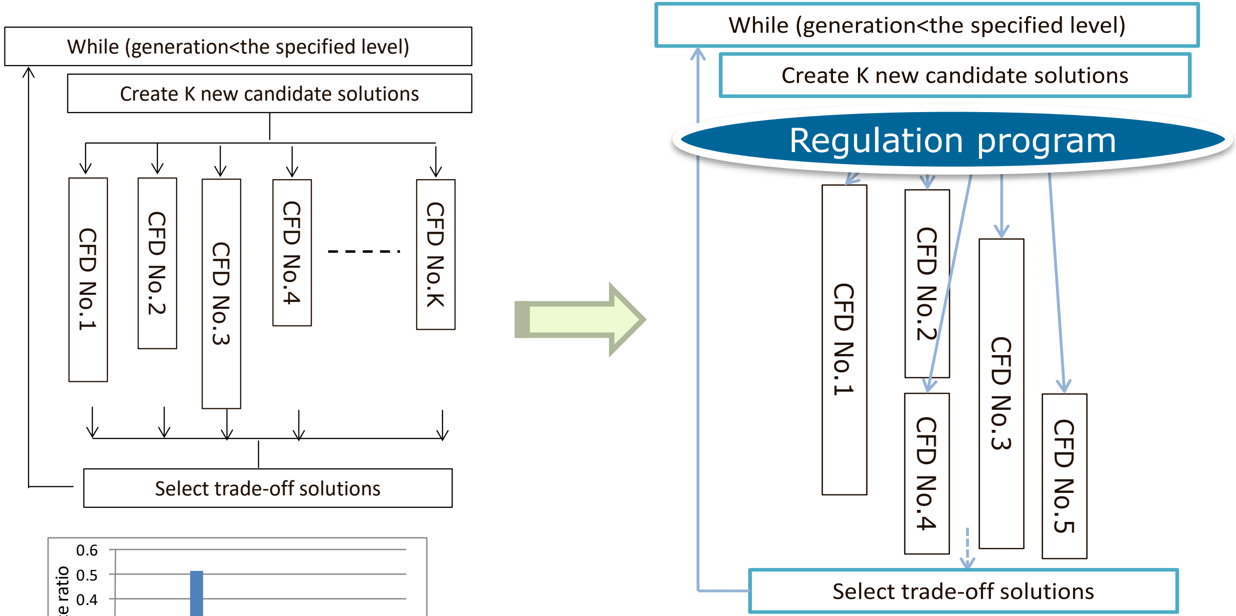
Multi Objective Genetic Algorism (GA)

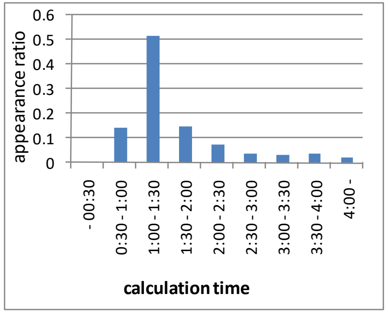


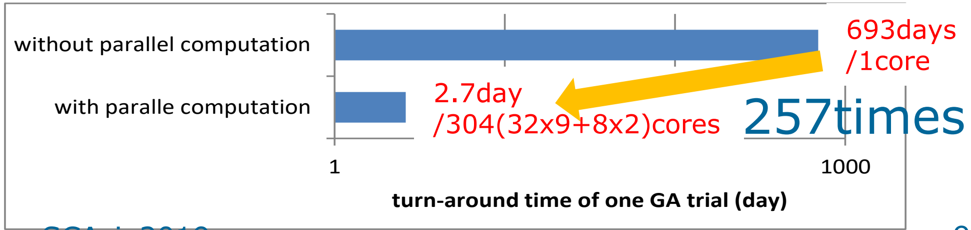
NSGA-II(non-dominated sorting GA)
Deb and Pratop, 2002)

- 1 case, 50 indivisuals, 10 generations: 500 CFD calculations
- 10 cases -> 5000 times CFD cals.
- 5 sets of 2-factor combination -> 25,000 CFD cals.

