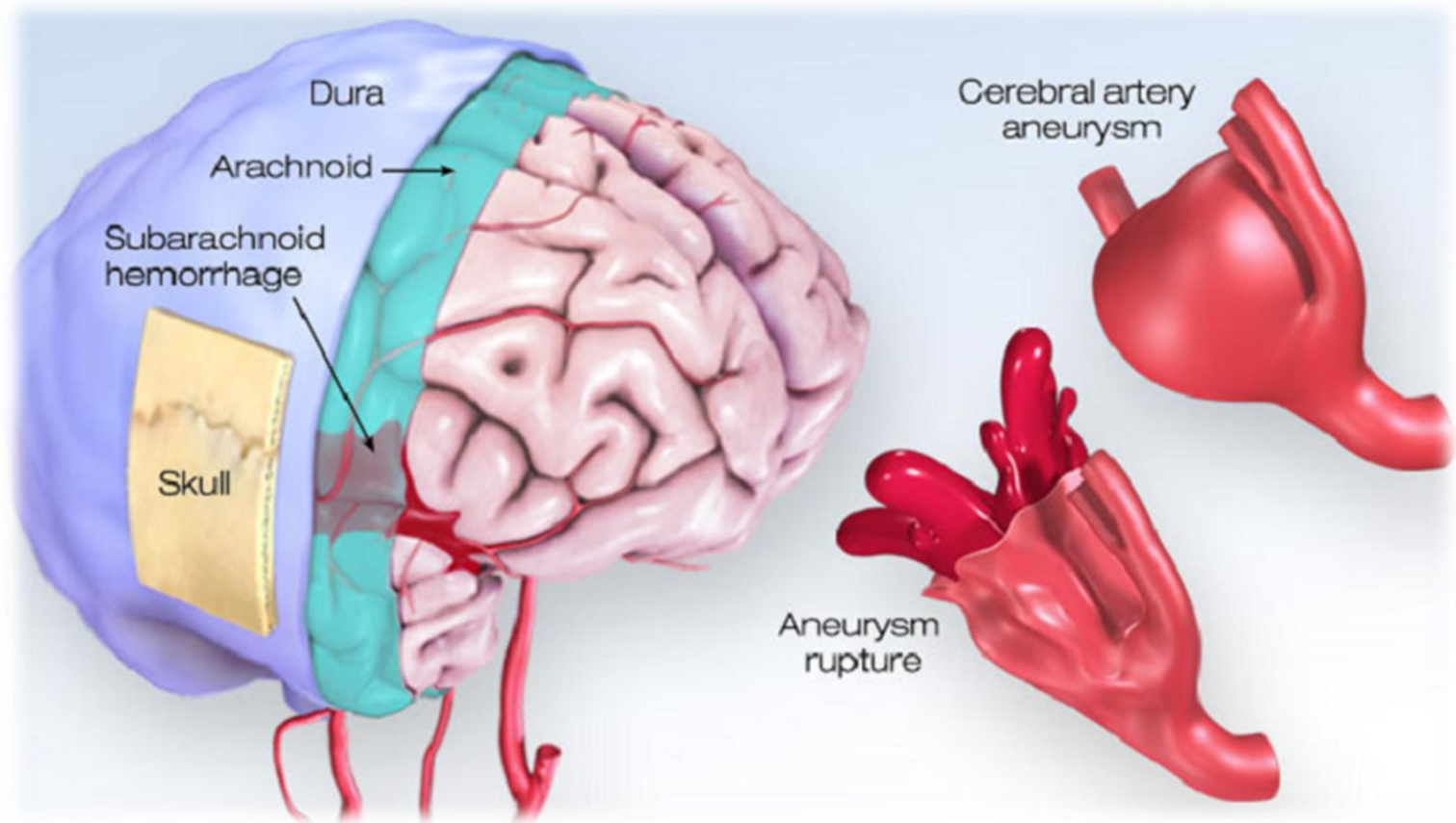# CFD-based hemodynamic study
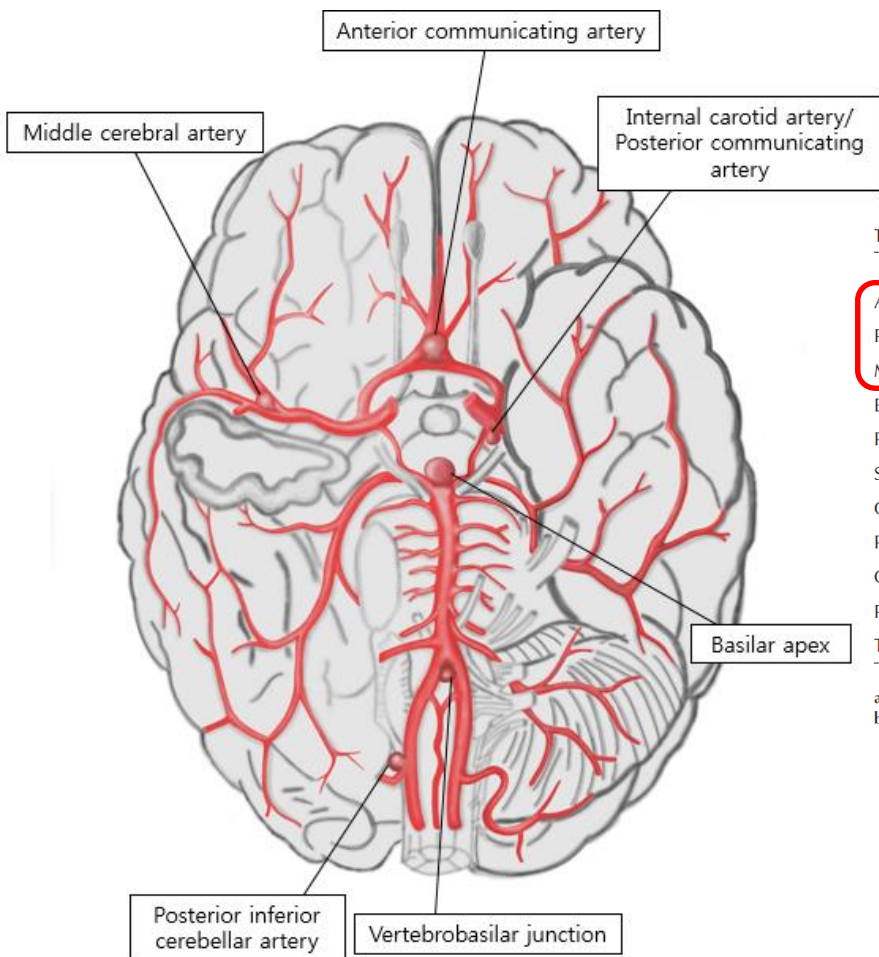# in cerebral aneurysms

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Aneurysm rupture

(www.strokeassociation.org-American Stroke Association)

Frequent locations of aneurysms

(works from Dr. Lee Ui Yun)

TABLE 1. Size and Location of Ruptured Aneurysms[a]

Size	<5 mm	6–10 mm	11–15 mm	16–20 mm	21–25 mm	>25 mm	Total
AComA	31	36	3	1	0	0	71
PComA	19	23	6	0	0	0	48
MCA	8	12	3	1	1	4	29
Basilar	8	23	2	2	0	1	36
PCA	3	6	2	0	0	0	11
SCA	4	0	0	0	0	0	4
Car	3	7	1	1	1	1	14
PICA	8	7	0	0	0	1	16
Opht	1	8	0	1	1	2	13
Peri	1	2	0	0	0	0	3
Total	86 (35%)	124 (50.6%)	17 (6.9%)	6 (2.4%)	3 (1.2%)	9 (3.7%)	245

[a] AComA, anterior communicating artery aneurysm; PComA, posterior communicating artery aneurysm; MCA, middle cerebral artery aneurysm; Basilar, basilar artery aneurysm; PCA, posterior cerebral artery aneurysm; SCA, superior cerebellar artery aneurysm; Car, carotid bifurcation aneurysm; PICA, posterioinferior cerebellar artery aneurysm; Opht, ophthalmic artery aneurysm; Peri, pericallosal artery aneurysm.

