Geometric Modeling and Characterization of the Circle of Willis

Hrvoje Bogunović

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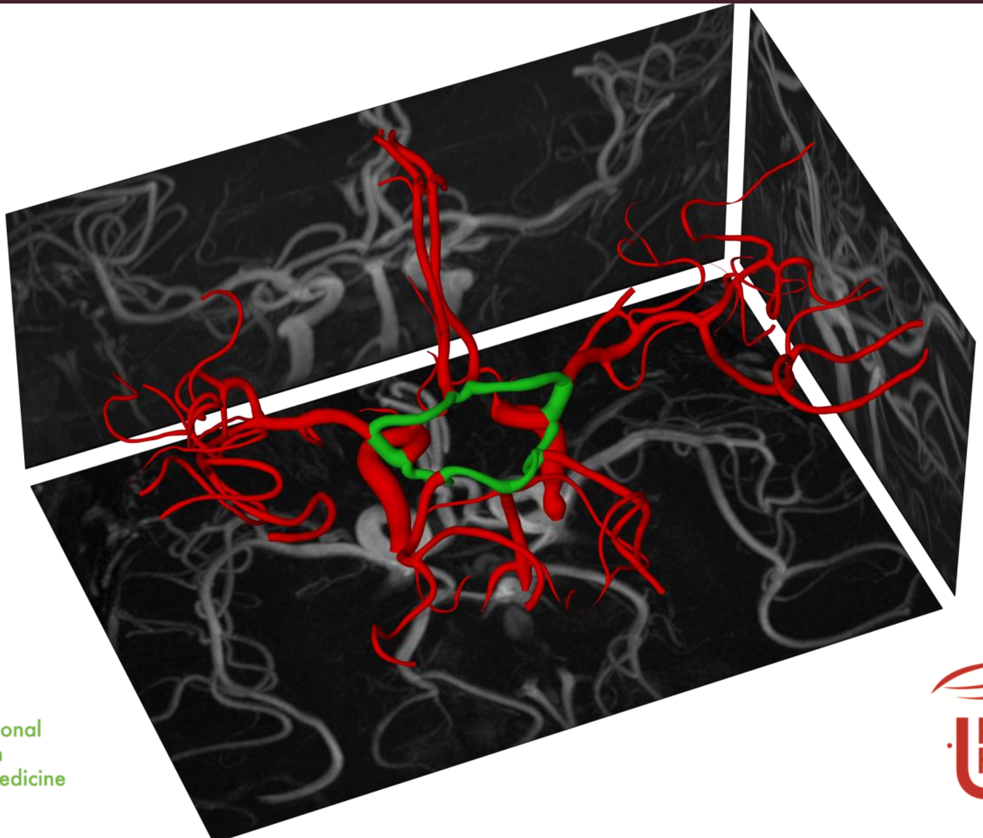

CISTIB Center for Computational Imaging & Simulation Technologies in Biomedicine

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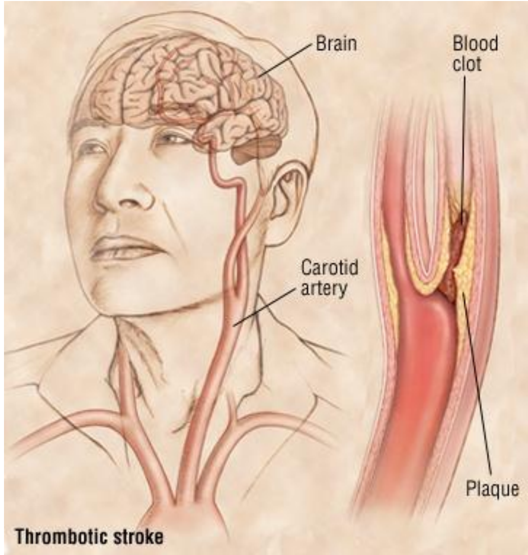
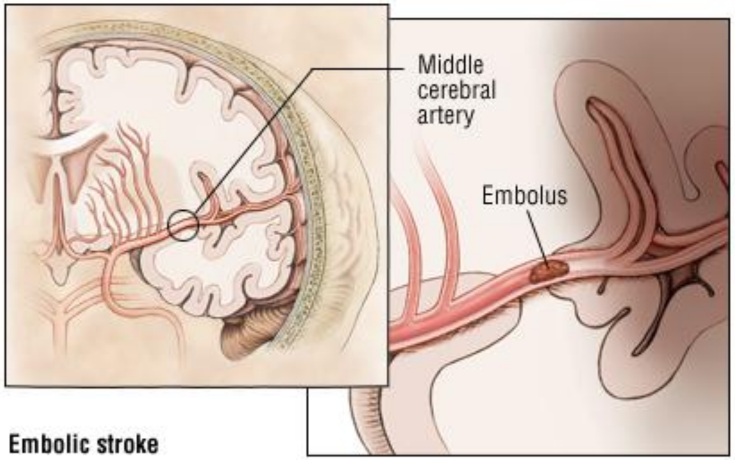
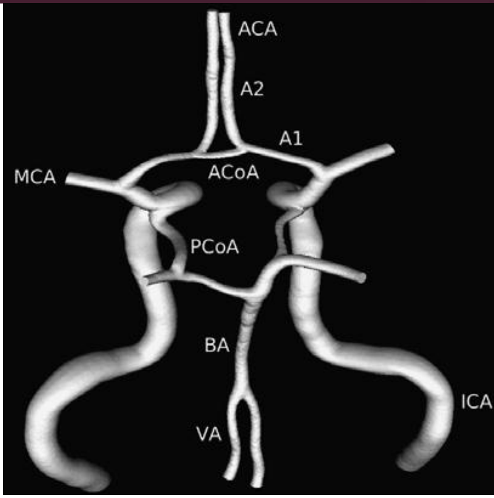
Clinical motivation