2nd level: parallelization of GA jobs







Details of HOKUSAI GreatWave

MPP System

Fujitsu PRIMEHPC FX100
- ・# of nodes:1080
  - \- # of cores:34,560(32/node)
- ・Total mem.:34.6TB (32GB/node)
- ・Inter-connect:Tofu2
  - \- Total Bandwidth:50GB/s×2/node
  - \- P2P Bandwidth:12.5GB/s×2
- ・Bandwidth for outbound:204GB/s

Frontend system

High Bandwidth Network

Mellanox SX6036×12(InfiniBand FDR) FBB

A part of RICC

- ・# of nodes: 589 (4712 cores)
- ・# of CPUs: 2/node (8cores/node)
  - \- CPU: intel Xeon X5570 2.93GHz
- ・Total mem: over 7TB
- ・Network: Infiniband QDR(4GB/s/node)

RIKEN Network

Online Storage (2.1PB)

MDS: RX300S8+Eternus DX200S3

OSS: RX300S8+NetAppE5600×14

File system: FEFS

Bandwidth:190GB/s

HSM Storage(7.9PB)

IBM TS4500 + TS1140×6

Control serve

Maintenance network

Computing Servers with GPU for Applications

SGI C2110G-RP5
- ・#of nodes:30(720 cores)
- ・#of CPUs:2/node(24cores/node)
  - \- CPU:Intel Xeon E5-2670 2.3GHz
- ・Total Mem.:1.9TB(64GB/node)
- ・GPU:NVIDIA Tesla K20X(4GPUs/node)
- ・Network:InfiniBand FDR (6.8GB/s/node)

Computing Servers with large memory for Applications

Fujitsu PRIMERGY RX4770 M1
- ・# of nodes:2(120 cores)
- ・# of CPUs: 4/node(60 cores/node)
  - \- CPU:Intel Xeon E7-4880v2 2.5GHz
- ・Total Mem.:2TB(1TB/node)
- ・Network:InfiniBand FDR×2 (13.6 GB/s/node)

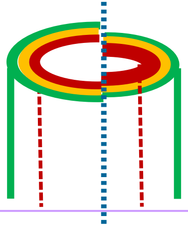
Determinant of artery shape

Assumed factors

- time-averaged WSS → ① minimized max WSS ② maximized min WSS
- local radius → ③ minimized inner surface area

enlargement

- High WSS



reduction

- Low WSS
- Radius is locally minimized

- WSSG (WSS gradient) → ④ minimized WSSG
- WSSTG (WSS temporary gradient) → ⑤ minimized WSSTG

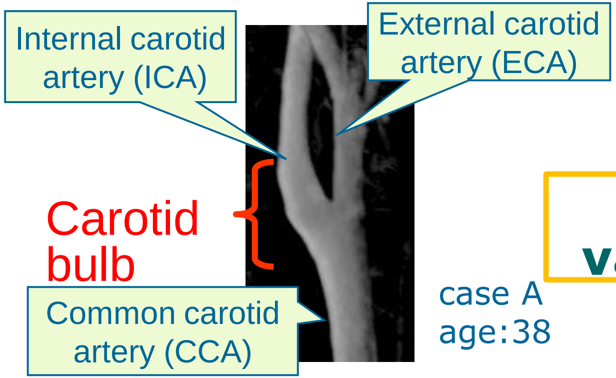
These are supposed to be causes of development of abnormal shapes.