(Forget et al., 2001, Neurosurgery, 49(6), 1322-1326)

What is the biggest concern in aneurysm?

Rupture ?

Unrupture ?

Meaningful solutions from

Computational Fluid Dynamics (CFD)

Roles of CFD in aneurysm study
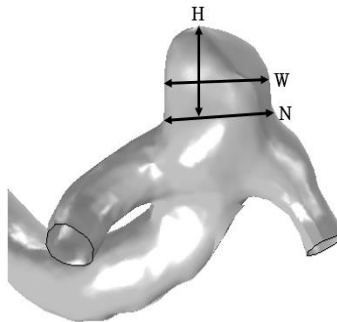
What is the biggest concern in aneurysm?

Rupture ? **Unrupture ?**

Geometry ⟷ **Hemodynamics**

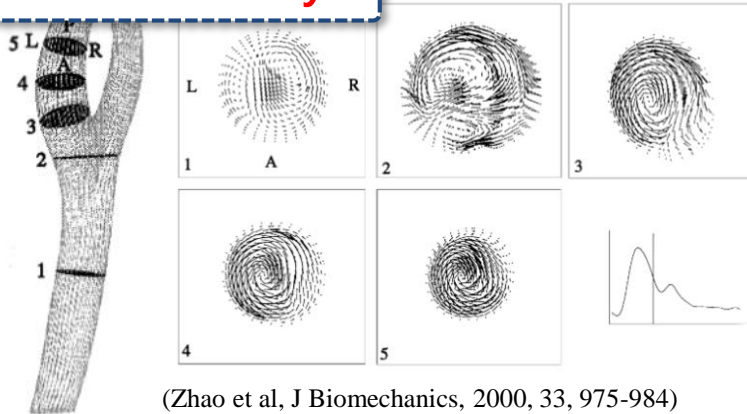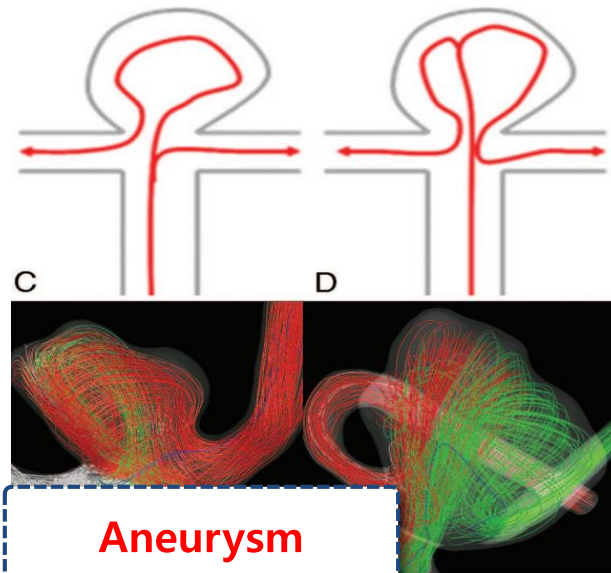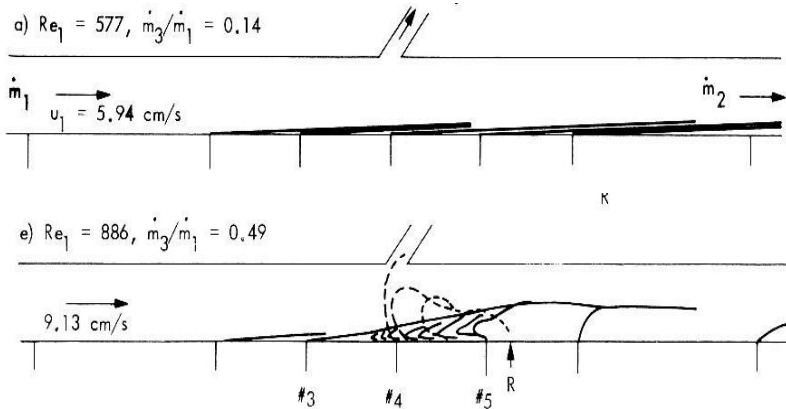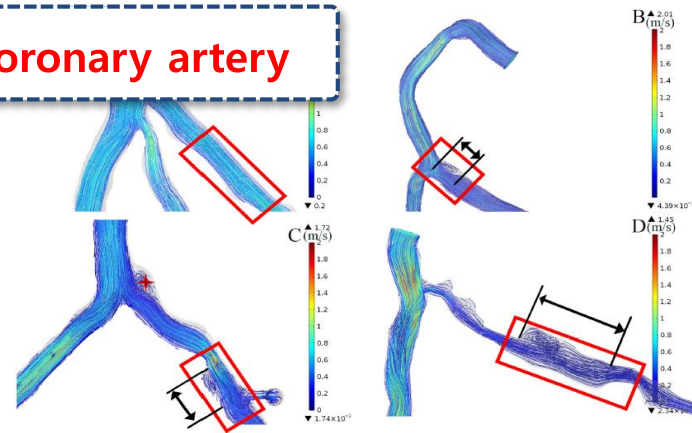| Morphological factors	Equations
Aspect ratio	$\dfrac{\text{Height}}{\text{Neck}}$
Bottleneck ratio	$\dfrac{\text{Width}}{\text{Neck}}$
Nonsphericity index	$1-(18\pi)^{1/3}\dfrac{\text{volume of aneurysm dome}^{2/3}}{\text{surface area of aneurysm dome}}$

(works from Dr. Lee Ui Yun)

Hemodynamic factors	Definitions or equations
Flow patterns	Flow stability, complexity, inflow jet
Time-averaged wall shear stress (WSS)	$\dfrac{1}{T}\int_0^T |WSS_i|\,dt$
Oscillatory shear index	$\dfrac{1}{2}\left\{1-\dfrac{\left|\int_0^T WSS\,dt\right|}{\int_0^T|WSS|\,dt}\right\}$
Relative residence time	$\dfrac{1}{(1-2\times OSI)\times TAWSS}$
Low wall shear stress area (LSA)	Area of low WSS below 10 % of WSS at parent artery
Ratio of LSA	$\dfrac{LSA}{\text{surface area of aneurysm dome}}\times 100$

Flows at aneurysms vs bifurcations

Carotid artery

(Zhao et al, J Biomechanics, 2000, 33, 975-984)

Coronary artery

(Peng et al, PLOS ONE, 2016, 11(6), 1-18)