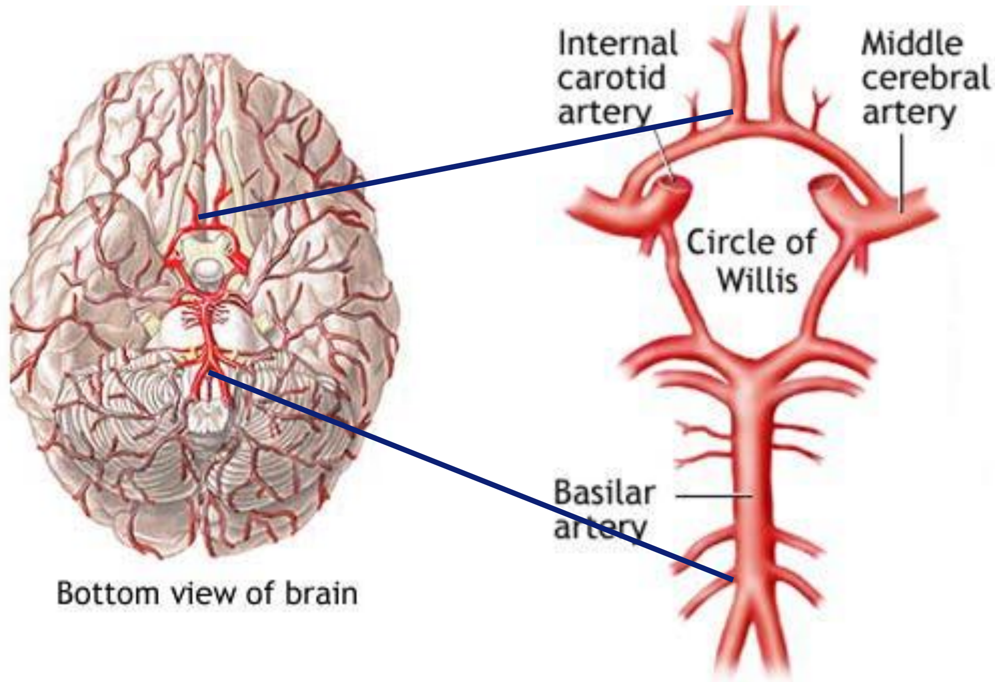
- Brain depends critically on its blood supply
  - 15% of cardiac output
- Cerebrovascular disease can lead to a stroke
  - Atherosclerosis
  - Aneurysms
- Stroke
  - Major cause of disability
  - Second leading cause of death
    - Western society
  - Ischemic (80%)
    - Thrombotic, embolic
  - Hemorrhagic (20%)

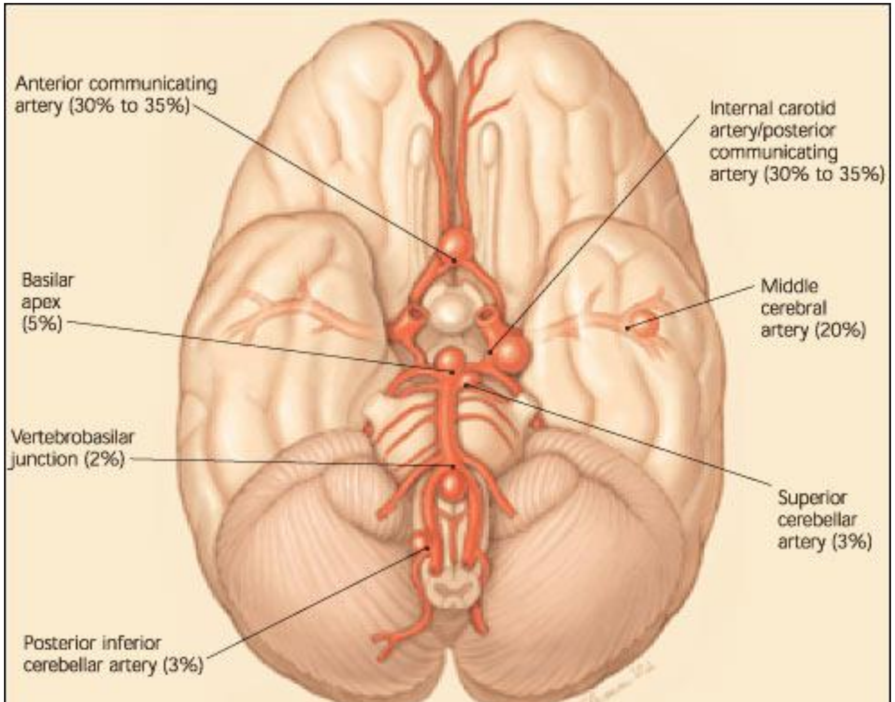




- Focus on the Circle of Willis
  - Conducts the blood flow from the anterior-left, anterior-right and posterior circulation to the brain
  - Arterial system forms a cycle by design
  - Common site of pathologies
  - Large anatomical variability

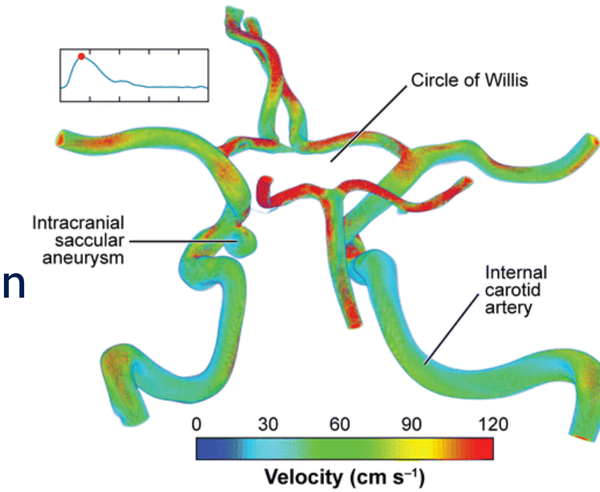






Cerebral aneurysms

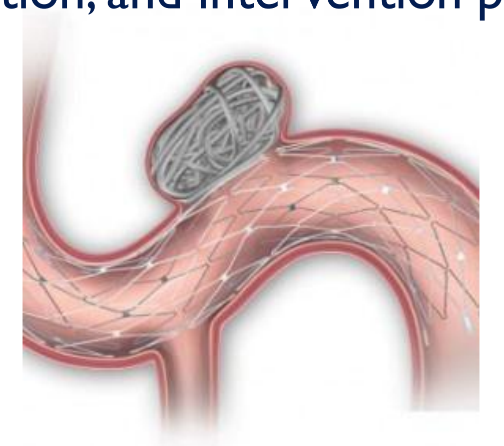
- Geometric risk factors*
  - Cerebral aneurysms occur at specific locations, at or near high curvature
  - Atherosclerosis often occurs at carotid bifurcation or close to arterial bendings
  - Hypothesis: hemodynamics responsible
    - Dependent on geometry