Computation target

Carotid artery bifurcation

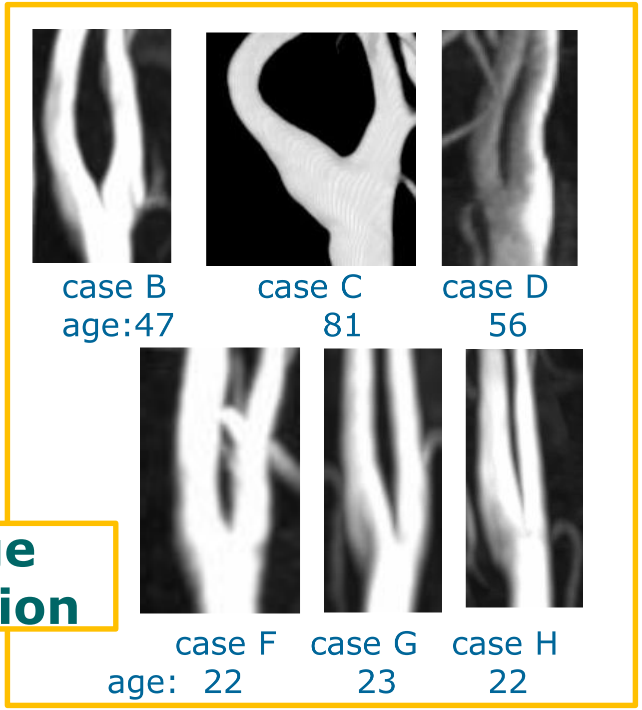
- Carotid bulb

- Large variations of the size of carotid bulb of individuals



case A
age:38

Large variation

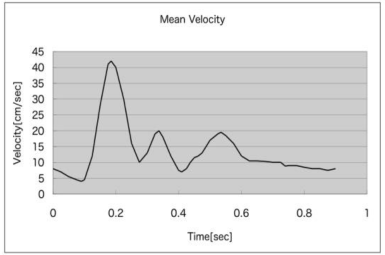


What are common factors?

Blood flow analysis

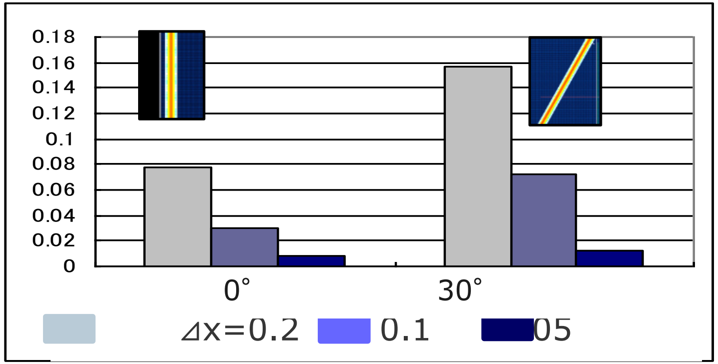
CFD analysis

- VOF and QUICK schemes
- Diameter at inlet was normalized as 1.0.
- Blood tube not elastic
- Re=1000
- Pulsatile flow

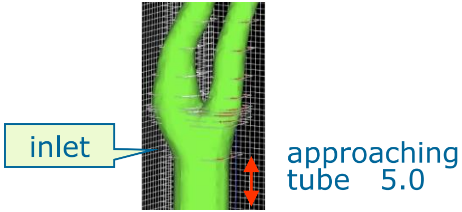


- Voxel size

⊿x=0.1



Error in calculated WSS against their theoretical values for three voxel sizes



	⊿x=0.2	0.1	0.05
No. of voxel	100,000	800,000	7,000,000
Calculation time(32CPU)	7min.	2hours	32hours

