FIELDS - Mitacs

Conference on Mathematics of Medical Imaging,
June 20-24, 2011

Toronto, 2011 Jun 21

An Integrated Morphology+CFD Statistical Investigation of Parent Vessel in Cerebral Aneurysms

EMORY

Alessandro VENEZIANI
Math & CS Department, Emory University, Atlanta, GA, USA
W H Coulter BioMedical Engineering Department, GA Tech & Emory, Atlanta, GA,USA

EMORY

Joint work with M. Piccinelli, T. Passerini (Emory), S. Vantini, L. Sangalli, P. Secchi (Politecnico di Milano, Italy) , L. Antiga (Orobix)

FIELDS - Mitacs

Acknowledgments:
ANEURISK
(2005-2008+)

Fondazione Politecnico di Milano

SIEMENS
Medical Solutions Italy (Ing. M. Fiorani)

MOX
Laboratorio di Modellistica e Calcolo Scientifico

LaBS
Laboratorio di Meccanica delle Strutture Biologiche

Istituto di Ricerche Farmacologiche
Mario Negri

ANEURISK

OSPEDALE MAGGIORE POLICLINICO, MANGIAGALLI E REGINA ELENA - FONDAZIONE IRCSS

Azienda Ospedaliera
Ospedale Niguarda Ca' Granda

Università degli Studi di Milano
Neurochirurgia

The BA Foundation Project:
Computational and Statistical Analysis of Cerebral Aneurysm Morphology
(2010-2011)

THE BRAIN ANEURYSM FOUNDATION

THE BRAIN ANEURYSM FOUNDATION

GOAL: Analyze the impact of morphology and hemodynamic and morphology on the development (rupture) of the aneurysm

Distinctive features:

a) Analysis of the parent vessel

b) Functional Principal Component Analysis (see M. Miller plenary) for the investigation of the data&simulations

Deliverable (expected Sept 2011):

A public Brain Aneurysm Images Repository + Data

STRUCTURE OF THE PROJECT

Clinical Data (DICOM)

GEOMETRICAL ANALYSIS

3D reconstruction and semi-automatic detection of relevant morphological features

DATA-BASE

NUMERICAL MODELING

3D Simulations, FSI, WSS Computation,…

STATISTICAL ANALYSIS

Correlation, Functional Data Analysis

ANEURISK

EMORY

FIELDS

Mitacs

Geometrical Reconstruction

Source: *Rotational Angiographies* from Niguarda Hospital, Italy

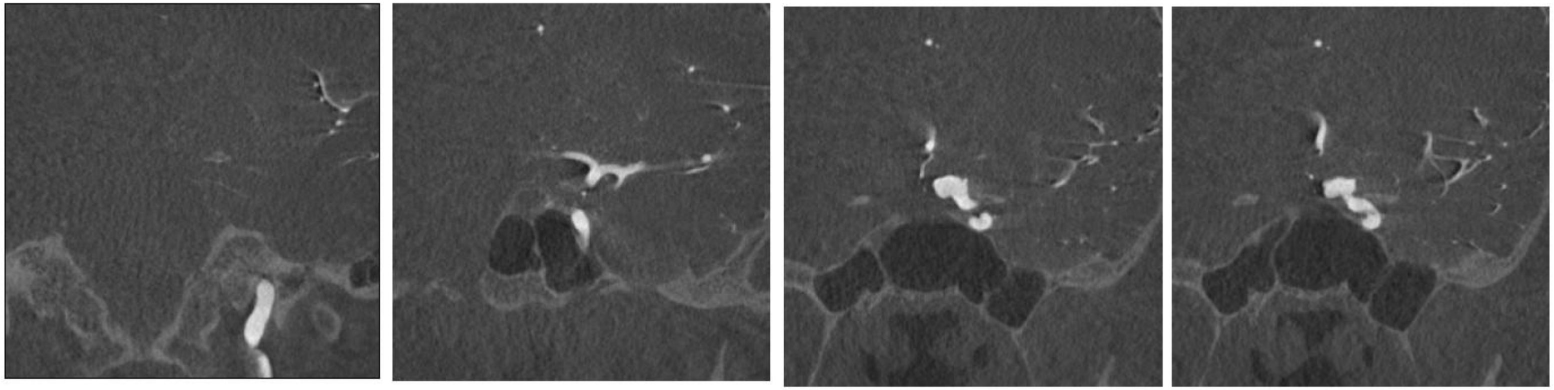
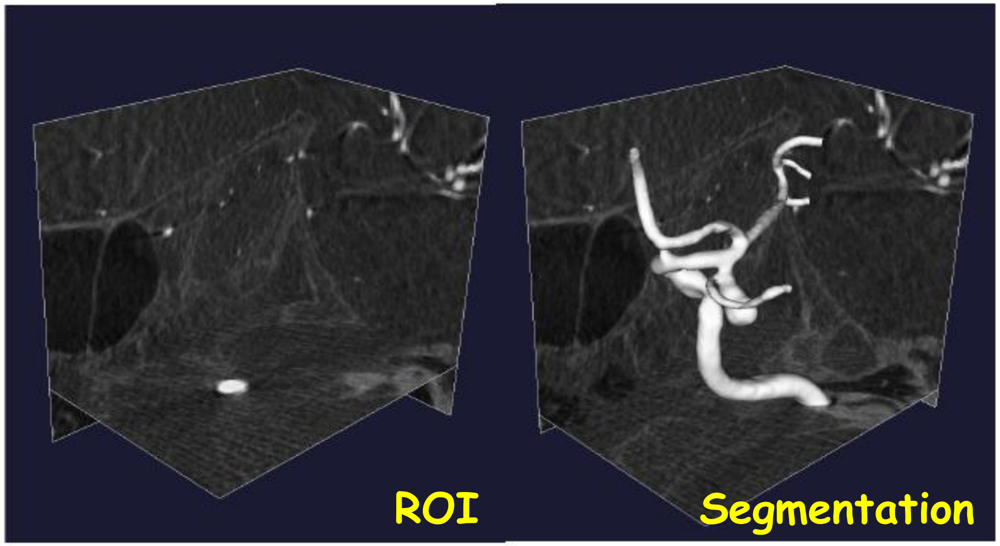
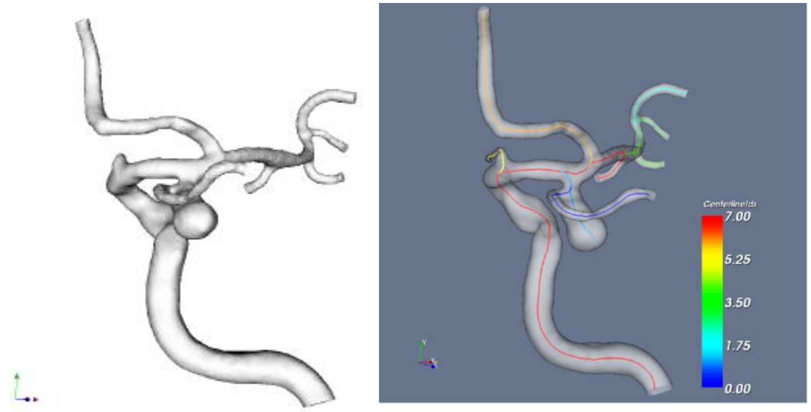
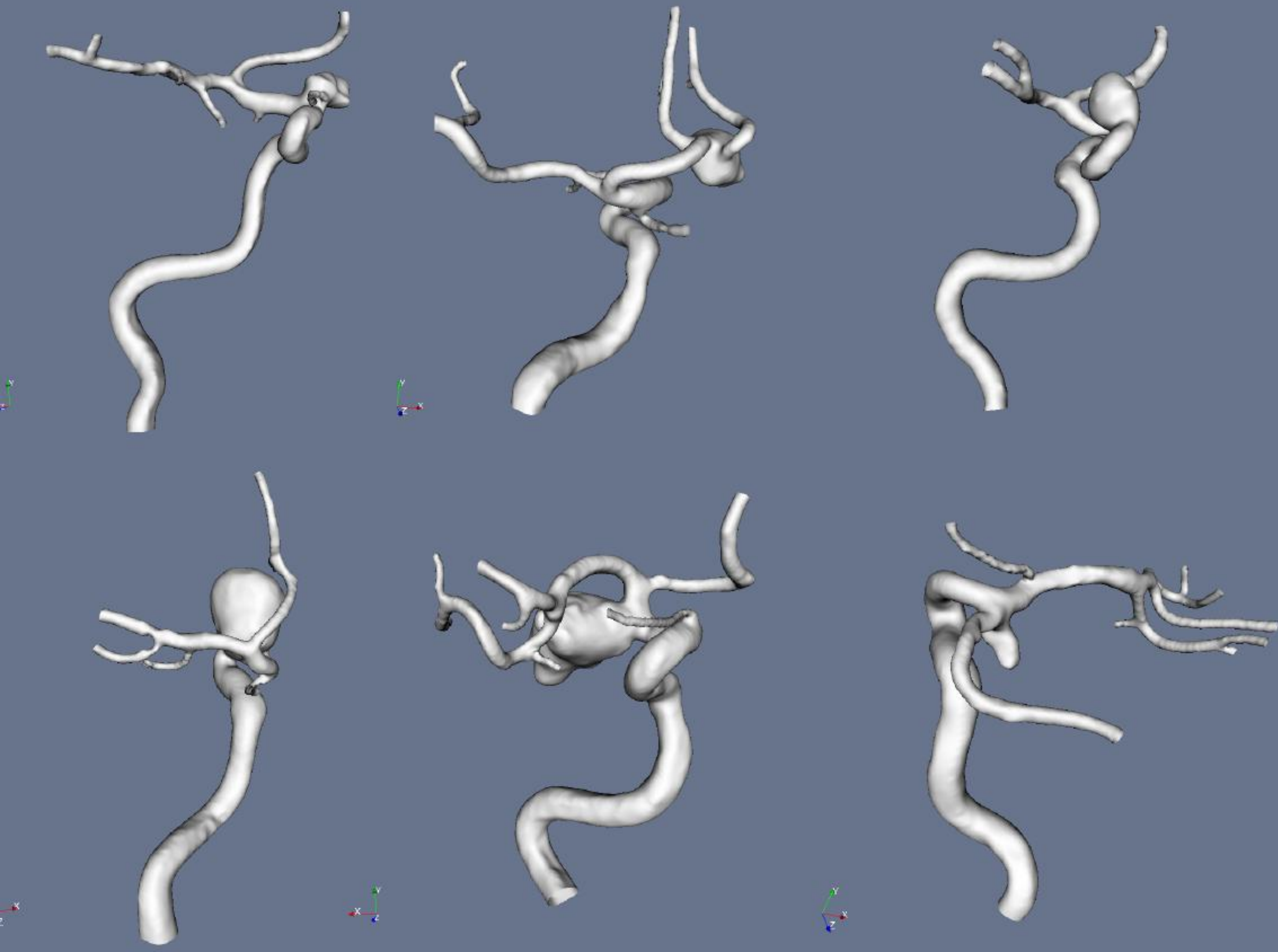