a) $Re_1 = 577$, $\dot{m}_3/\dot{m}_1 = 0.14$

$\dot{m}_1$ $u_1 = 5.94$ cm/s $\dot{m}_2 \rightarrow$

e) $Re_1 = 886$, $\dot{m}_3/\dot{m}_1 = 0.49$
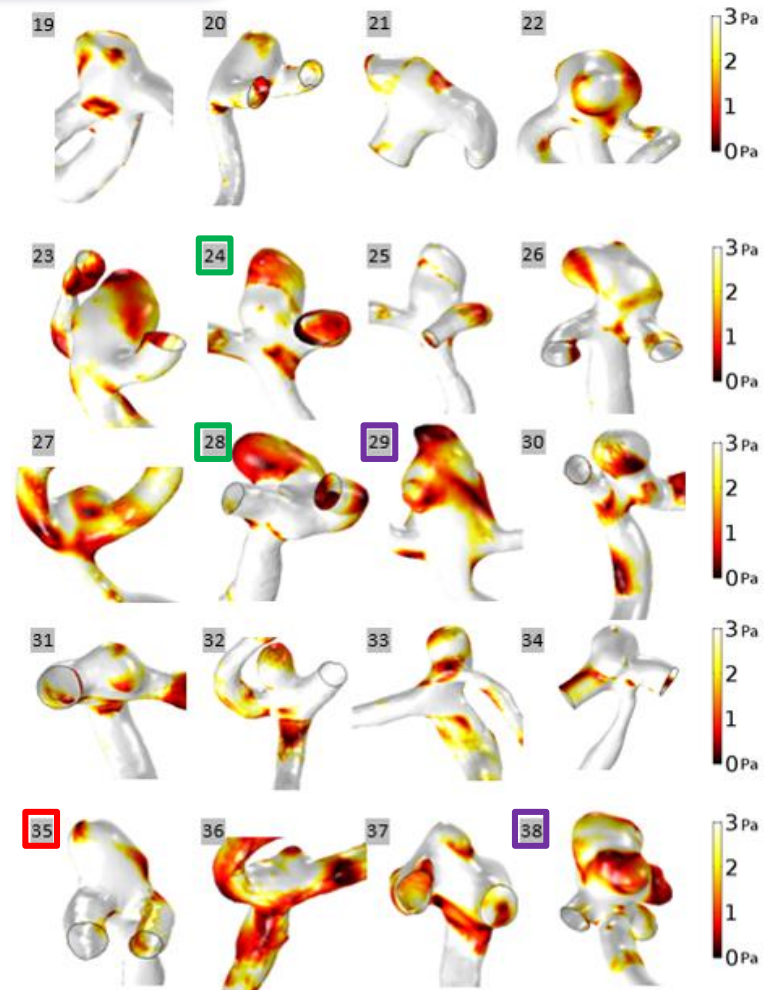
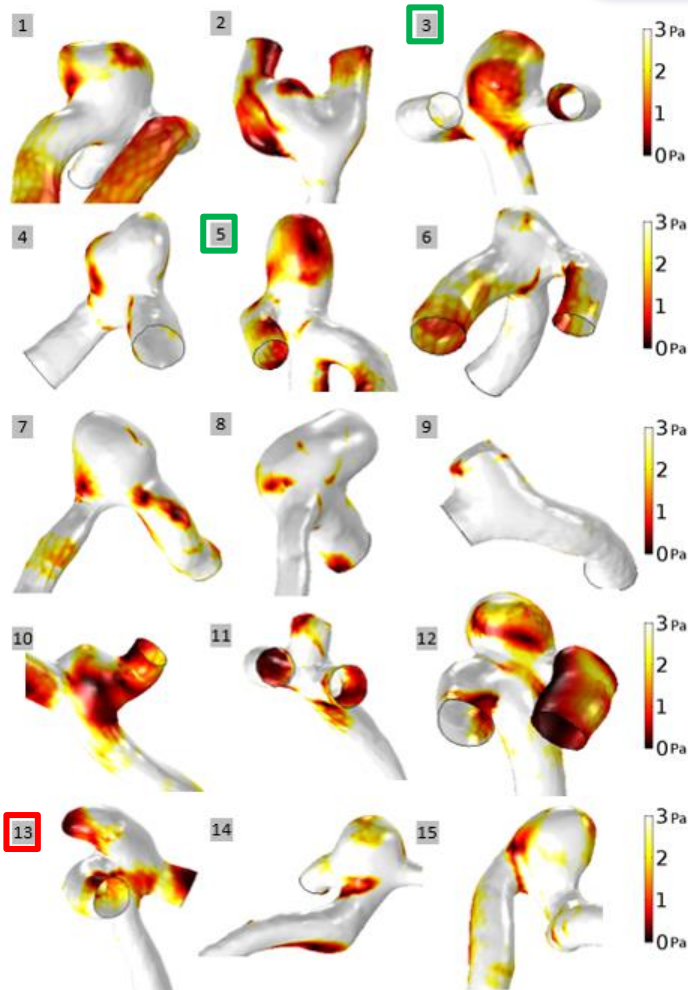9.13 cm/s

#3   #4   #5   R

Aneurysm

Castro et al, Am J Neuroradiol, 2009, 30, 297-302)

Rupture risks of aneurysms

Unruptured aneurysm

WSS

Ruptured aneurysm

(works from Dr. Lee Ui Yun)

Rupture risks of aneurysms

Unruptured aneurysm

Flow complexity

Ruptured aneurysm

Simple flow
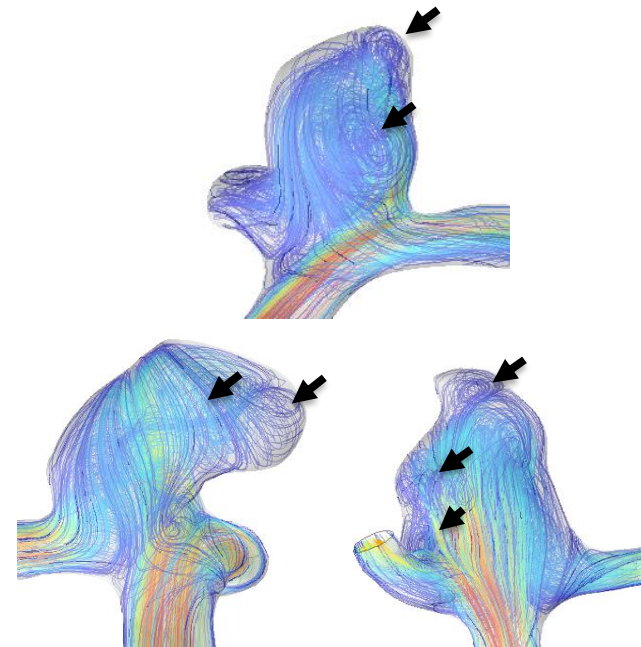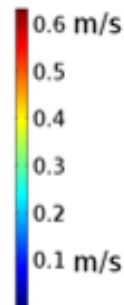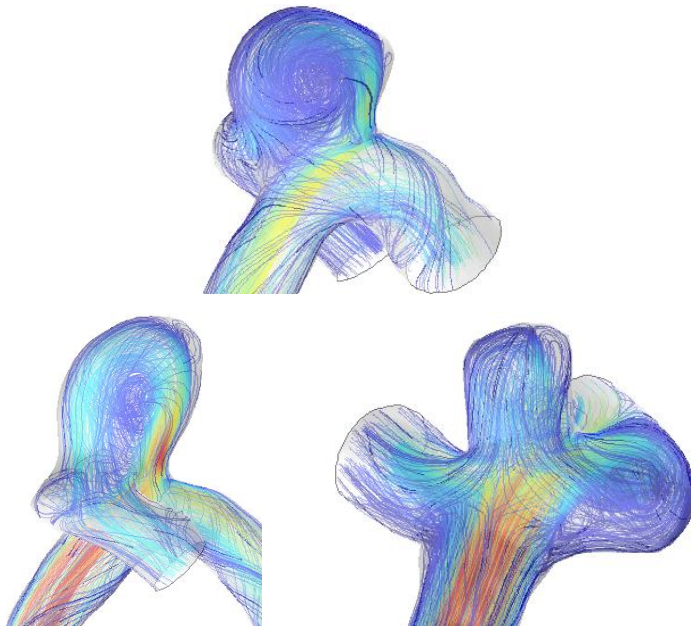
Complex flow

Rupture risks of aneurysms

Unruptured aneurysm   **Inflow jet**   **Ruptured aneurysm**

Simple flow   **Complex flow**
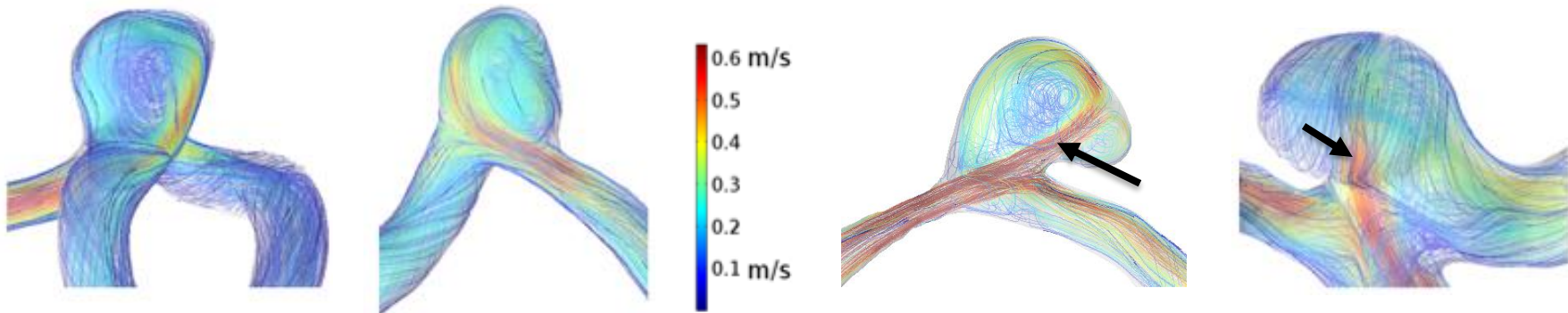
	Unruptured	Ruptured	χ^2	P value
Flow complexity				
Simple	14	0	28.000	< .001
Complex	4	24		
Inflow jet				
Diffused	15	9	8.823	.004
Concentrated	3	15		