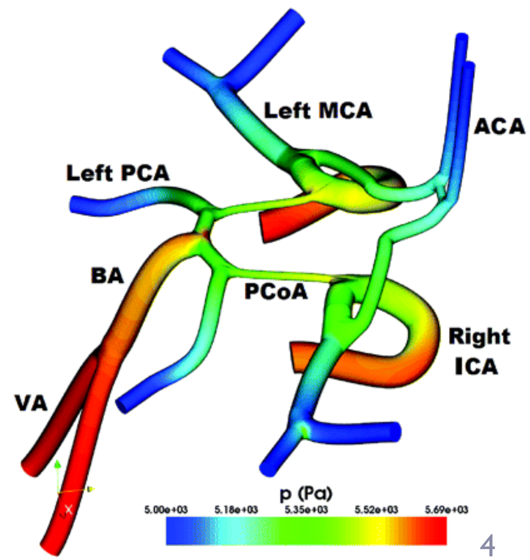


Humphrey JD, Taylor CA. 2008. Annu. Rev. Biomed. Eng. 10:221–46.

* Friedman et al., Atherosclerosis, vol. 46, pp. 225–231, Feb. 1983.

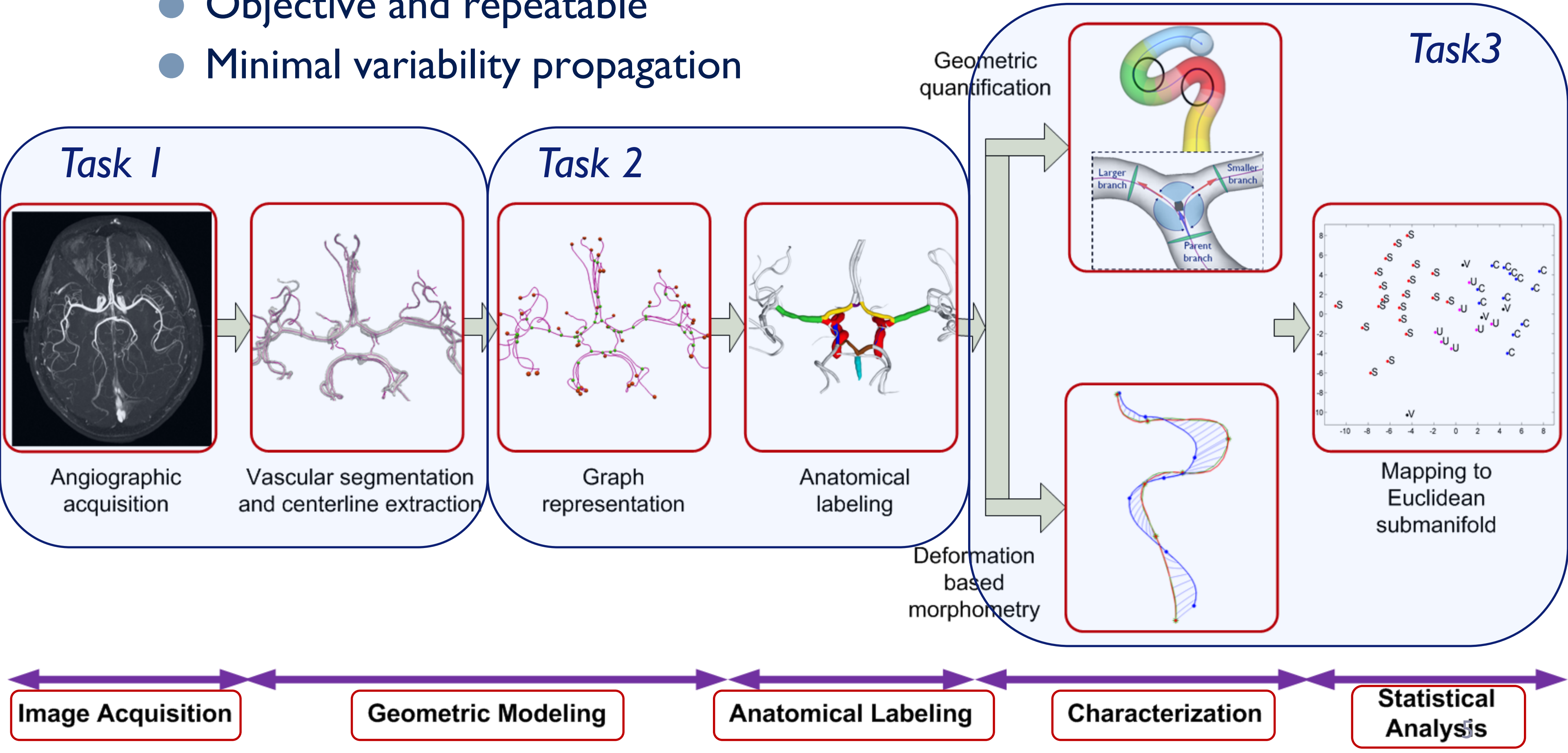
- Endovascular treatment difficulty
  - Device selection, and intervention planning
  - Stent fitness



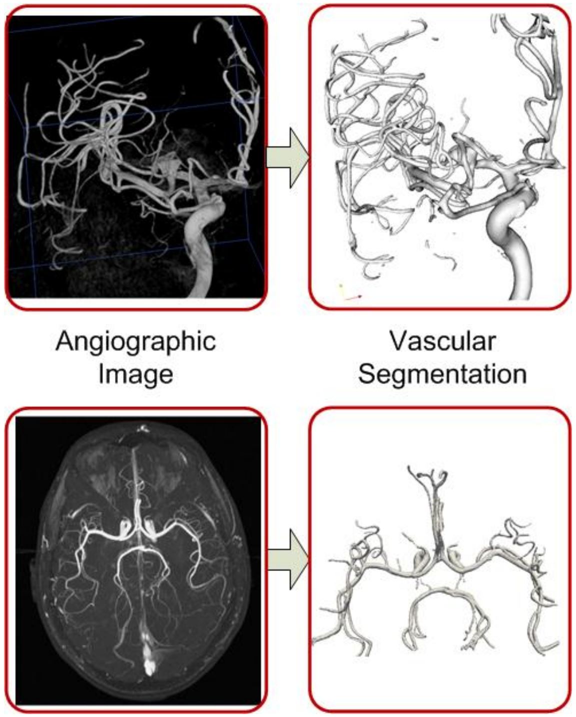


Alnaes et al., Stroke, 2007.