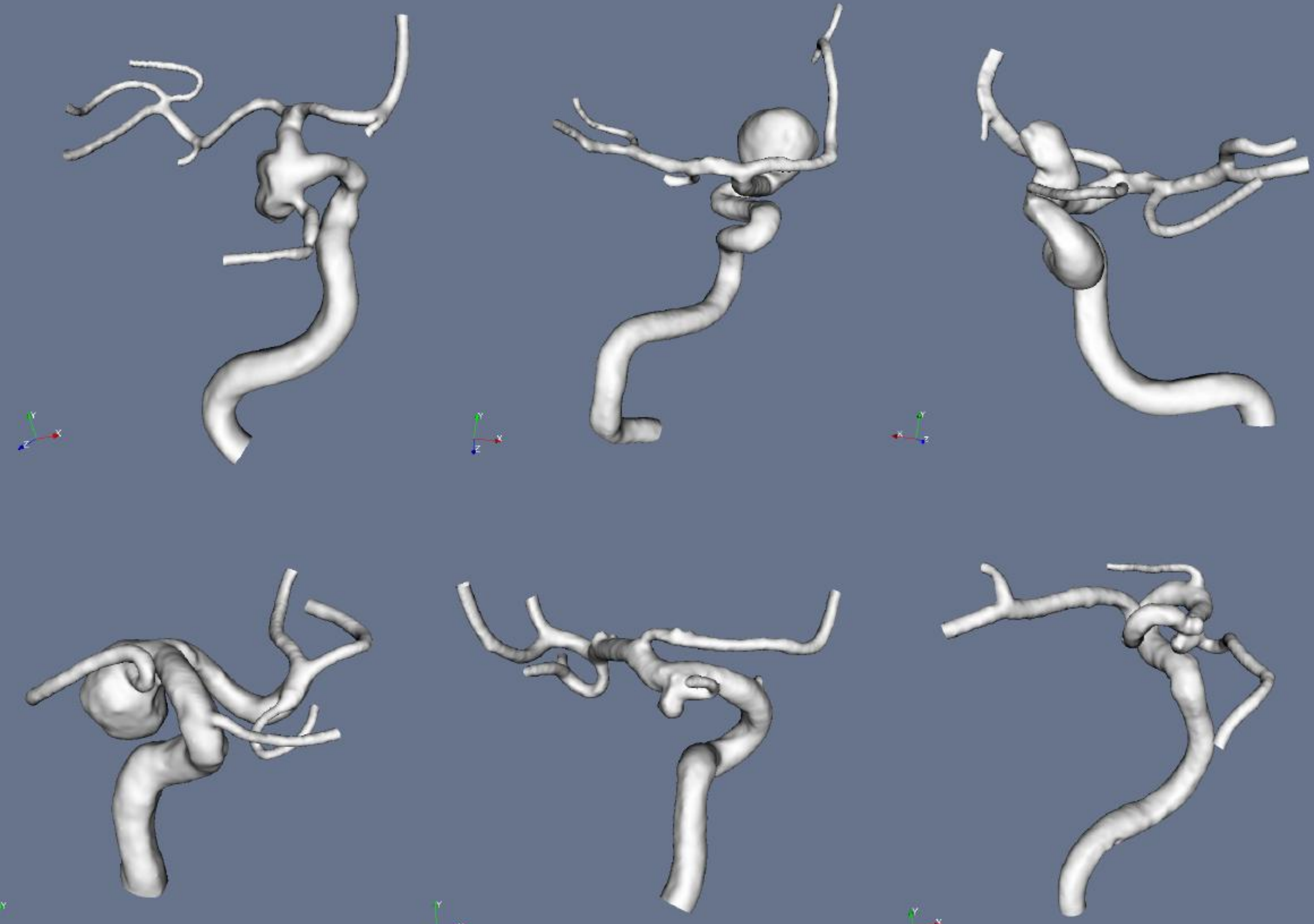
Image Manipulation: **Vascular Modeling ToolKit** (L. Antiga, M. Piccinelli)