Rupture risk in aneurysms

Risk factors	Unruptured aneurysm	Ruptured aneurysm
Aspect ratio	Low	High
Flow pattern	Simple, stable	Complex, unstable
Time-averaged wall shear stress	High	Low
Oscillatory shear index	Low	High
Relative residence time	Low	High
Low wall shear stress area	Low	High

(works from Dr. Lee Ui Yun)

Parameter ranking in aneurysm rupture

Table 1   Parameter-ranking results

Parameter	# of studies	# of studies positive correlation	# of studies negative correlation	Non-contradictory/total ratio	Confirmatory/total ratio	Power score	Correlation type
Aspect ratio	19	15	0	0.79	0.79	15	Positive
LSA	17	9	0	0.53	0.53	9	Positive
Aneurysm size (height)	19	9	1	0.42	0.47	8	Positive
Min WSS	10	0	7	0.70	0.70	7	Negative
Average WSS	23	2	9	0.30	0.39	7	Negative
Size ratio	8	6	0	0.75	0.75	6	Positive
OSI (average)	16	5	0	0.31	0.31	5	Positive
Flow complexity	9	5	0	0.56	0.56	5	Positive
Number of vortices (multiple)	3	3	0	1.00	1.00	3	Positive
LSA ratio	4	3	0	0.75	0.75	3	Positive
Inflow conc index	5	4	1	0.60	0.80	3	Positive
Shear conc Index	4	3	0	0.75	0.75	3	Positive
Energy loss ratio	4	2	0	0.50	0.50	2	Positive
Max WSS	16	4	2	0.13	0.25	2	Positive
VD ratio	4	0	2	0.50	1.00	2	Negative
Nonsphericity index	3	2	0	0.67	1.00	2	Positive

VS, Viscous Dissipation.

Liang L, *et al*. *J NeuroIntervent Surg* 2018;**0**:1–6. doi:10.1136/neurintsurg-2018-014246

Reviewed 46 studies; total 81 parameters (morphology + hemodynamics)

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Counterpoint of CFD: Closing the gap

Counterpoint: Realizing the Clinical Utility of Computational Fluid Dynamics—Closing the Gap

(American Journal of Neuroradiology, 2012, 33(3), 396-398)

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University at Buffalo
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Potential utility of CFD in neurointerventional and neurosurgical treatment of cerebral aneurysms

1) **A large number of hemodynamic parameters** have surfaced recently, which are confusing and confounding.

2) CFD involves **assumptions** that might make results questionable.

3) **MANY isolated groups** are working on MANY cases with MANY DIFFERENT PRECEDURES.

Skepticism remains due to the many assumptions and variability of modelling choices between isolated research groups.
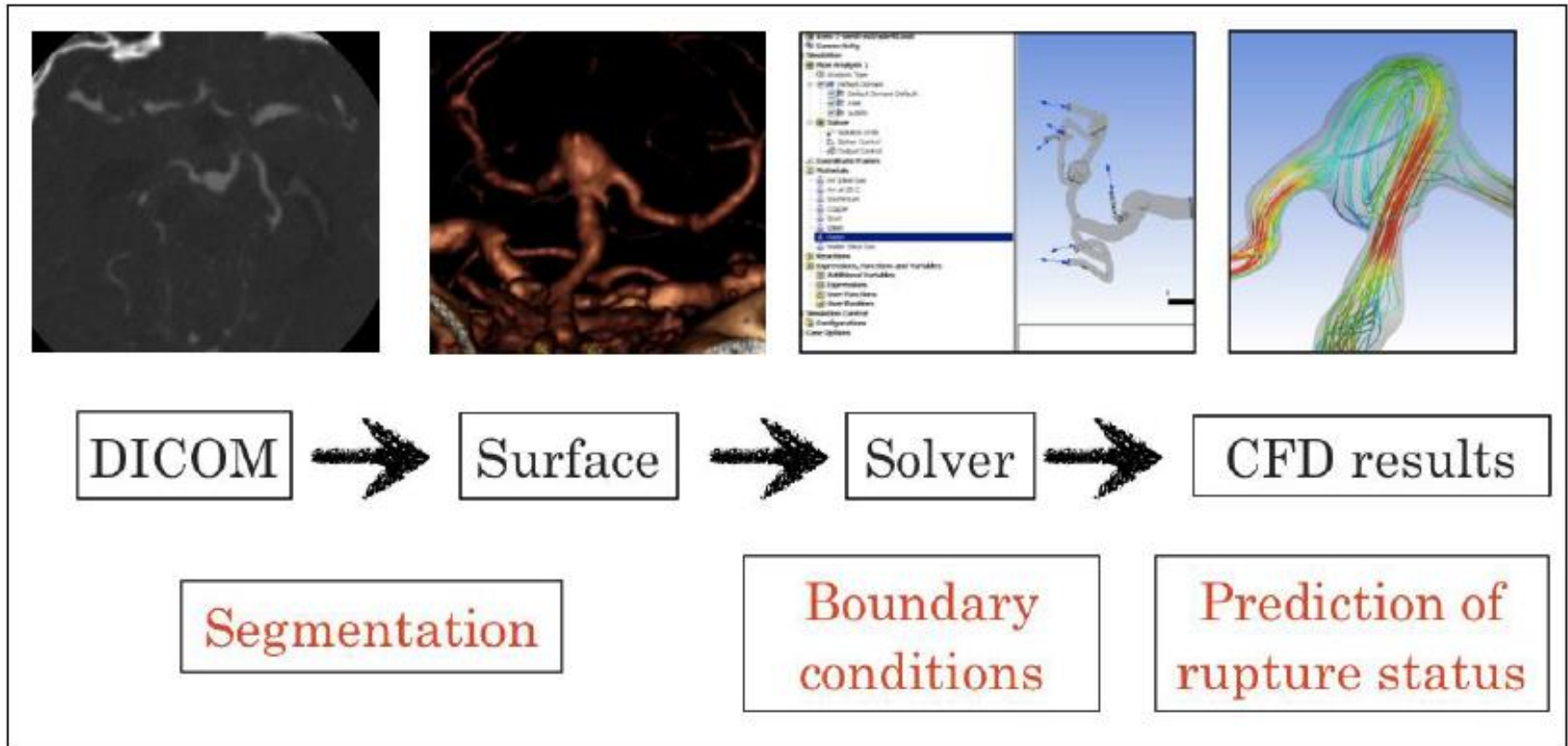
(From Announcement of the "International Aneurysm CFD Challenge 2015")
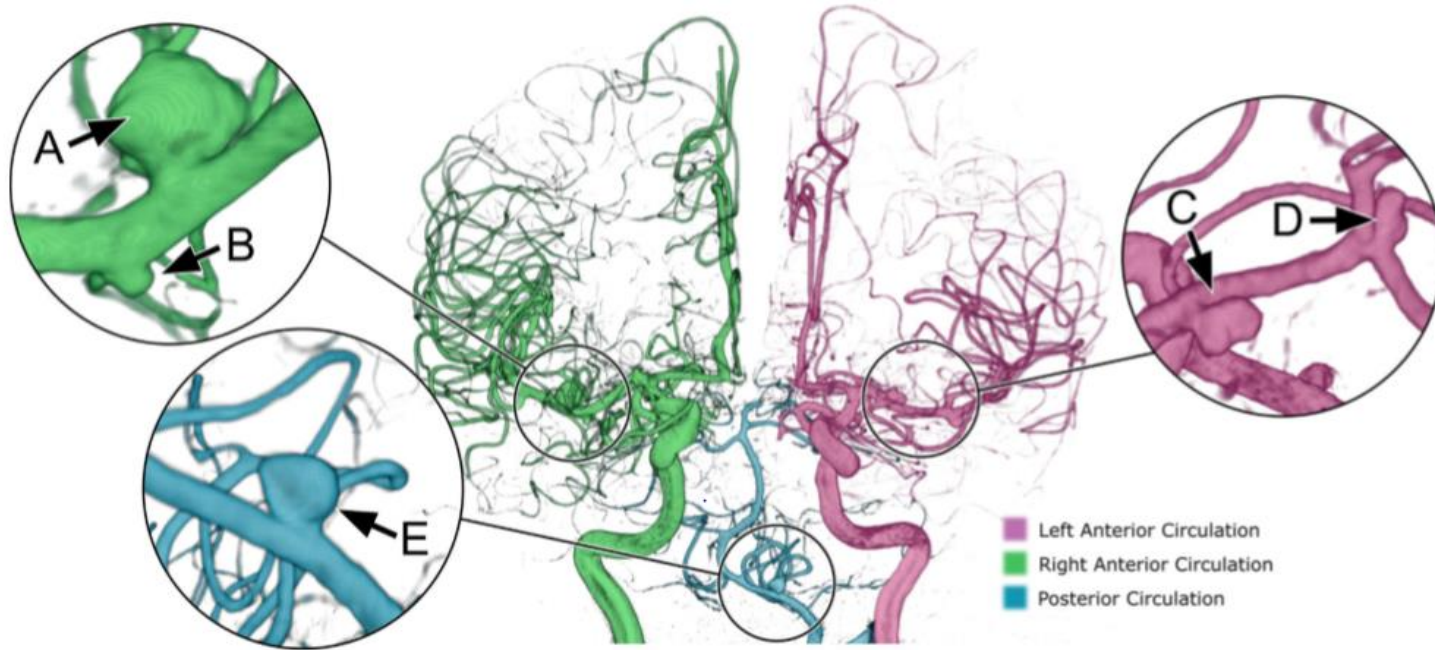
DICOM files for 5 aneurysms