Result of optimization
case of shape A

Optimized parameter

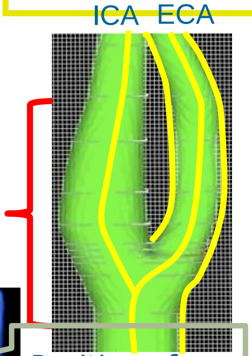
- radius of ICA

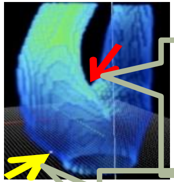
Assumed factors

- Minimize max WSS
- Minimize inner surface area

Assumed factors

- Minimize max WSS
- Maximize min WSS

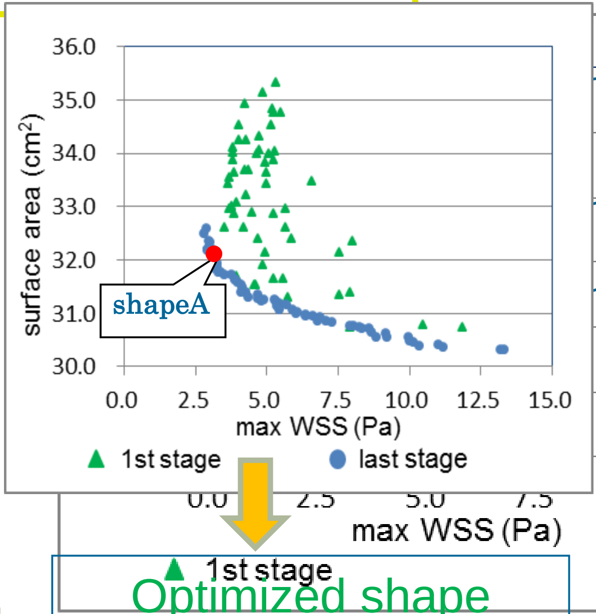


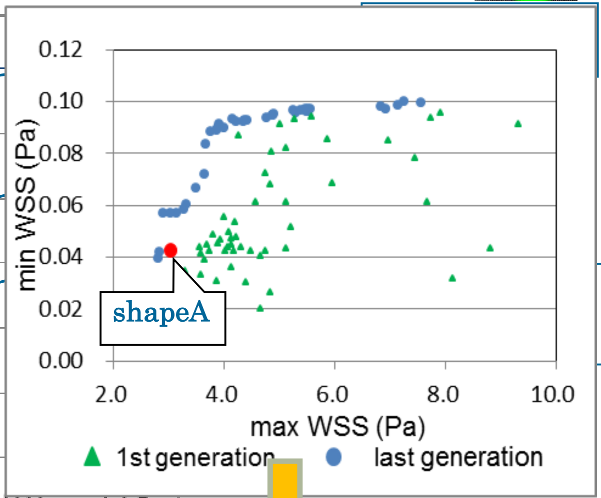


Position of high WSS (2.92)

Position of low WSS (0.0426)

area: 32.2

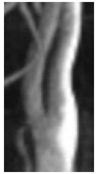




Optimized shape

Not optimized shape

Step1
Optimized parameter:
radius only

Combination of summed factors		case: A age: 38	B 47	C 81	D 56	E 22	F 23	G 22
								
1	max WSS, surface area	Y	Y	Y	Y	Y	Y	Y
2	max WSS, min WSS	n	n	Y	n	n	n	n
3	WSSG, surface area	n	Y	n	n	n	Y	Y
4	WSSG, min WSS	n	n	n	n	n	n	Y
5	WSSTG, surface area	n	n	n	Y	Y	n	Y
6	WSSTG, min WSS	n	n	n	n	Y	Y	Y

Y: optimized shape
n：not optimized shape

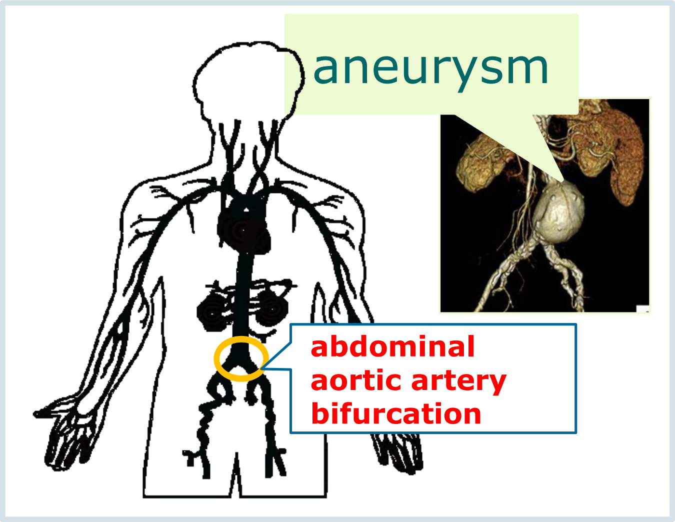
Step 2
radius and center line

max WSS, surface area	Y	Y	Y	Y	Y	Y	Y

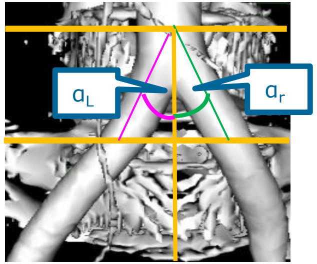
Abdominal aortic bifurcation

- Abdominal aneurysm often occurs.
- Variation
  - Bifurcation angle
  - Degree of asymmetry of blanches