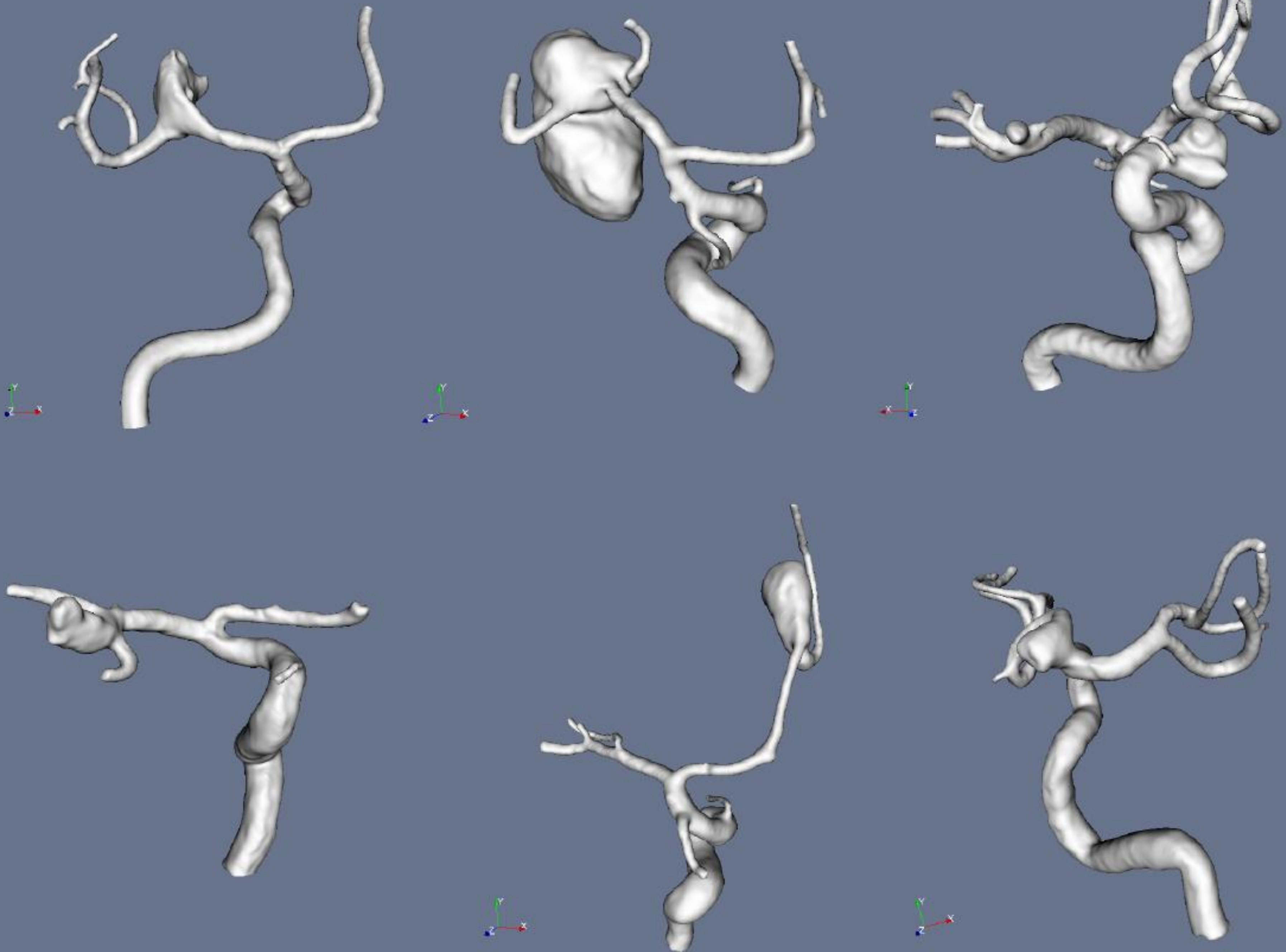




3D Model







Identification of morphological features

M. Piccinelli et al, IEEE Trans Biomed Imag 2009
VMTK

Radius

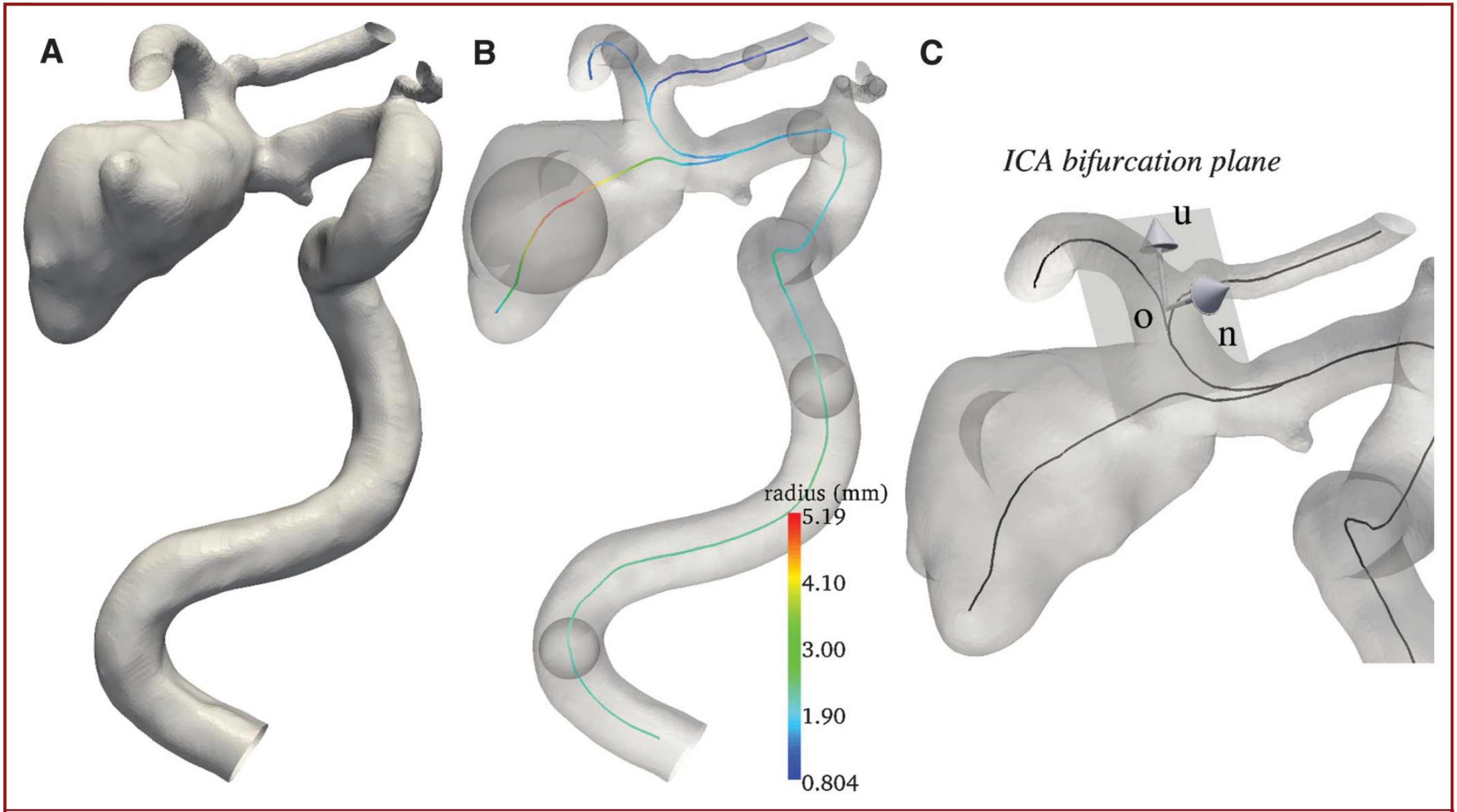


FIGURE 1. **A**, *three-dimensional model of an internal carotid artery (ICA) bearing an aneurysm.* **B**, *artery and aneurysmal sac centerlines; a few maximal inscribed spheres are included.*[15] **C**, *definition of the ICA bifurcation reference system composed of normal (n), up-normal (u), and origin (o), and the ICA bifurcation plane.*

Branching

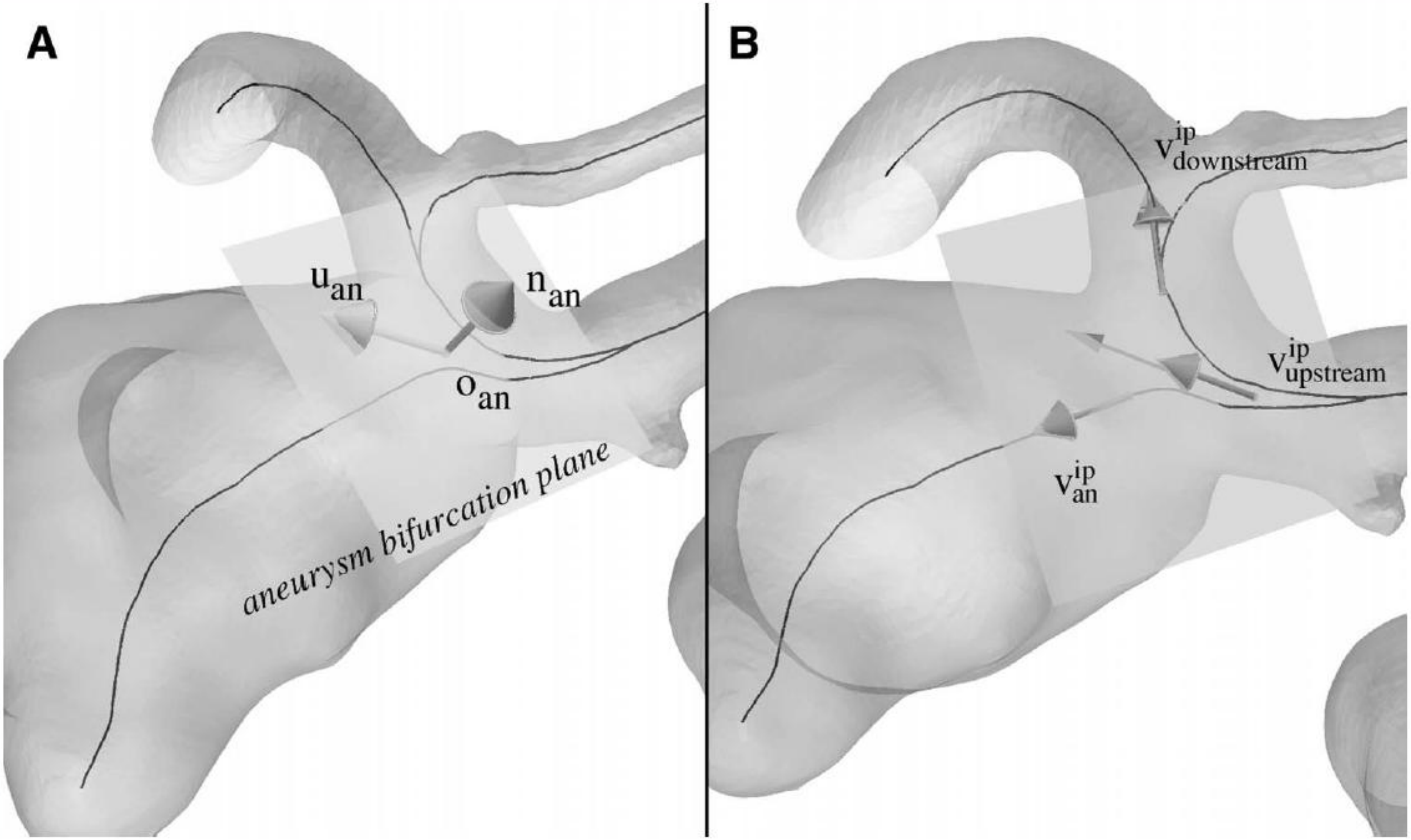


FIGURE 2. **A**, *definition of the aneurysm bifurcation reference system composed of normal (n_{an}), up-normal (u_{an}), and origin (o_{an}) and the aneurysm bifurcation plane.* **B**, *in-plane aneurysm bifurcation vectors characterizing the directions of the internal carotid artery and aneurysm branches arriving at and departing from the aneurysm bifurcation. The upstream vector lying on the bifurcation plane is also shown.*

Curvature & Tortuosity of the ICA

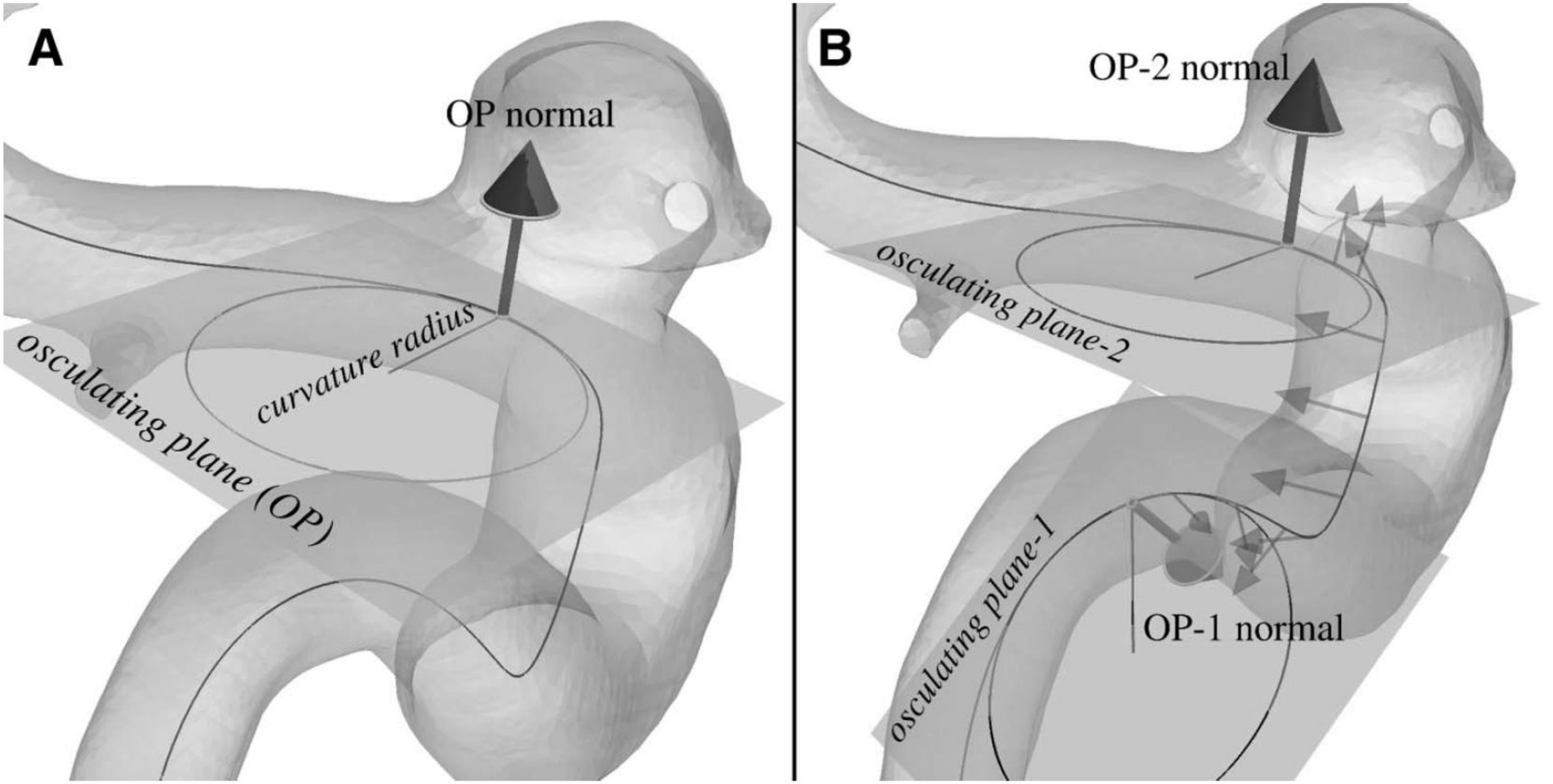


FIGURE 3. *Local geometrical characterization of the internal carotid artery (ICA).* **A**, *representation of the local osculating plane (OP) and the osculating circle tangent to the curve at one point of the ICA centerline. The curvature at each point is defined as the inverse of the radius of the osculating circle.* **B**, *rotation of the local osculating plane between 2 points of the siphon centerline.*