- Processing pipeline for image-based, subject-specific geometry characterization of the Circle of Willis
- High level of automation
  - Objective and repeatable
  - Minimal variability propagation

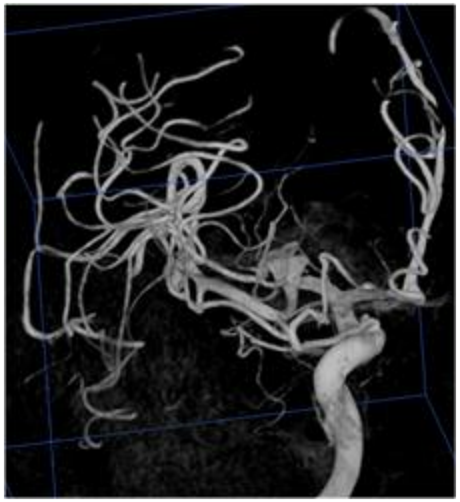


T1: SEGMENTATION OF CEREBRAL VASCULATURE

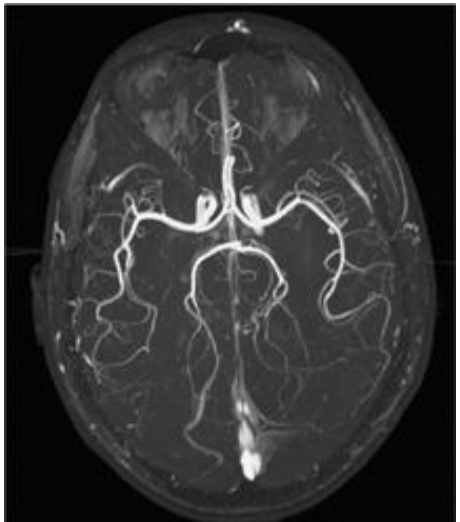


H. Bogunović, J.M. Pozo, M.C. Villa-Uriol, C.B.L.M. Majoie, R. Van Den Berg, H.A.F. Gratama Van Andel, J.M. Macho, J. Blasco, L. San Román, A.F. Frangi: Automated segmentation of cerebral vasculature with aneurysms in 3DRA and TOF-MRA using geodesic active regions: an evaluation study. *Medical Physics*, vol. 38(1), Jan. 2011, pp. 210-222.

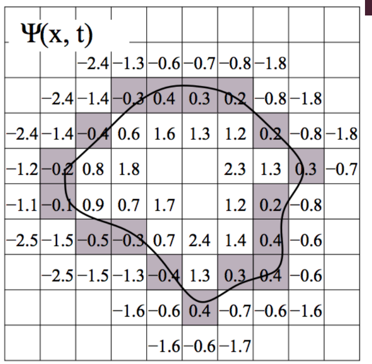
- Objective: From angiographic image obtain accurate geometric model of vasculature containing pathologies (aneurysms)
  - Focus on 3DRA and MRA imaging modalities



- 3DRA
  - Invasive: contrast injected into artery + radiation
  - Treatment planning and evaluation
  - High image spatial resolution (0.2x0.2x0.2 mm^3)



- ToF-MRA
  - Non-invasive, no contrast, no radiation
  - Screening and follow-up. Volunteers.
  - Anisotropic spatial resolution (0.5x0.5x0.8 mm^3)
  - Full CoW observed



Geodesic Active Regions (GAR)

- Geometric deformable model using the level set framework
  - Completely automated (including initalization)

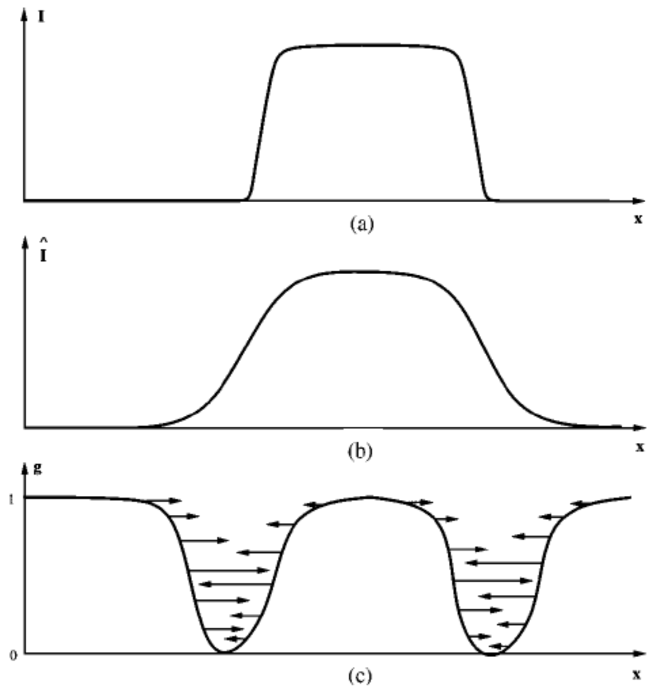
region curvature gradient

$$\frac{\partial}{\partial t}\Phi + \zeta\left(k_{out} - k_{in}\right) \mid \nabla\Phi \mid - \eta(\varepsilon g K_m \mid \nabla\Phi \mid + \nabla g \cdot \nabla\Phi) = 0$$