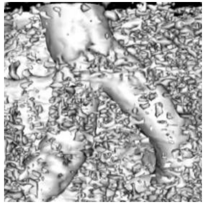
Second bifurcation target



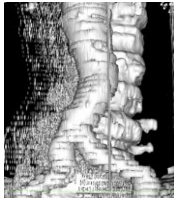
shape I
age 48



shape II
age 84

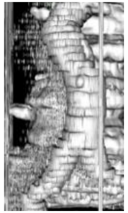


shape III
67

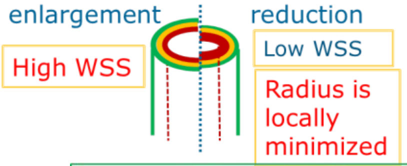


shape IV
age 64

shape V
69

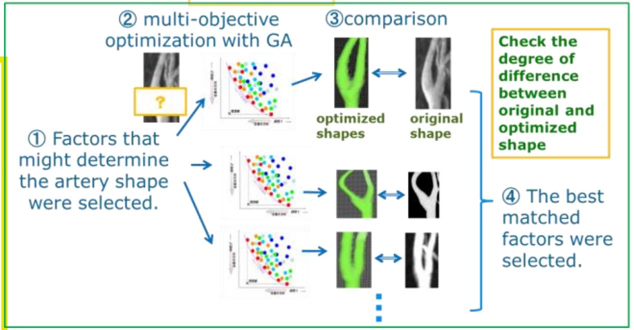


Actual case: shape I



Assumed factors

- Minimize max WSS
- Minimize inner surface area

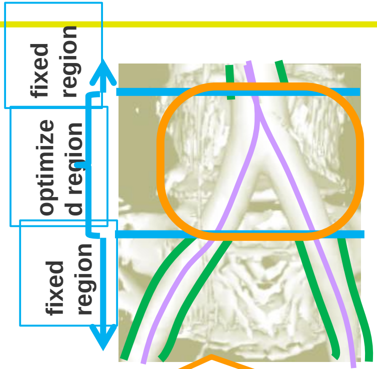


Optimization

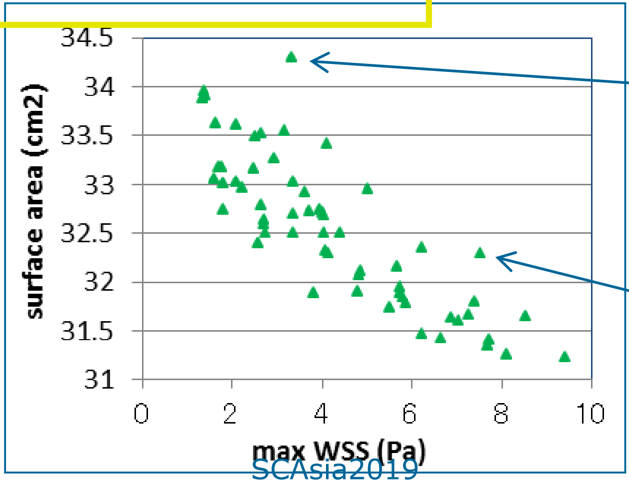
·Optimized parameter

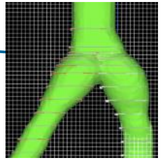
1st step: radius

·NSGAII(non-dominated sorting genetic algorithm) Deb, K. et. al. (2002)