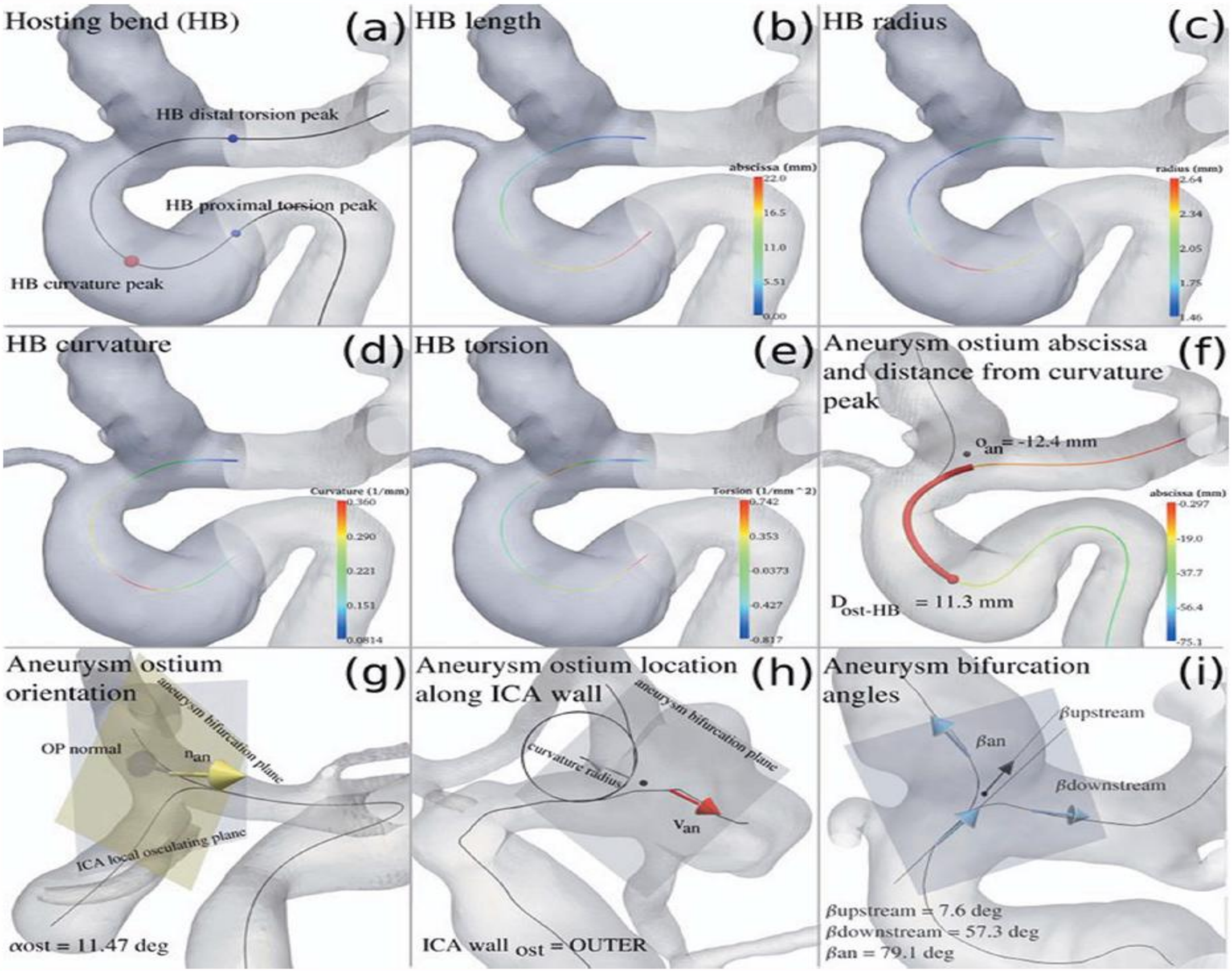
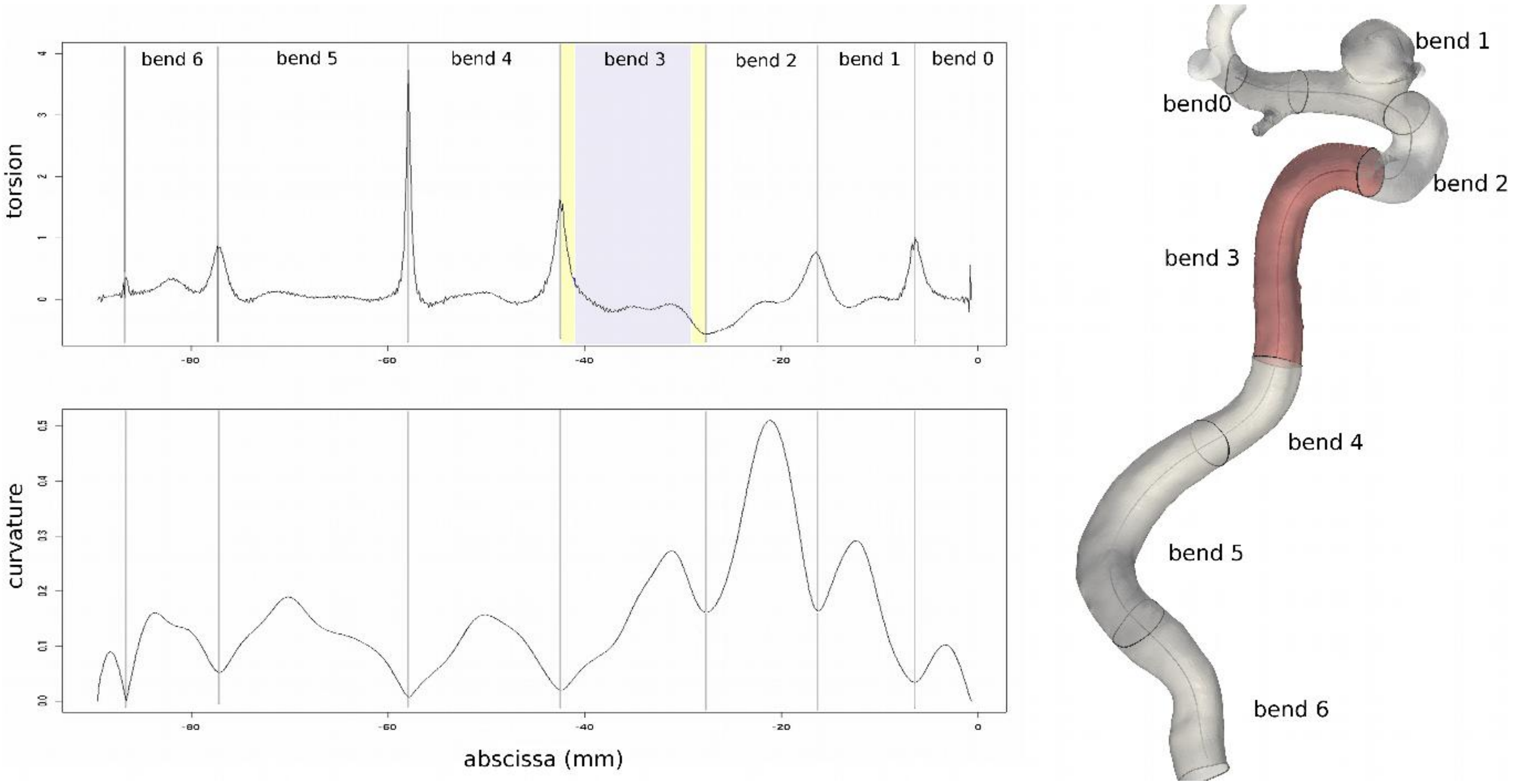


FIGURE 5. *Parameters for the geometric characterization of the internal carotid artery (ICA) and aneurysms with respect to the parent vessel.* **A**, *definition of the bend hosting the aneurysm (HB).* **B**, *length of the HB.* **C**, *radius values along the HB.* **D**, *curvature along the HB.* **E**, *torsion along the HB.* **F**, *position of the aneurysm ostium along the ICA centerline in terms of distance from the ICA bifurcation (abs_{ost}) and distance from the HB curvature peak ($D_{ost\text{-}HB}$).* **G**, *aneurysm ostium orientation (α_{ost}) calculated as the angle between the local ICA osculating plane normal (OP normal) and the aneurysm bifurcation plane normal (n_{an}).* **H**, *location of the aneurysm on the inner or outer wall of the hosting ICA.* **I**, *in-plane angles between the vascular branches arriving at and departing from the aneurysm bifurcation. Computed values are reported for a subset of the parameters.*

Bends identification



First results & statistical analysis (R)