- Gradient term:
  - From geodesic active contour (GAC)
  - Surface at local gradient maximum (objective)

$$g = \frac{1}{1 + |\nabla \hat{I}|^p}$$

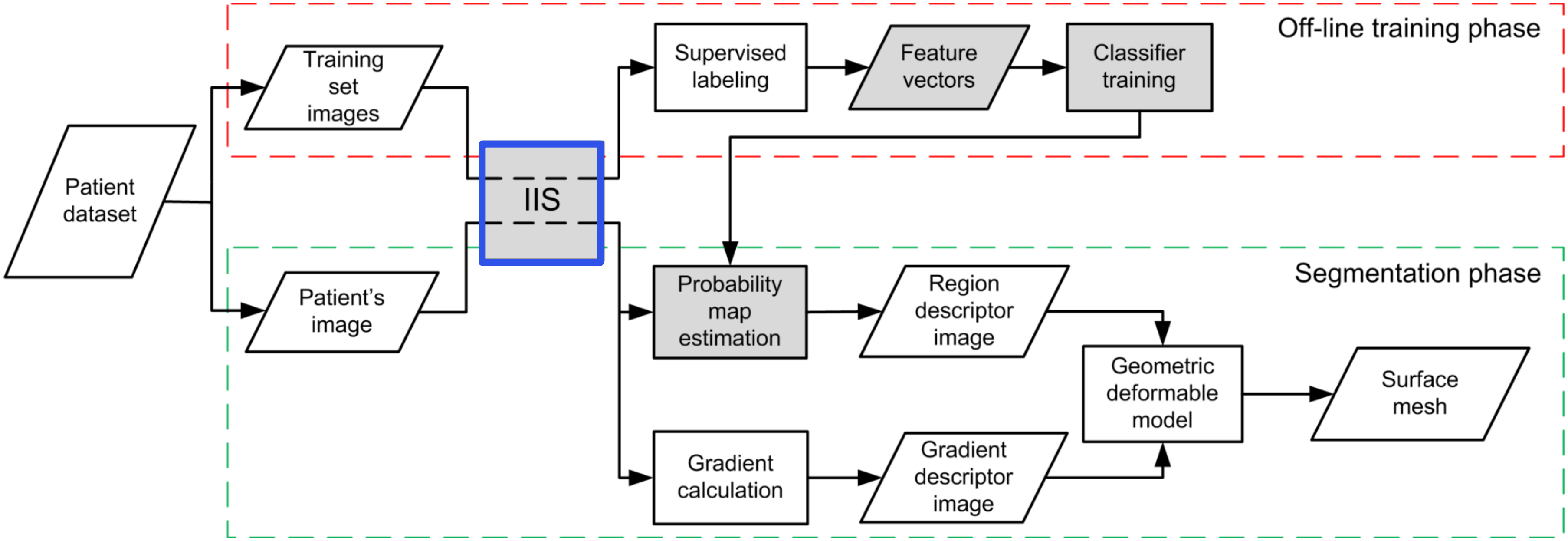
- Region term: use of training-set
  - Learns vessel and background features
  - Differential invariants (multiscale)
    - Intensity
    - Gradient magnitude, Laplacian ...



V. Caselles et al., GAC, Int. J. Comp. Vision, 1997.

GAR workflow

- 3DRA and MRA: No correspondence tissue-intensity
- Introduction of the image intensity standardization (IIS)



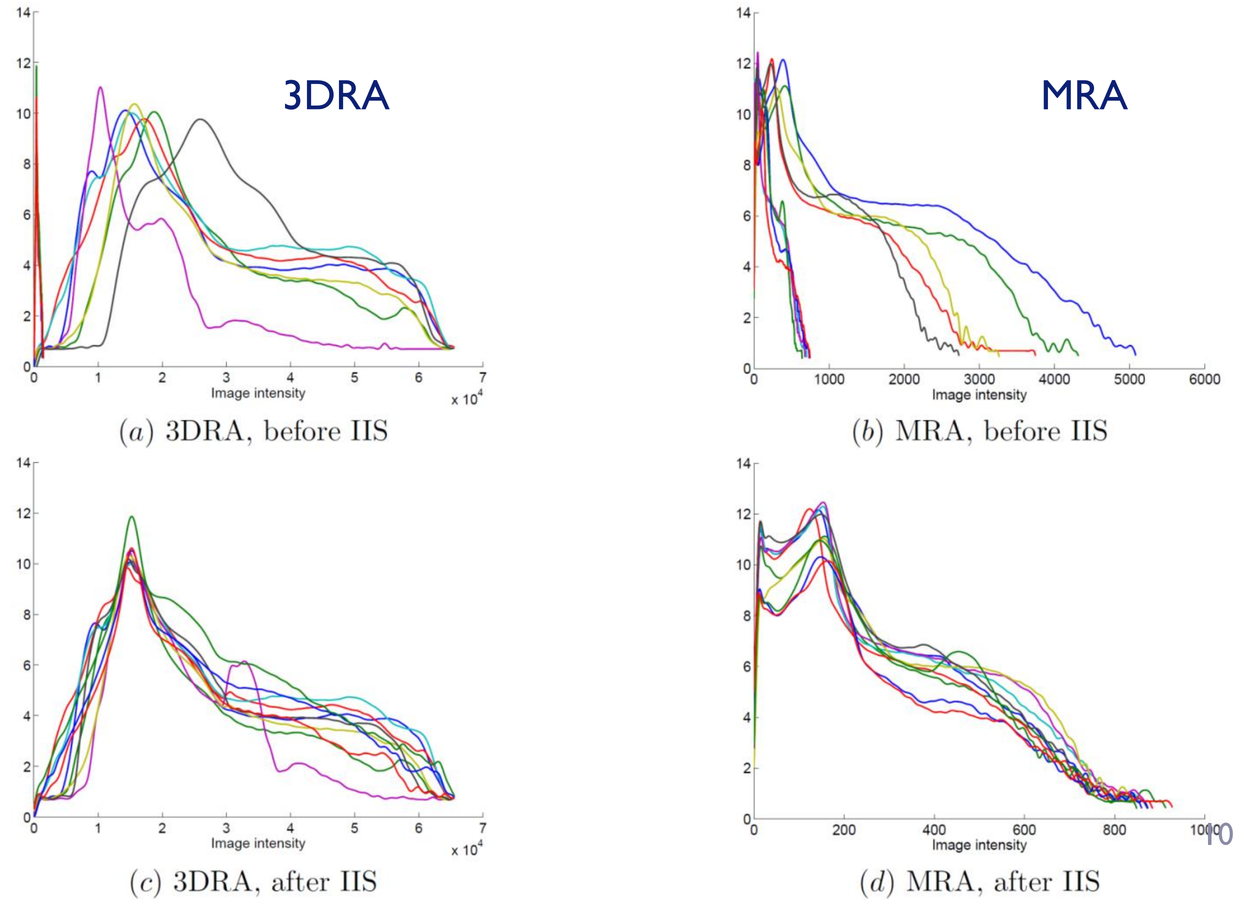
M. Hernandez and A. F. Frangi, Medical Image Analysis, 2007.