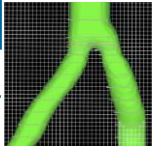


Radii of both blanches were defined as same value





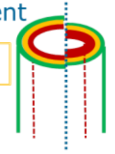
max WSS: 3.31
area: 34.3



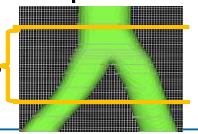
max WSS: 7.13
area: 32.29

Assumed factors

- Minimize max WSS
- Minimize inner surface area

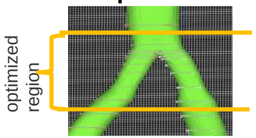


shape 1



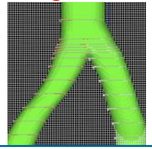
max WSS: 0.61
area: 33.6

shape 2

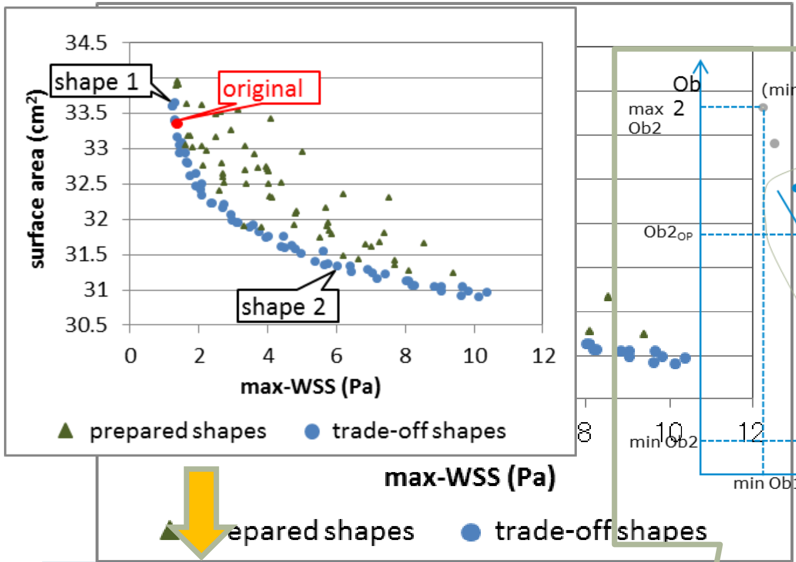


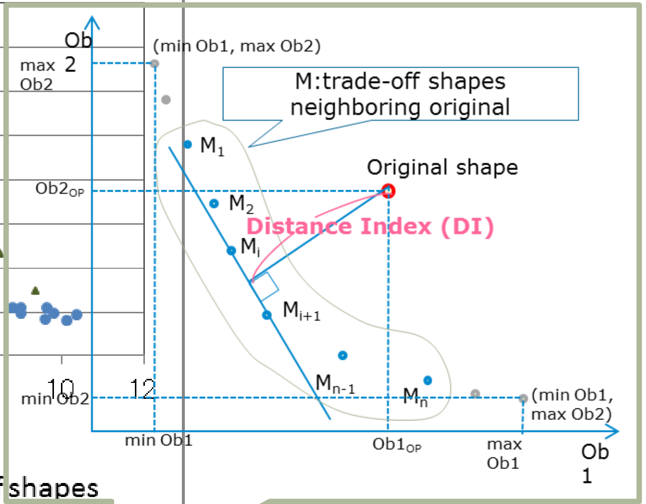
max WSS: 6.03
area: 31.3

original



max WSS: 0.65
min WSS: 0.056
Max WSSG: 4.85
area: 33.4

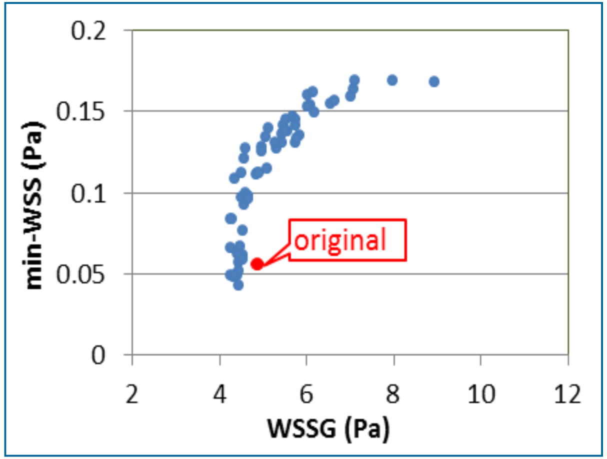




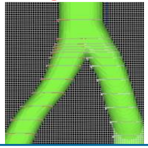
Optimized shape

DI (Difference Index)=0.0012

Assumed factors
- Minimize max WSSG
- Maximize min WSS



original

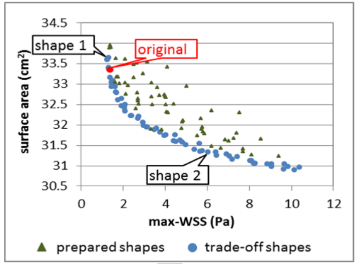


max WSS: 0.65
min WSS: 0.056
Max WSSG:
4.85
area: 33.4

Not optimized shape

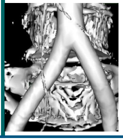
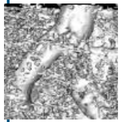
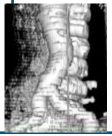
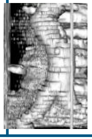
DI=0.1023