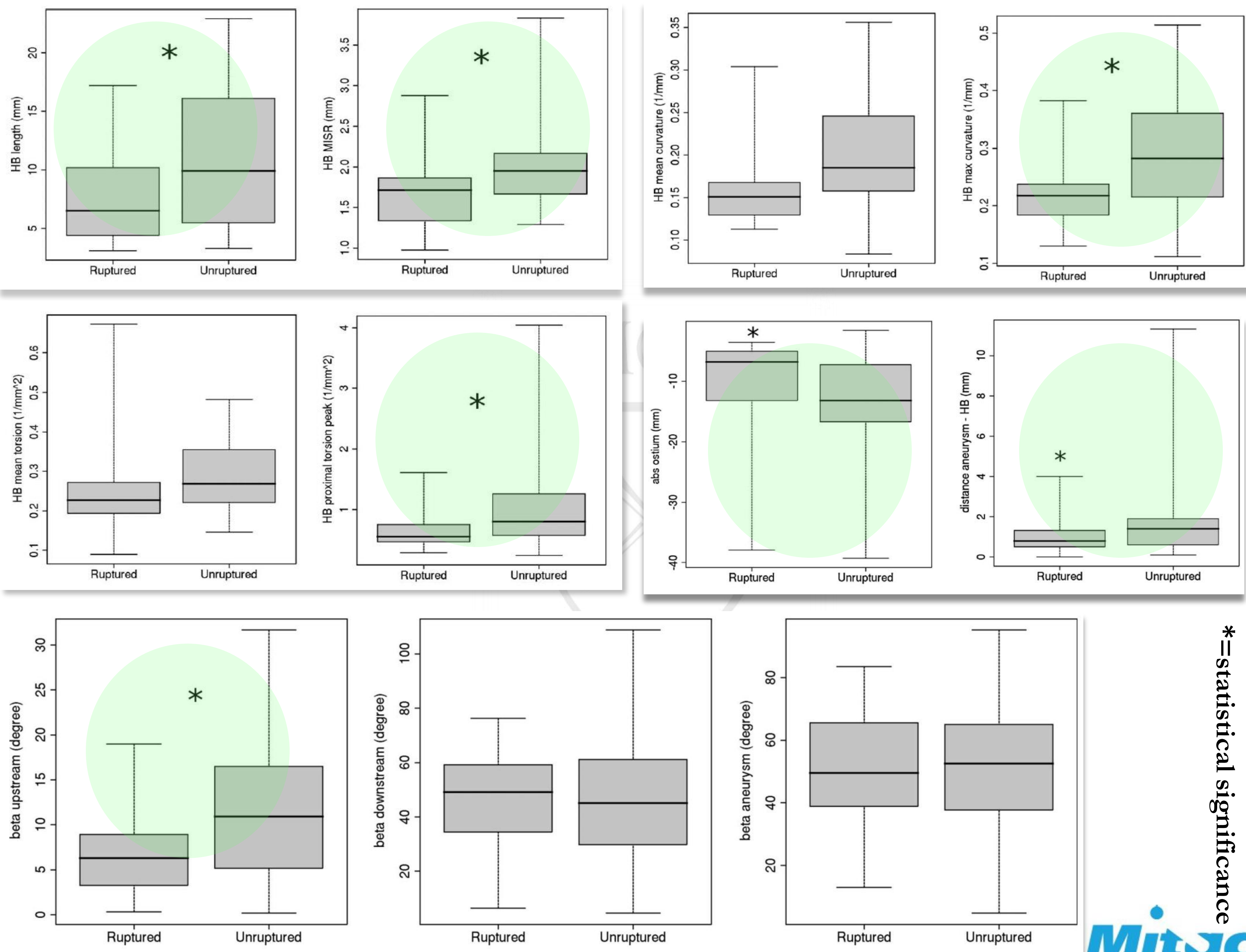
TABLE 2. Terminology, Symbols, and Descriptions of Geometric Parameters[a]

Symbol	Description
ICA bends terminology and geometric parameters	
HB	The bend hosting the aneurysm
l_{HB}	Length of the hosting bend
$misr_{HB}$	Maximum inscribed sphere radius of the hosting bend
c_{HB}^{mean}	Mean curvature of the hosting bend
c_{HB}^{max}	Maximum curvature of the hosting bend
t_{HB}^{mean}	Mean torsion of the hosting bend
t_{HB}^{prox}	Torsion value at the proximal hosting bend end point
t_{HB}^{dist}	Torsion value at the distal hosting bend endpoint
HB BTR	Ratio between inner bend mean torsion value and t_{HB}^{mean}
Aneurysm ostium geometric parameters	
abs_{ost}	Curvilinear abscissa (
$D_{ost\text{-}HB}$	Distance measured a curvature peak of
α_{ost}	Angle between 2 pla plane and the ane
ICA $wall_{ost}$	Classification of aneu outer wall of the I
Angles between aneurysm bifurcation branches	
$\beta_{upstream}$	Angle between the I the up-normal uni
$\beta_{downstream}$	Angle between the I branches of the IC
β_{an}	Angle between the I aneurysm vector

[a]ICA, internal carotid artery.

TABLE 3. Mean ± SD, Minimum, and Maximum Values for All Geometric Parameters[a]

Geometric Parameter	Mean ± SD	Minimum	Maximum
l_{HB}	9.82 ± 5.61	3.10	22.90
$misr_{HB}$	1.90 ± 0.49	0.98	3.83
c_{HB}^{mean}	0.19 ± 0.06	0.08	0.36
c_{HB}^{max}	0.27 ± 0.10	0.11	0.51
t_{HB}^{mean}	0.28 ± 0.10	0.10	0.67
t_{HB}^{dist}	0.68 ± 0.78	0.01	4.40
t_{HB}^{prox}	1.05 ± 0.91	0.23	4.04
HB BTR	0.71 ± 0.19	0.28	1.01
abs_{ost}	−12.73 ± 8.38	−1.70	−39.26
$D_{ost\text{-}HB}$	2.08 ± 2.70	0.00	11.30
α_{an}	38.53 ± 22.80	1.51	86.83
$\beta_{upstream}$	10.44 ± 7.44	0.18	31.67
$\beta_{downstream}$	46.59 ± 23.37	4.67	108.78
β_{an}	51.35 ± 22.77	4.78	95.19



*=statistical significance

Some conclusions

- ❑ Ruptured aneurysms of ICA are in a *more distal position*

- ❑ Ruptured aneurysms are *close to the peak of curvature* of each segment

- ❑ Upstream tracts of the parent vasculature in ruptured aneurysms intersect *aneurysm region with smaller angles*, so that they do align more with the flow divider

- ❑ Bends hosting ruptured aneurysms are *shorter, with a smaller radius, a less marked peak of curvature and a less abrupt torsion peak* at the proximal bend boundary compared to those hosting unruptured aneurysms

M. Piccinelli, S. Bacigaluppi, E. Boccardi B. Iordache, A. Remuzzi, A. V., L. Antiga, Neurosurgery (2011)

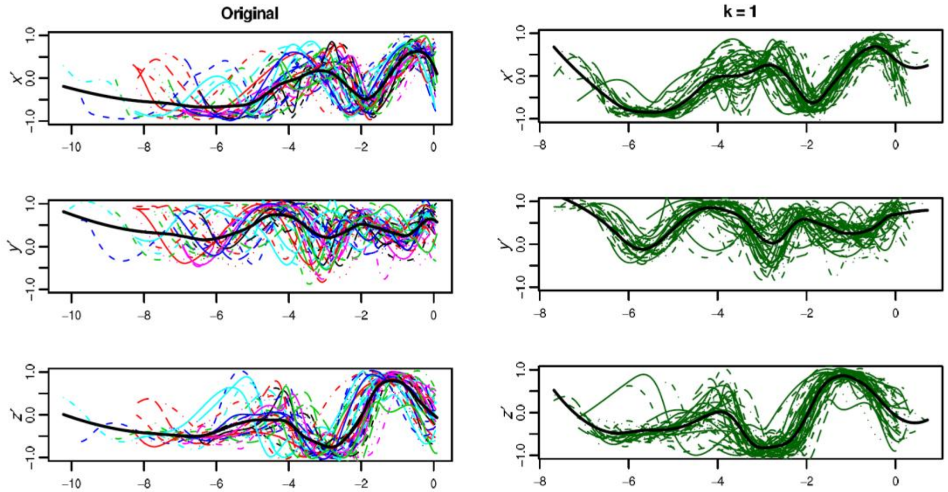


Fig. 3 Left: first derivatives with respect to the curvilinear abscissa of the centerlines coordinates ($x' = dx/ds$, $y' = dy/ds$, $z' = dz/ds$) of the estimated ICA, reconstructed from images after the free knot interpolation. The black thick curve represents the template reconstructed by the data without alignment. Right: first derivatives of centerlines after the alignment. We identified here just one cluster of data ($k = 1$). The template of this cluster is represented again by the black thick line.