H. Bogunović, et al., SPIE Medical Imaging, 2008.

H. Bogunović et al, Medical Physics,2011.

GAR - Image Intensity Standardization (IIS)

- Non-linear signal registration to a histogram reference
  - Similarity metric: normalized cross-correlation
  - Reference per modality



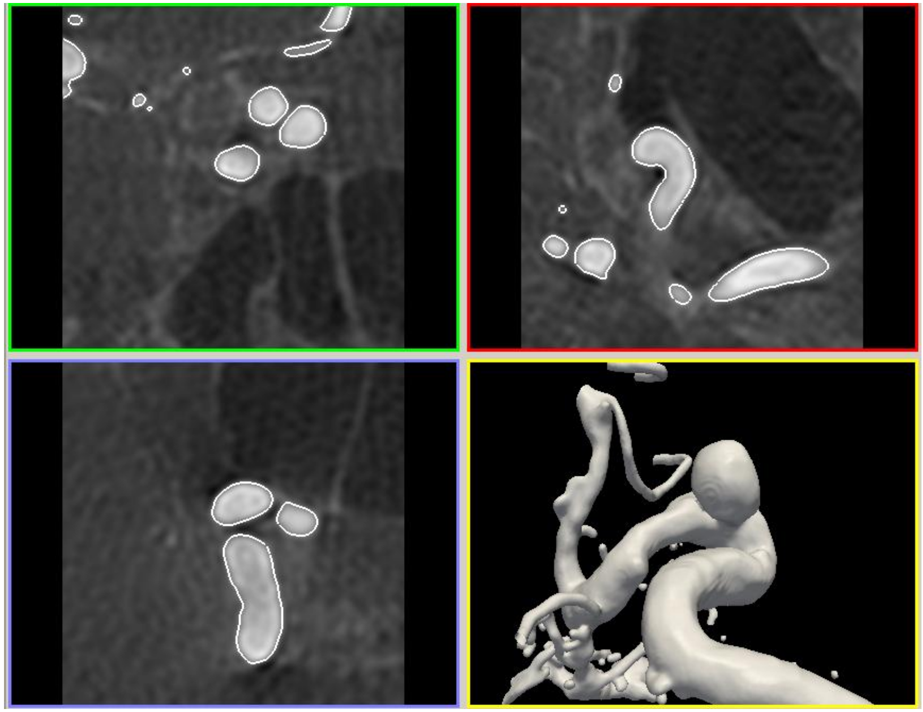
(a) 3DRA, before IIS

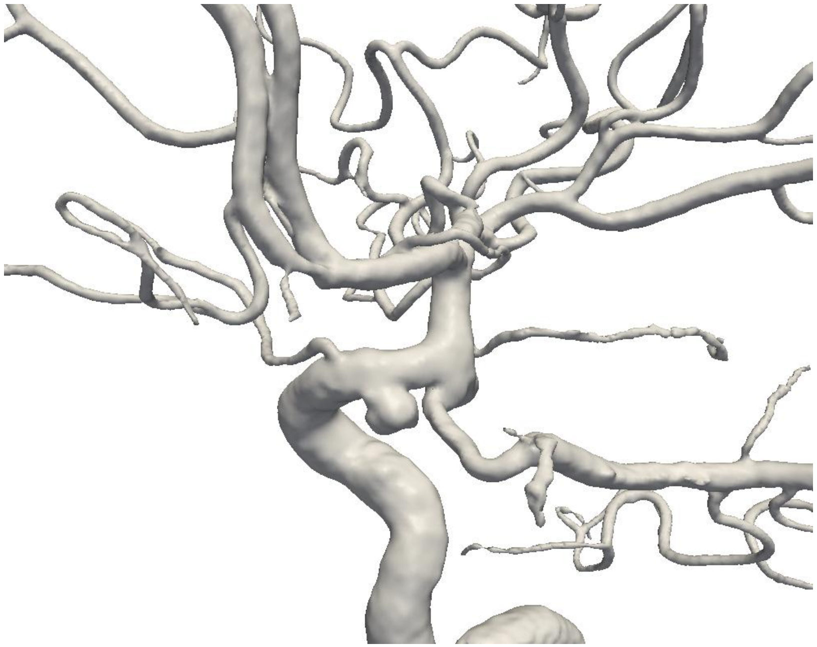