Fig. 1 Illustration of the five IAs from the investigated aneurysm patient. Aneurysms A and B were located on the M1 segment of the right anterior circulation and C on the left M1 segment, respectively. Aneurysm D was found on the left middle cerebral artery bifurcation and aneurysm E was located on the left posterior inferior cerebellar artery. The image data were acquired using 2D and 3D digital subtraction angiography, while only 3D rotational angiography data were provided to the MATCH participants

(BERG et al, International Journal of Computer Assisted Radiology and Surgery, 2019 online published https://doi.org/10.1007/s11548-019-01986-2)

How to close the gap

TABLE 1. Summary of team/simulation characteristics.

	Experience[a]			
	High	Medium	Low	All
Number of teams	5	13	8	26
Continent[b]				
Europe	1.5	6.5	3	11
North or South America	1.5	3.5	4	9
Asia	2	3	1	6
Segmentation software[c]				
Mimics	2	2	1	5
VMTK	1	4	0	5
ITK-Snap	1	1	2	4
3D Slicer	0	1	2	3
Simvascular	0	0	2	2
Other	2	5	2	9
CFD software				
Fluent	3	4	1	8
CFX	2	2	0	4
Star-CCM+	0	0	3	3
OpenFOAM	0	2	0	2
Simvascular	0	0	2	2
Other	0	5	2	7

TABLE 1. Summary of team/simulation characteristics.

	Experience[a]			
	High	Medium	Low	All
Rheology model				
Newtonian	4	13	6	23
Non-Newtonian	1	0	2	3
Viscosity (cPoise)				
3.5	3	5	4	12
3.7	0	1	1	2
4.0	2	7	3	12
Density (g/cm^3)				
1.05–106	4	11	7	22
Other (1.0–1.05)	1	2	1	4
Temporal scheme				
Steady	4	7	4	15
Pulsatile	1	6	4	11
Inlet location				
MCA	0	11	6	17
ICA	5	2	2	9
Inflow scaling[d]				
Same flow rate ($n = 0$)	2	3	1	6
Same Re ($n = 1$)	0	1	1	2
Same velocity ($n = 2$)	1	6	3	10
Same WSS ($n = 3$)	2	1	1	4
Other	0	2	2	4
Inflow BC				
Plug	2	7	4	13
Poiseuille	3	3	2	8
Womersley	0	2	2	4
Other	0	1	0	1
Outflow BC				
Zero pressure	4	10	4	18
Cube (Murray's) law	1	1	2	4
Other	0	2	2	4

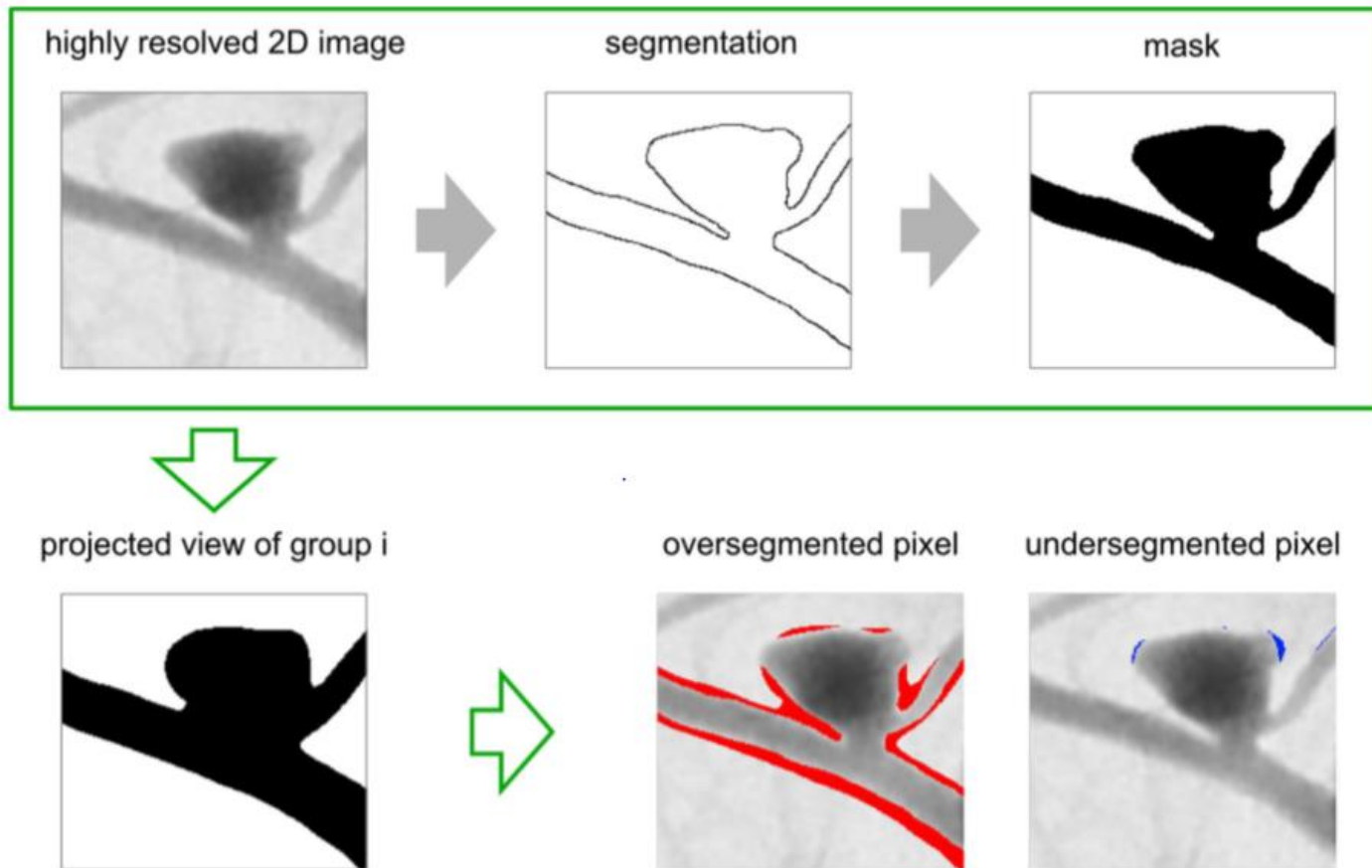(VALEN-SENDSTAD et al, Cardiovascular Engineering and Technology, 2018, 9(4), 544-564)

FIGURE 2. Illustration of the comparison technique developed to quantify the difference between the highly resolved 2D images and the individual segmentation result from each participating group. After segmenting the 2D image, a mask was created, which was compared pixel-wise with the projected view of the individual group. Hence, over- and underestimation were evaluated as exemplified on the bottom right.