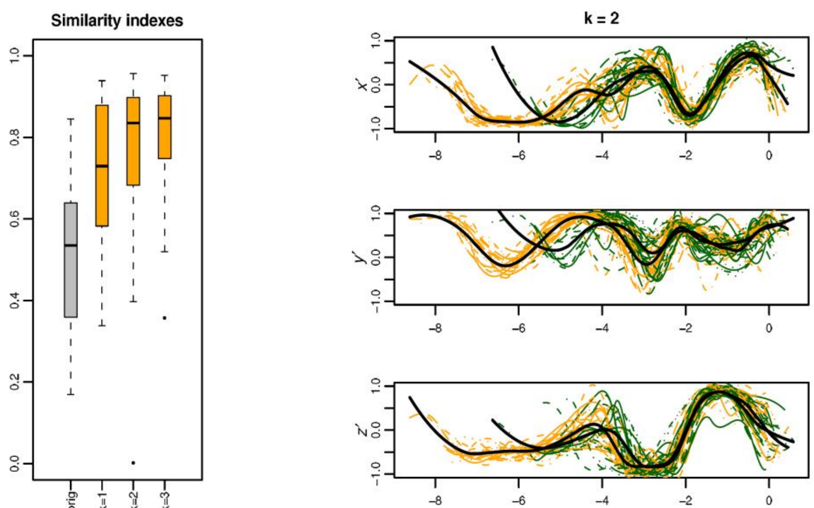
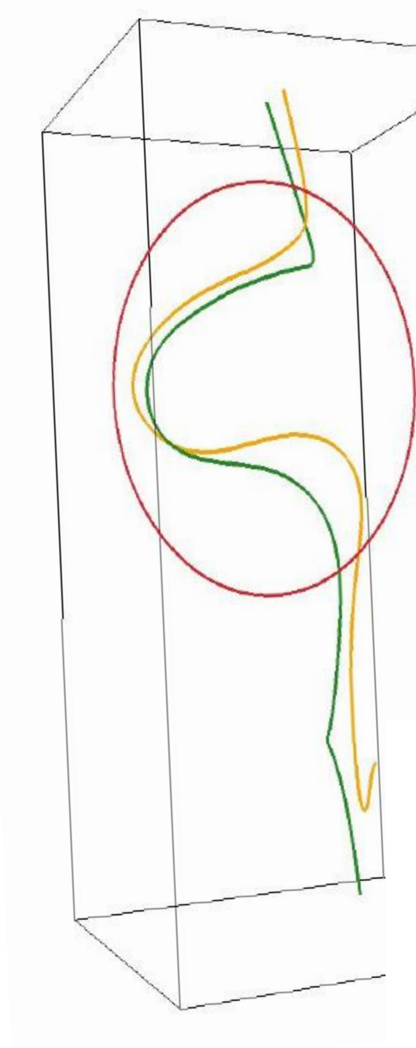
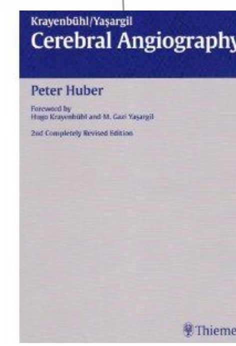


Fig. 4 Left: boxplots of similarity indexes between each curve and the corresponding template for original estimated centerlines and for centerlines aligned and clustered in k groups, $k = 1, 2, 3$. Right: After the alignment, a better clustering is obtained with two groups ($k = 2$), whose templates are represented by the solid thick lines.

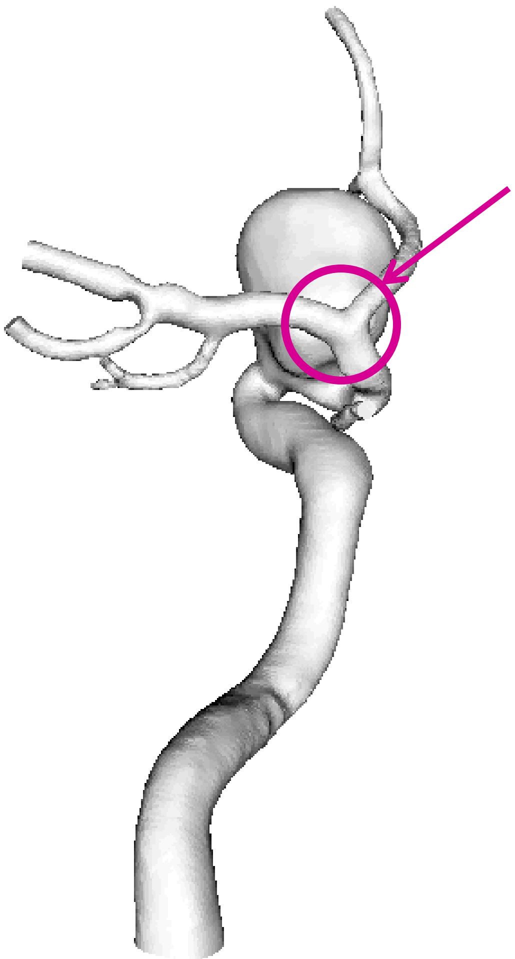




Position	at/after ICA bifurcation	along ICA	No aneurysm
Ω	70%	48%	0%
S	30%	52%	100%

s in Cerebral

RUPTURED vs UNRUPTURED



L (Lower): Aneurysms *proximal* w.r.t. carotid bifurcation

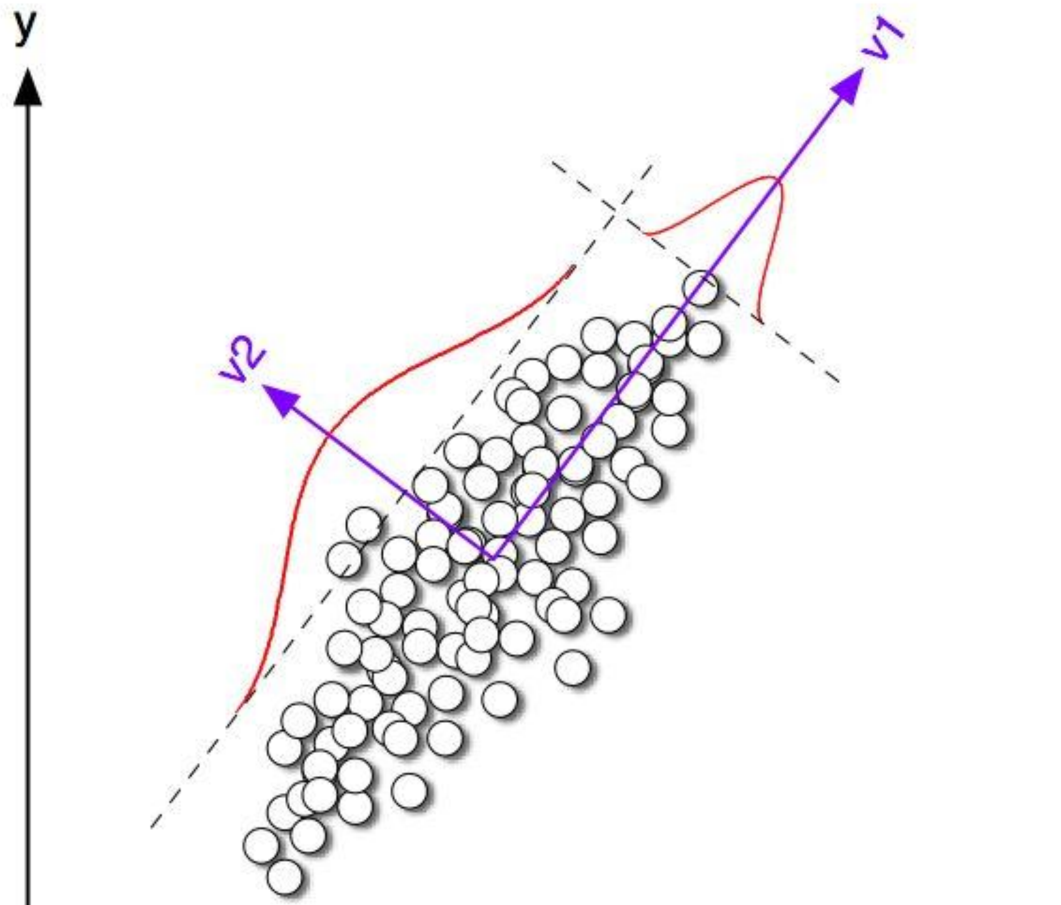
U (Upper): Aneurysms *distal* w.r.t. carotid bifurcation

R: Ruptured aneurysms

N: Unruptured Aneurysms

Group		Size	Position		
			ICA	MCA	ACA
U	UN	11	1	5	5
	UR	16	1	2	13
L	LN	13	13	0	0
	LR	9	9	0	0
No		3	0	0	0
Total		52	24	7	18

PCA and Functional PCA



PCA and Functional PCA

PCA

$$\begin{aligned} X &\in L^2(\Omega; R^n) \qquad \Sigma = [\sigma_{ij}] = E[(X_i - \mu_i)(X_j - \mu_j)] = cov(X_i, X_j) \\ \beta &\in R^n \end{aligned}$$

$$\begin{aligned} \beta_1 &= argmax_{\beta}[var(\beta' X)] \\ \beta_2 &= argmax_{(\beta\ :\ \beta'\Sigma\beta_1 = 0)}[var(\beta' X)] \\ \ldots &= \ldots \\ \beta_n &= argmax_{(\beta\ :\ \beta'\Sigma\beta_i = 0\ \forall i=1,2,\ldots,n-1)}[var(\beta' X)] \end{aligned}$$

$$\{\beta_1, \beta_2, \ldots, \beta_n\} = eigenvectors(\Sigma)$$

Functional PCA

$$\begin{aligned} X(t) &\in L^2(\Omega; L^2([0,T])) \qquad \Sigma(t,s) = E[(X(t) - \mu(t))(X(s) - \mu(s))] = cov(X(t), X(s)) \\ \beta(t) &\in L^2([0,T]) \end{aligned}$$

$$\begin{aligned} \beta_1(t) &= argmax_{\beta(t)}[var(\int_0^T \beta(t) X(t) dt)] \\ \beta_k(t) &= argmax_{(\beta(t)\ :\ \int_0^T \int_0^T \beta(t)\Sigma(t,s)\beta_i(s) ds dt = 0\ \forall i=1,2,\ldots,k-1)}[var(\int_0^T \beta(t) X(t) dt)] \end{aligned}$$

$$\{\beta_1(t), \beta_2(t), \ldots\} = eigenfunctions(\Sigma(t,s))$$

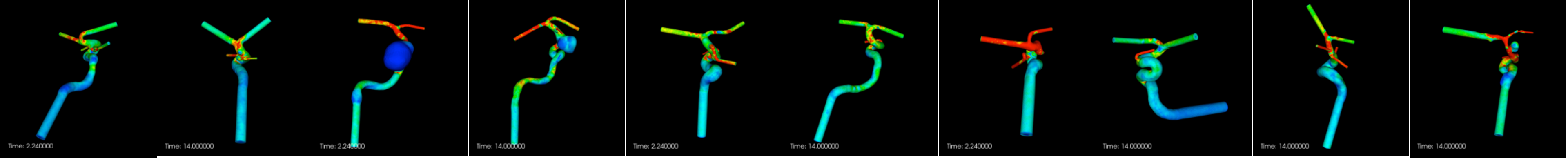
Some other conclusions (purely morphological analysis)