(b) MRA, before IIS

(c) 3DRA, after IIS

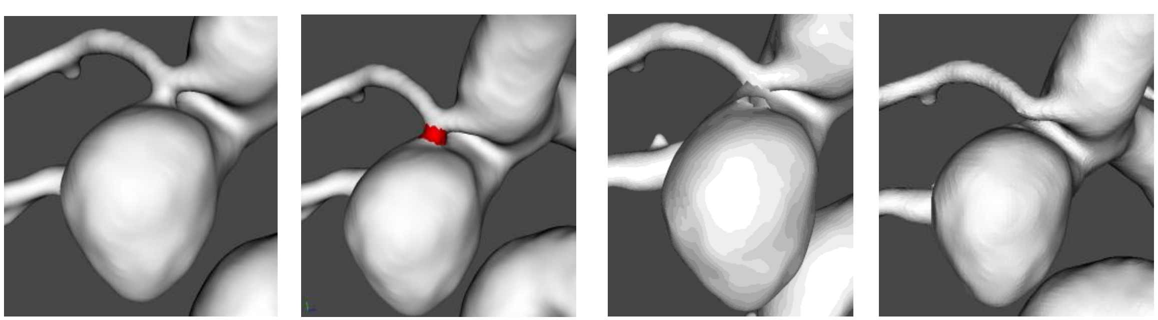
(d) MRA, after IIS

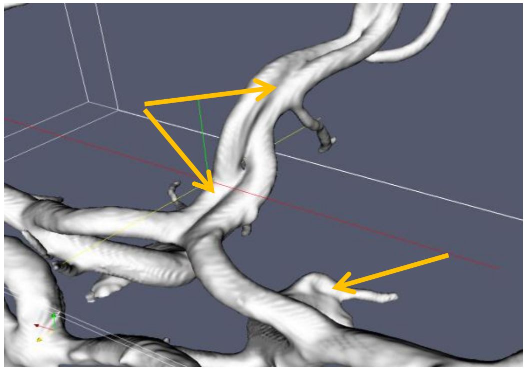
T1: Segmentation



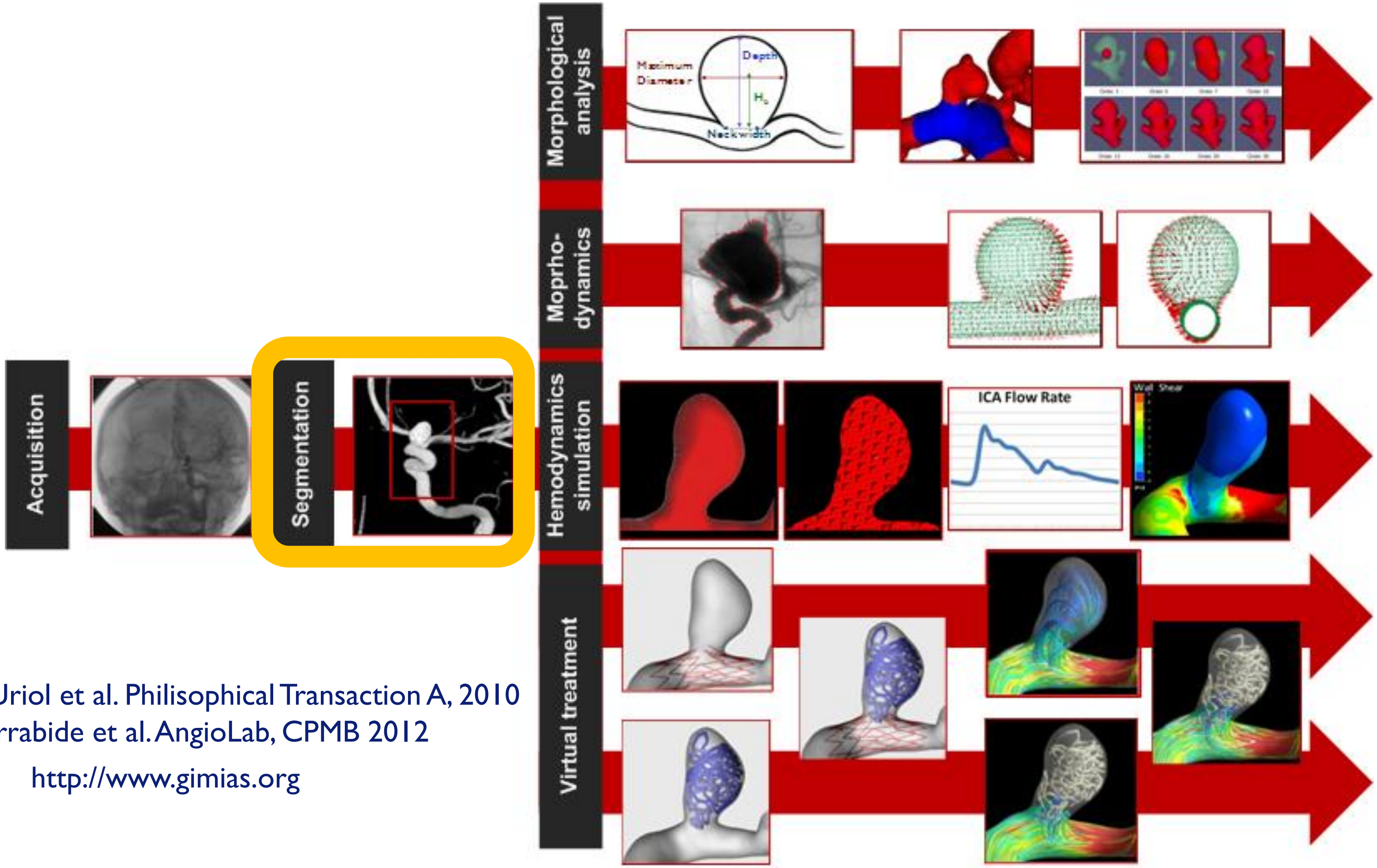


- Difficult problem: Touching vessels
  - Requires manual post-processing



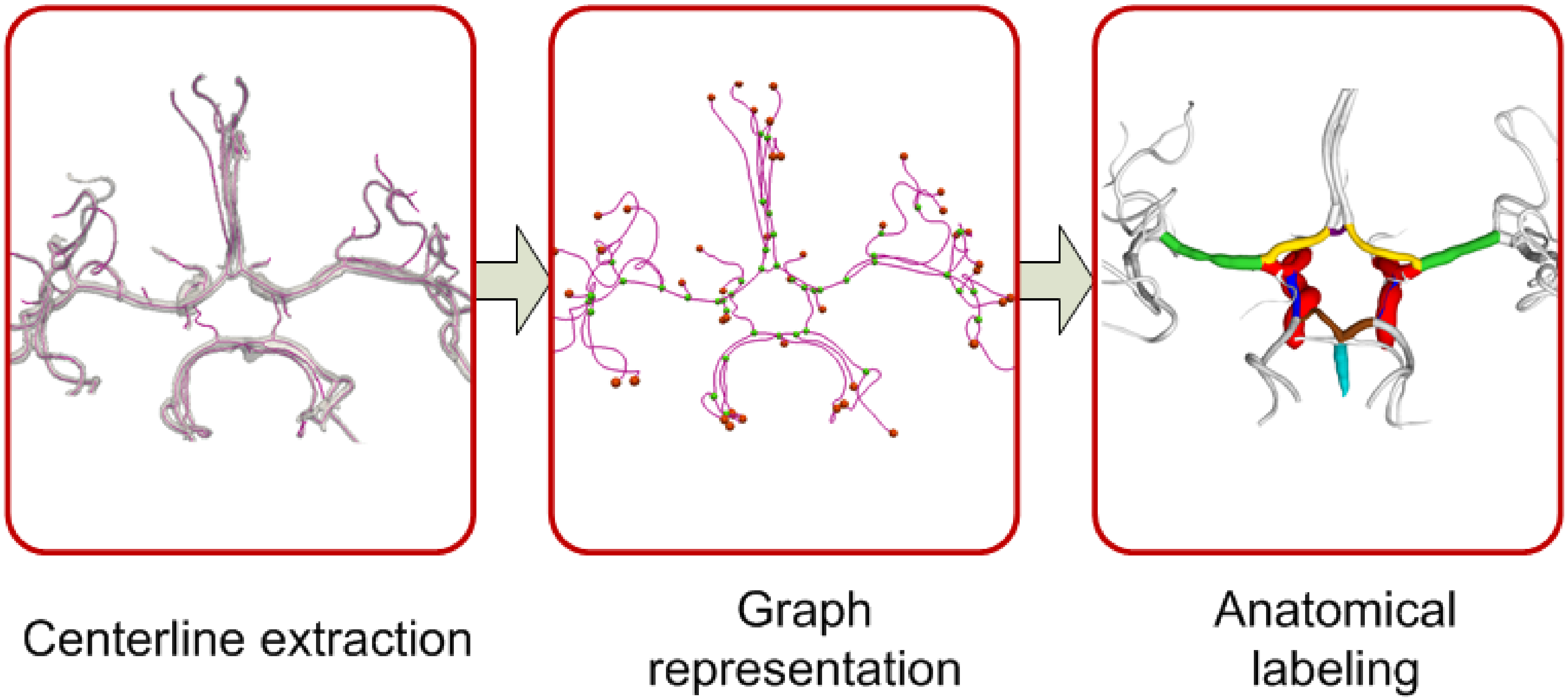


Use in aneurysm management pipeline



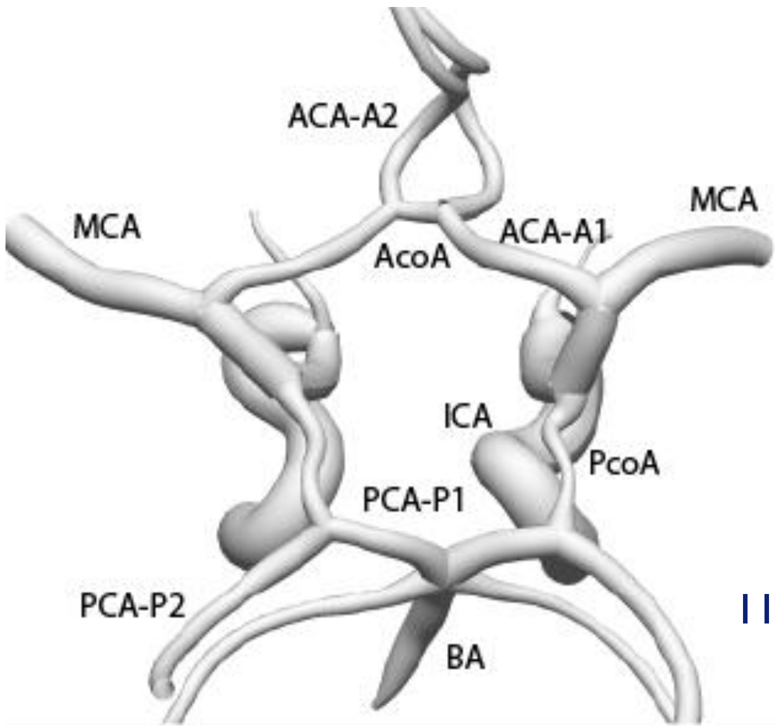