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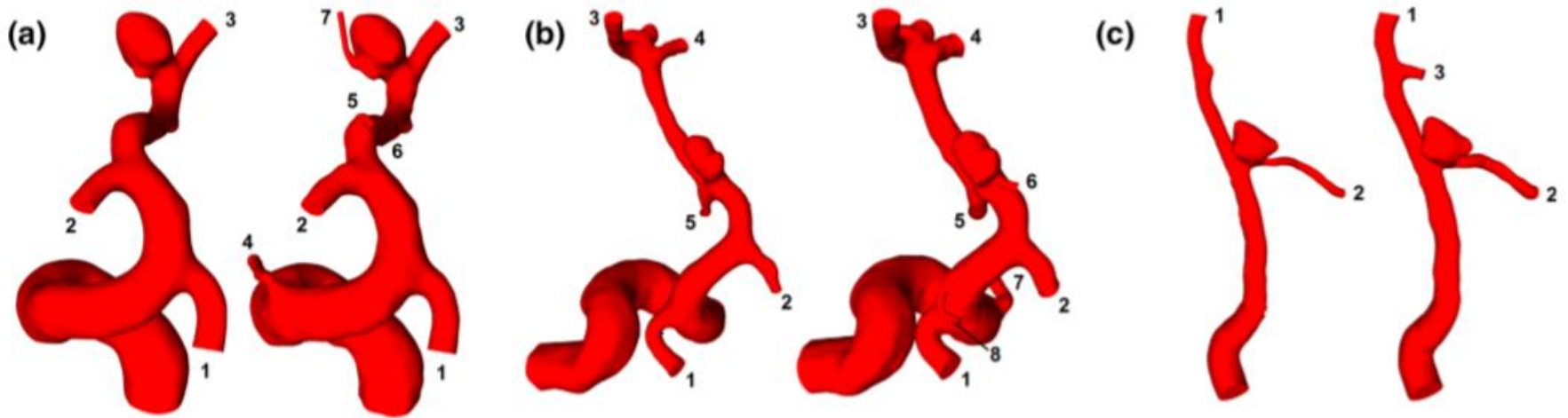BIOMEDICAL ENGINEERING SOCIETY FOR CIRCULATION

Segmentation

FIGURE 3. Illustration of representative groups providing segmentation results with the lowest and the highest number of considered outlet cross-sections: (a) right anterior circulation [group 21 (3 outlets) vs. group 23 (7 outlets)], (b) left anterior circulation [group 18 (5) vs. group 7 (8)], and (c) posterior circulation [group 15 (2) vs. group 7 (3)].

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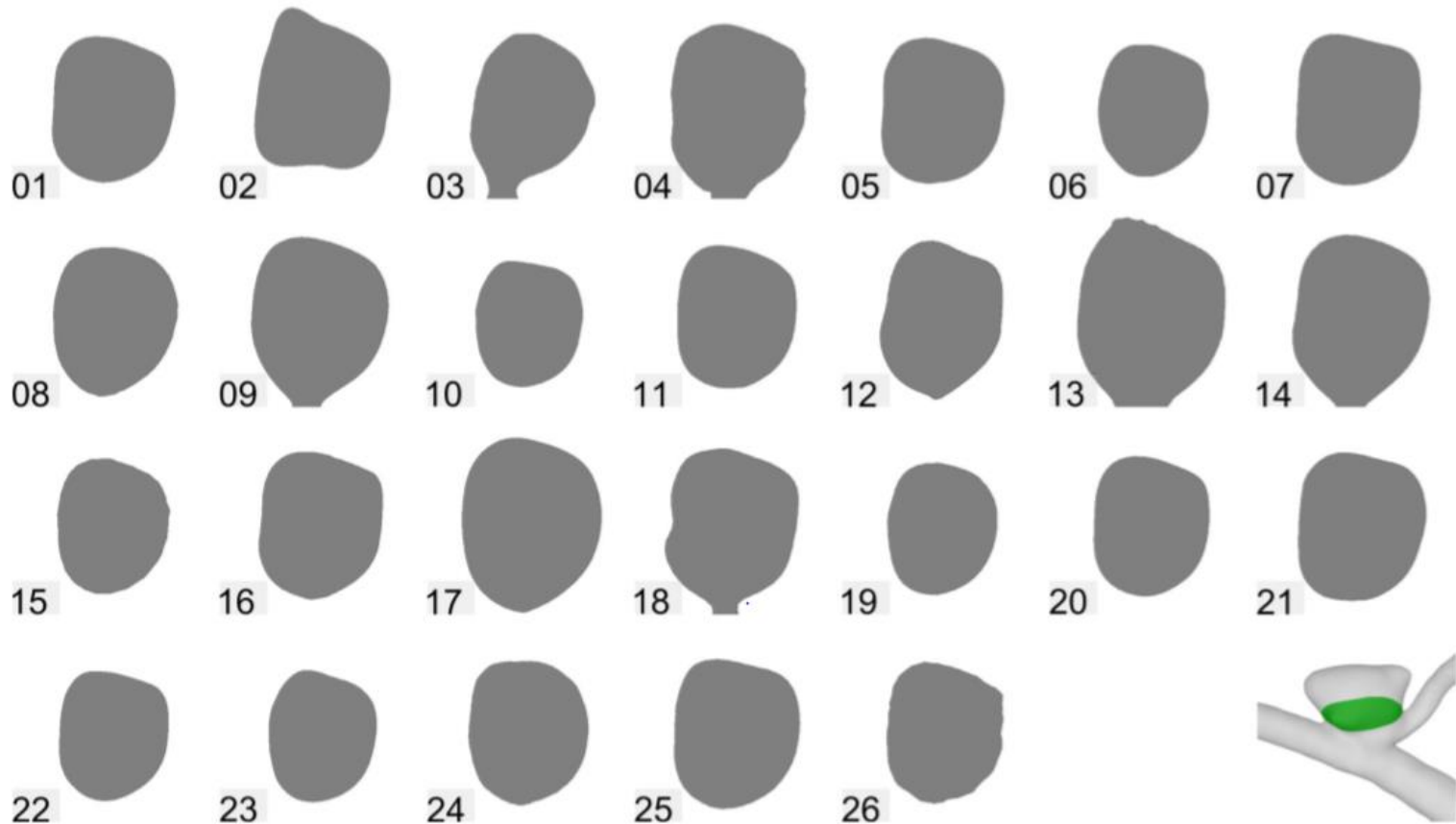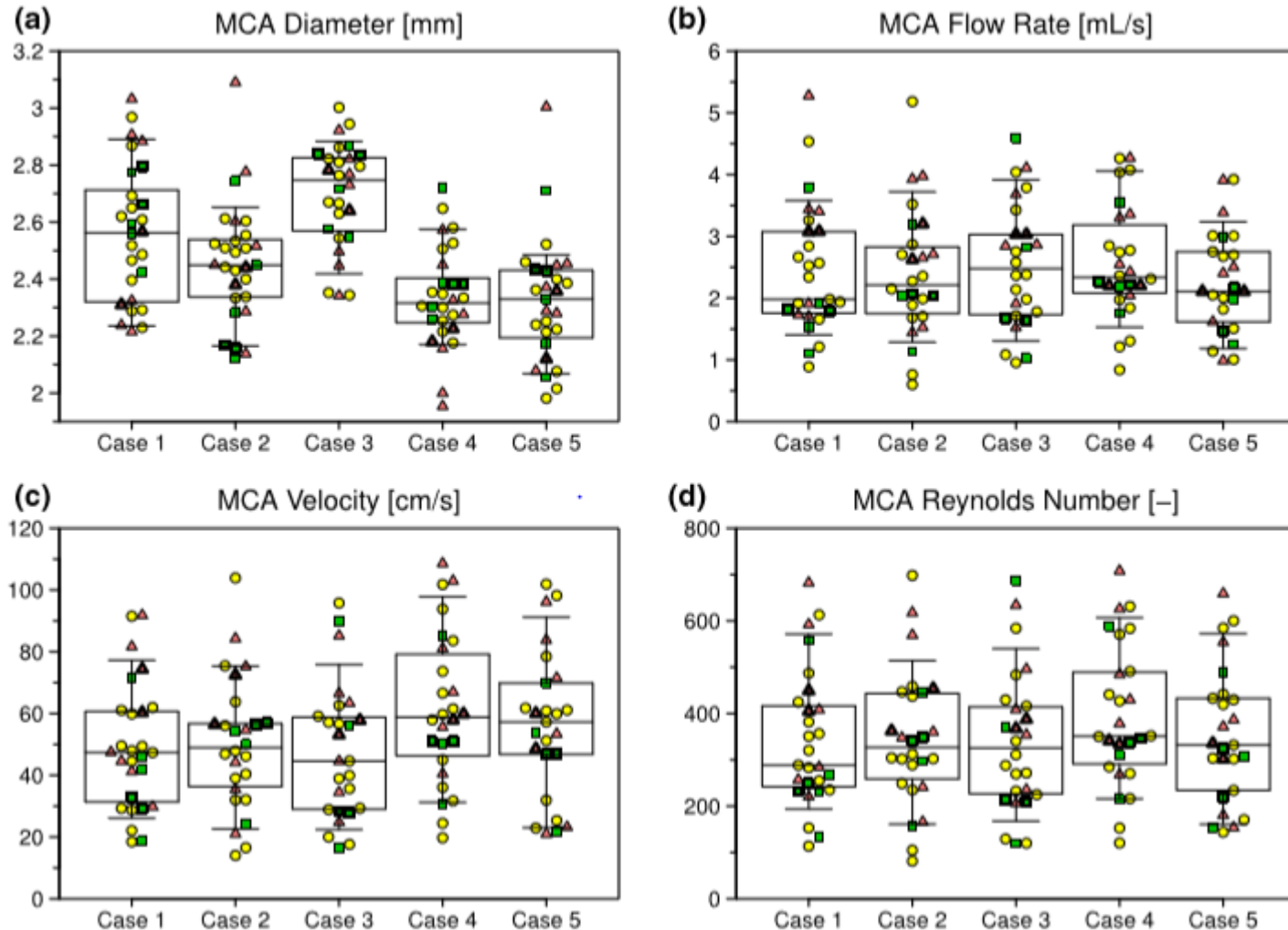
How to close the gap