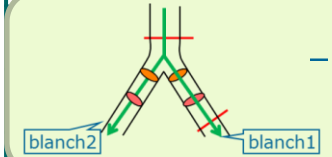
Assumed factors
- Minimize max WSS
- Minimize inner surface area



Optimized shape

DI=0.0012

		Abdominal artery bifurcation					Summary (average)	**Carotid artery (7cases)**
	case	I	II	III	IV	V		
Combination of summed factors								
1st step Optimized parameter: **radius only**								
F1	max-WSS, surface area	**0.0012**	**0.0027**	**0.0103**	**0.0092**	**0.0029**	**0.0052**	**0.0054**
F2	max-WSS, min-WSS	0.0162	0.4115	0.6806	0.0535	0.0415	0.2401	0.0414
F3	WSSG, surface area	0.0065	0.0064	0.0324	0.0278	0.0227	0.0191	0.0221
[illegible]	[illegible]	[illegible]	[illegible]	0.2514	0.0978	0.1808	0.1360	0.0679
[illegible]	[illegible]	[illegible]	[illegible]	0.0500	0.0536	0.0125	0.0259	0.0202
[illegible]	[illegible]	[illegible]	[illegible]	0.3175	0.1653	0.0500	0.1349	0.0669
2nd step Optimized parameter: **radius and center line**								
F1	max-WSS, surface area	0.0023	0.0001	**0.0998**	0.0004	**0.0757**	0.0356	0.0067



– Center line of blanches were defined independently.

Original shape is not optimized one!

Elongation of artery

- Increase of blood flow
- Stiffness, Cardiac hypertrophy, Aging, Blood pressure etc.

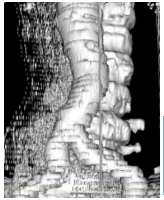
⇩

3rd step: optimized parameter

Center line → with fixing length with its original one

Radius

Case III

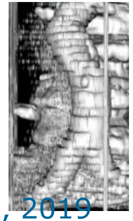


Without fixing length: DI=0.0998

⇩

With fixing length: DI=0.0072

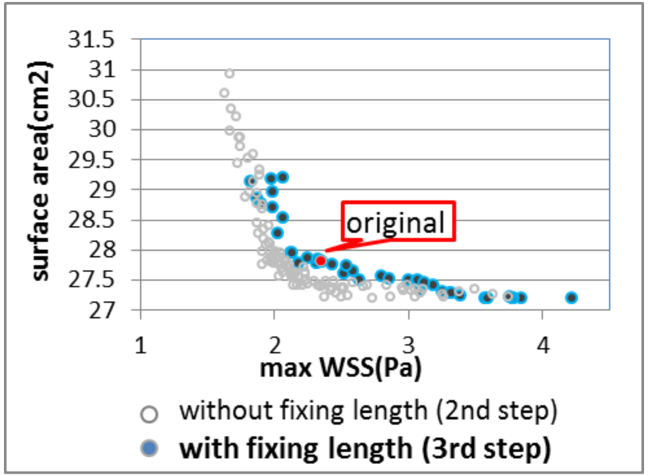
Case V



Without fixing length: DI=0.0757

⇩

With fixing length: DI=0.0099



Summary

Optimization is usually performed minimizing/maximizing certain target factors under certain conditions. We examined if it can be used as unknown factor searching method of biological adaptation.

We tested it using CFD and GA to artery adaptation at two bifurcations: carotid and abdominal bifurcation.

Results

- Combination of minimizing both max time-averaged WSS and local radius is the best in tested factors as well as at two bifurcation part.

- This approach is very useful to find new things.