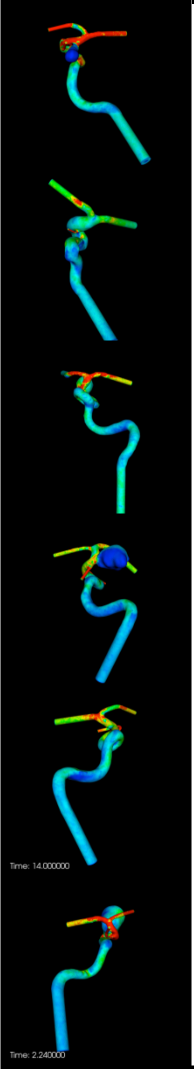
- ❑ ICA hosting proximal aneurysms (**L class**) are
  - ✓ *more bended*
  - ✓ *smaller*
  - ✓ *less tapered*

  than ICA for **U class** (distal aneurysms)

- ❑ No aneurysms class is similar to L

L. Sangalli, P. Secchi, S. Vantini, A. V., Jou Am Stat Assoc (2009)





Analysis reinforcement: Including CFD

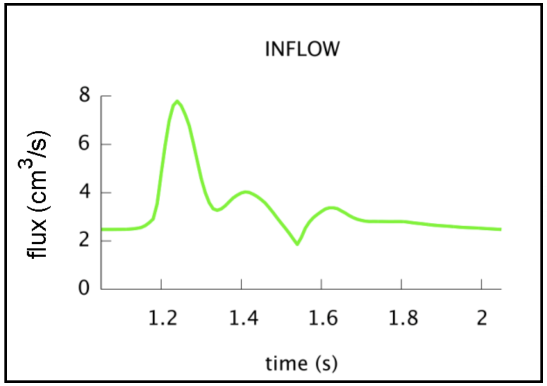
Unsteady incompressible Navier-Stokes equations