Segmentation

FIGURE 5. Illustration of the ostium cut-plane for the ruptured aneurysm E located at the left PICA. Notice the inconsistencies with respect to size and shape.

(a) MCA Diameter [mm]
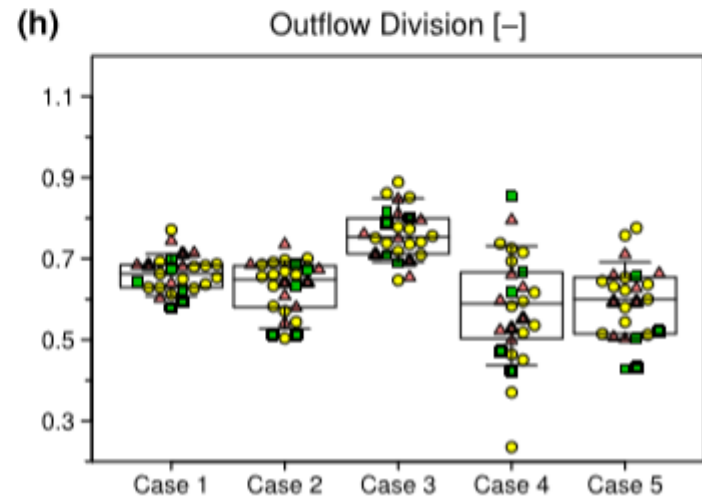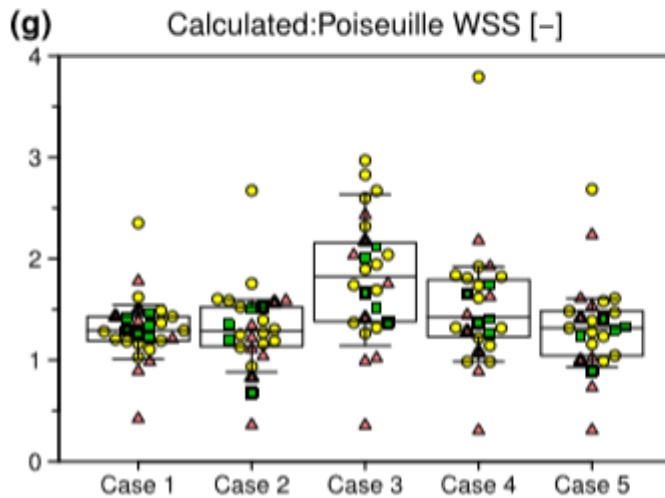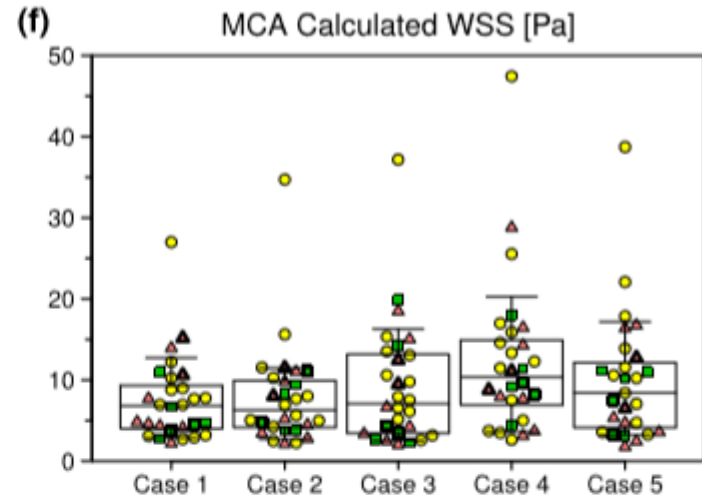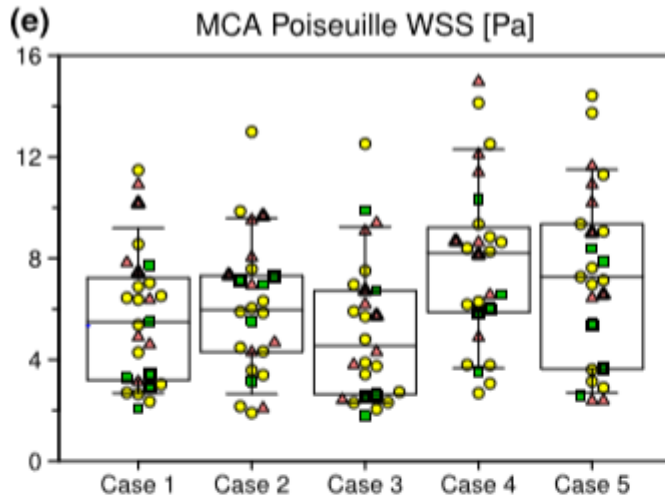(b) MCA Flow Rate [mL/s]
(c) MCA Velocity [cm/s]
(d) MCA Reynolds Number [–]

(VALEN-SENDSTAD et al, Cardiovascular Engineering and Technology, 2018, 9(4), 544-564)

(VALEN-SENDSTAD et al, Cardiovascular Engineering and Technology, 2018, 9(4), 544-564)
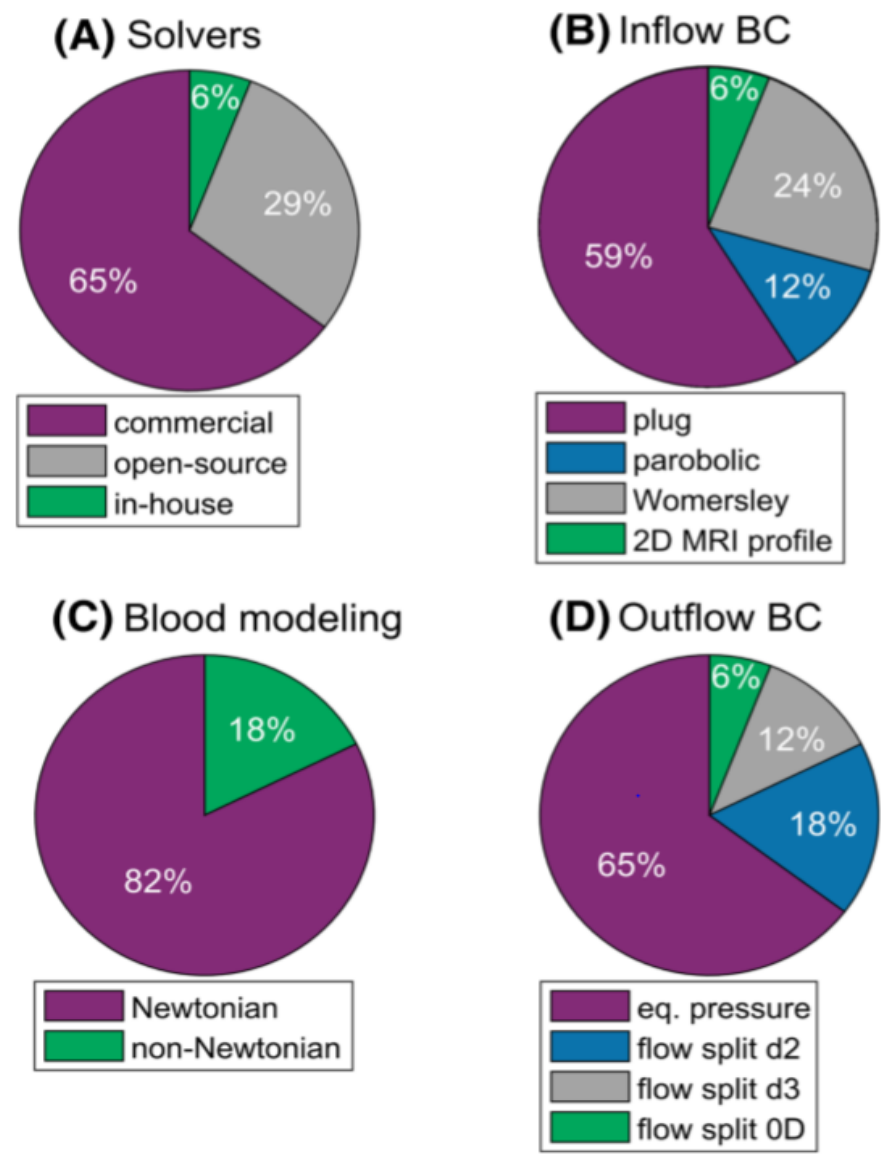
Table 1 Each group's technical details regarding the corresponding hemodynamic simulation and analysis as well as individual selections of the aneurysm with the highest rupture probability (correct choices are highlighted as bold)

Group	Inlet boundary condition	Blood treatment	Time dependency	Outlet boundary condition	Time step size	Parameters	No. param.	Aneurysm choice
1	**Womersley**	**Newtonian**	**Unsteady**	**Zero pressure**	**1E−02**	**Morph/hemo**	**16**	**E**
2	Plug	Non-Newt.	Unsteady	Zero pressure	1E−03	Morph/hemo	4	A
3	Plug	Newtonian	Steady	Zero pressure	–	Morph/hemo	2	C
4	Plug	Newtonian	Steady	Murray (d2)	–	Hemo	1	D
5	Womersley	Newtonian	Unsteady	0D model	1E−04	Morph/hemo	6	A
6	**2D PC-MRI**	**Non-Newt.**	**Unsteady**	**Constant pressure**	**1E−02**	**Morph/hemo**	**3**	**E**
7	Plug	Non-Newt.	Steady	Murray (d2)	–	Morph/hemo	4	A
8	**Womersley**	**Newtonian**	**Unsteady**	**Zero pressure**	**1E−03**	**Morph/hemo**	**4**	**E**
9	Womersley	Newtonian	Unsteady	0D model	1E−04	Morph/hemo	2	D
10	Plug	Newtonian	Unsteady	Zero pressure	5E−07	Hemo	2	D
11	Parabolic	Newtonian	Steady	Murray (d3)	–	Morph/hemo	2	A
12	Plug	Newtonian	Unsteady	Pressure waveform	5E−03	Hemo	3	C
13	Plug	Newtonian	Unsteady	Murray (d2)	1E−03	Morph/hemo	3	C
14	Plug	Newtonian	Unsteady	Zero pressure	5E−04	Morph/hemo	4	A
15	**Parabolic**	**Newtonian**	**Unsteady**	**Zero pressure**	**7E−03**	**Hemo**	**5**	**E**
16	Plug	Newtonian	Steady	Zero pressure	–	Hemo	5	C
17	Plug	Newtonian	Unsteady	Pressure waveform	1E−03	Morph/hemo	6	A

The following criteria are presented: (1) type of inlet boundary condition: constant (plug), parabolic, Womersley or phase-contrast magnetic resonance imaging (PC-MRI) profile, (2) blood treatment, assuming Newtonian or Non-Newtonian behavior, (3) time dependency: steady-state or time-varying simulations, (4) type of parameters for rupture risk assessment: morphologic and/or hemodynamic, (5) number of considered parameters, (6) selected aneurysm with the highest rupture probability

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(A) Solvers — commercial 65%, open-source 29%, in-house 6%

(B) Inflow BC — plug 59%, parobolic 12%, Womersley 24%, 2D MRI profile 6%

(C) Blood modeling — Newtonian 82%, non-Newtonian 18%

(D) Outflow BC — eq. pressure 65%, flow split d2 18%, flow split d3 12%, flow split 0D 6%

Group	Rupture risk assessment strategy	Parameters	
		Morph	Hemo
1	**Logistic regression models (based on CFD simulations of 1920 aneurysms) [7]**	**9**	**7**
2	Rupture resemblance score (based on CFD simulations of 542 aneurysms) [25]	2	2
3	Aneurysm size and energy loss [26]	1	1
4	WSS difference between the maximum and minimum flow condition	0	1
5	Combination of size, irregularity, low aspect ratio and low WSS, high OSI, high-frequency WSS instabilities [27]	3	3
6	**Location, diameter, WSS**	**2**	**1**
7	Location, size, ratio of volume and volume of least bounding sphere, streamlines, and WSS	3	1
8	**Internal scoring system based on dome/neck ratio, blebs, TAWSS, change in instantaneous WSS, OSI on daughter blebs**	**2**	**3**
9	Visual inspection of morphology (non-spherical shape) and flow instability (turbulent-like flow)	1	1
10	Pressure and WSS ratios	0	2
11	Size and low WSS	1	1
12	WSS, TAWSS, OSI	0	3
13	Rupture resemblance score (based on CFD simulations of 542 aneurysms) [25]	1	2
14	Aspect ratio, pressure difference, OSI, rupture risk parameter based on WSS and averaged velocity	1	4
15	**TAWSS, OSI, RRT, pressure distribution, stagnation points**	**0**	**5**
16	Relative changes of WSS, velocity, pressure, vorticity, helicity	0	5
17	Size, aspect ratio, WSS, OSI, RRT, ICI	2	4

Thank you very much!