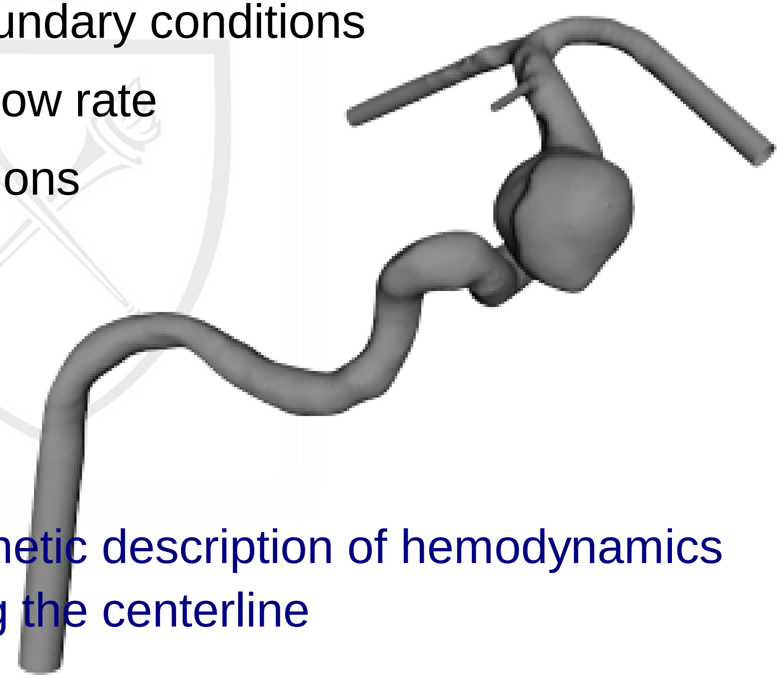
Hypotheses & Design

Rigid vessel walls: no-slip boundary conditions

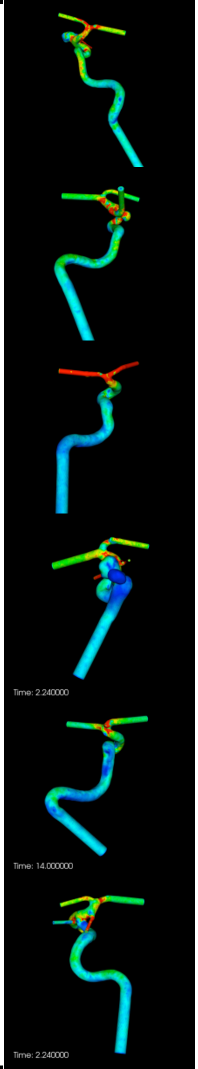
Inflow BC: Realistic velocity flow rate

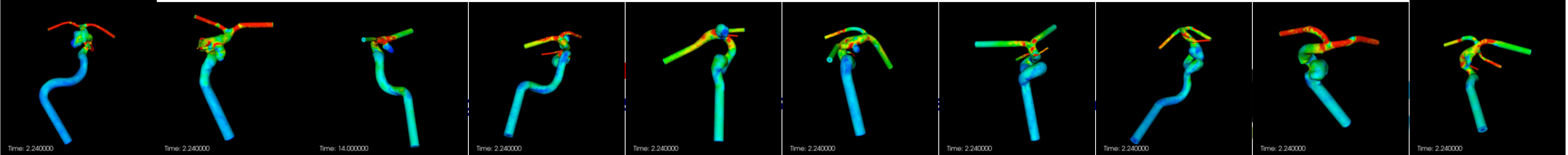
Outflow BC: No-stress conditions



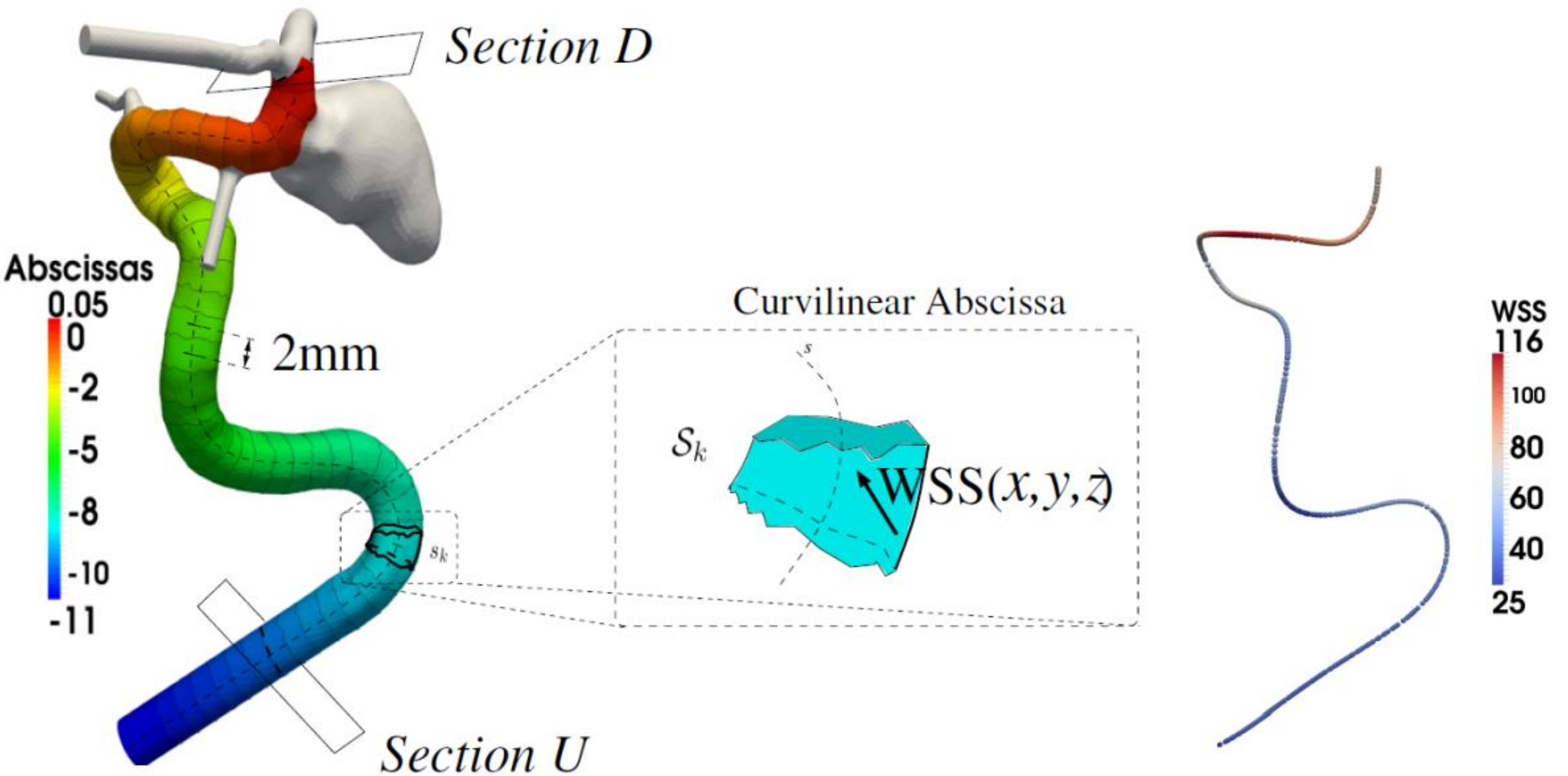


Synthetic description of hemodynamics along the centerline

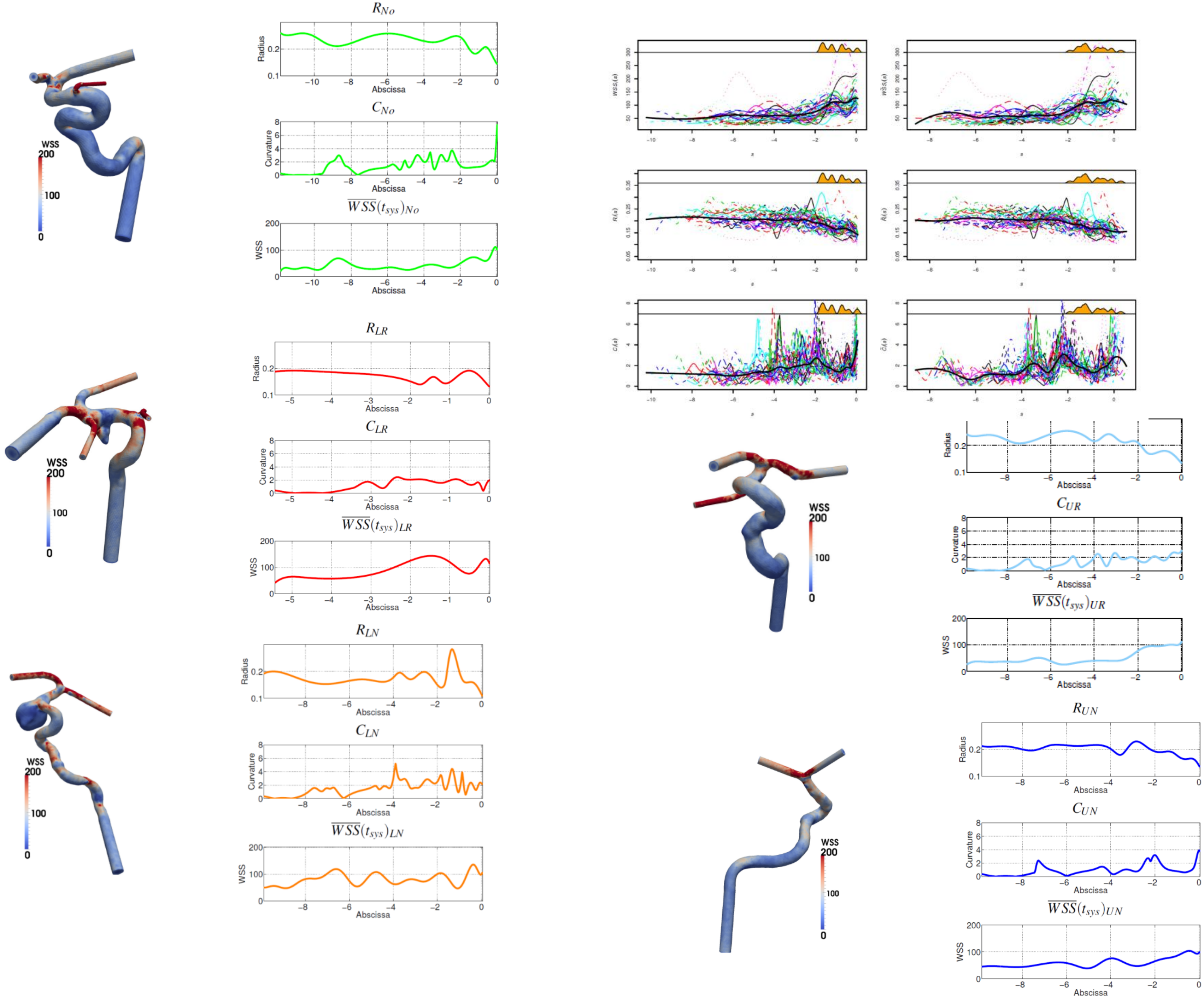




Average WSS as function of the curvilinear abscissa



$$\overline{\mathrm{WSS}}_i(s_k,t) = \left\| \frac{1}{|\mathscr{S}_k|} \int_{\mathscr{S}_k} \mathrm{WSS}_i(x,y,z,t)\, d\mathscr{S} \right\|$$



WSS
200
100
0
R_No
Radius
Abscissa
C_No
Curvature
WSS(t_sys)_No
WSS
R_LR
C_LR
WSS(t_sys)_LR
R_LN
C_LN
WSS(t_sys)_LN
C_UR
WSS(t_sys)_UR
R_UN
C_UN
WSS(t_sys)_UN

FPCA Results

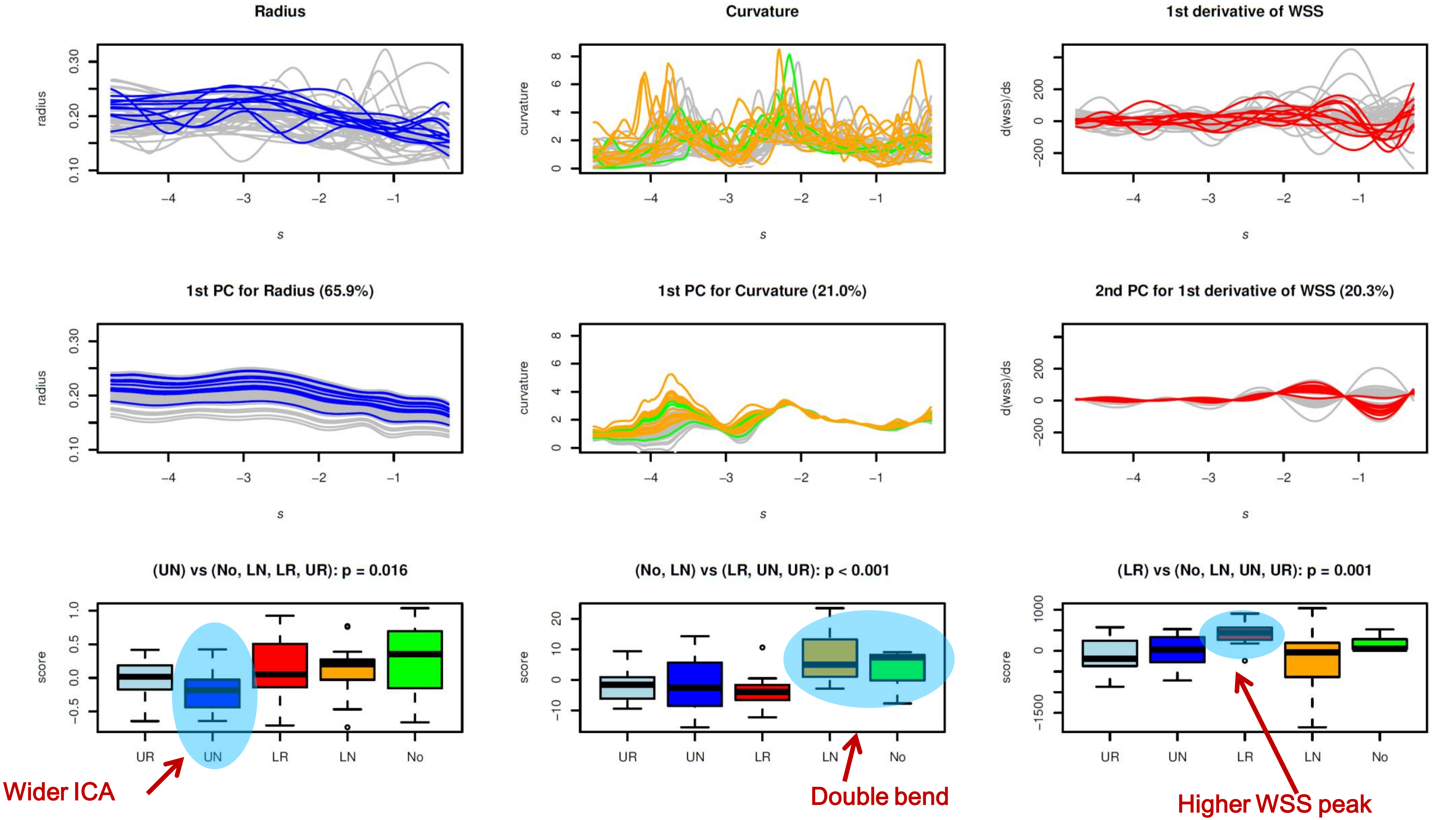
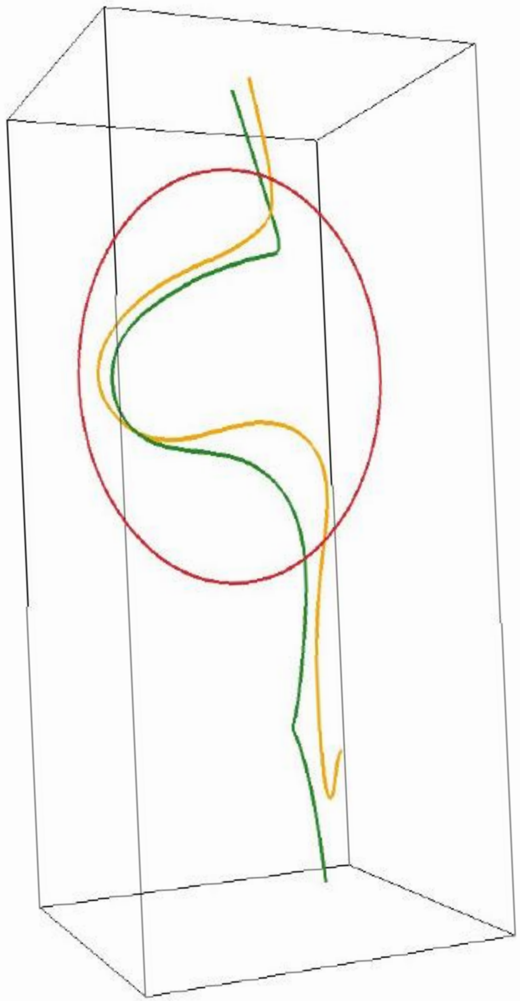


Fig. 12 First column: analysis of ICA radius profiles along aligned centerlines. Second column: analysis of curvature profiles of aligned ICA centerlines. Third column: analysis of the first derivative of the WSS profiles along aligned ICA centerlines. First row: aligned profiles. Second row: projections of subject profiles on the corresponding mode of variability. Third row: boxplots of subject scores on these principal components separated per subject group.

SYNTHESIS



Conjecture

1) There are two statistical significant clusters of Internal Carotid Arteries, S (2 bends) and Ω (1 bend)

2) Double Bends probably ``protect'' the aneurysms, by dissipating blood energy, resulting in a lower rupture risk

TO BE VALIDATED

Conclusions:

- GENERAL: Proper ***statistical methods*** for the integrated ***knowledge extraction – numerical simulations treated as measured data***

- SPECIFIC: Some parent vessel features potentially provide ***landmarks for the assessment of a risk of rupture***

TO DO LIST

1. Extend the number of variables analyzed (inclusion of the sac - in preparation)
2. Extend the number of samples
3. Validate our mechanical interpretation

⇨**REPOSITORY**