M-C. Villa-Uriol et al. Philisophical Transaction A, 2010
I. Larrabide et al. AngioLab, CPMB 2012
http://www.gimias.org

T2: ANATOMICAL LABELING OF THE CIRCLE OF WILLIS

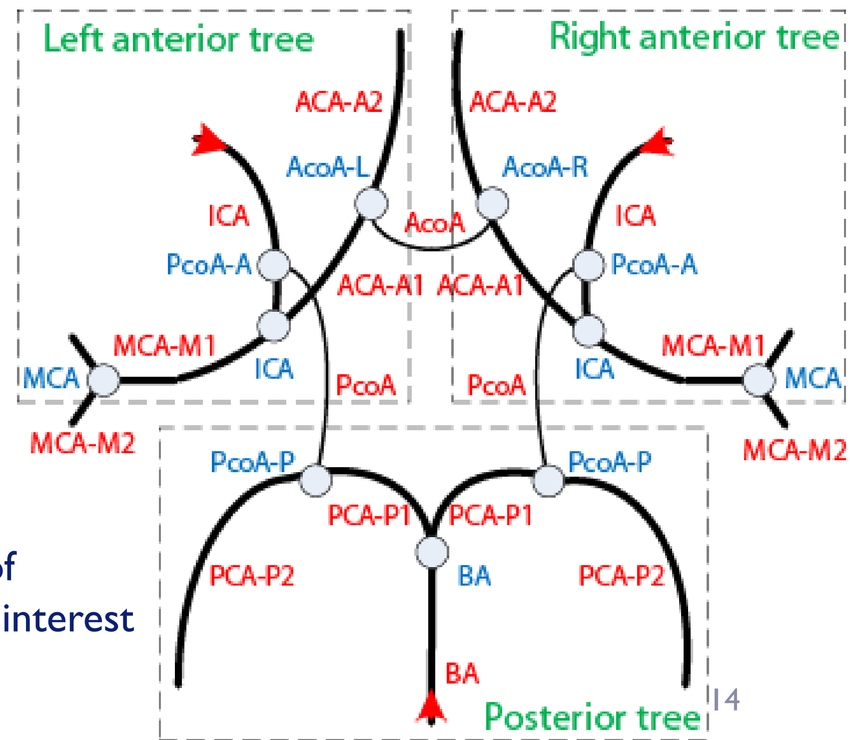


H. Bogunović, J.M. Pozo, R. Cardenes, L. San Roman, and A.F. Frangi: Anatomical labeling of the Circle of Willis using maximum a posteriori estimation. *Under Review.*

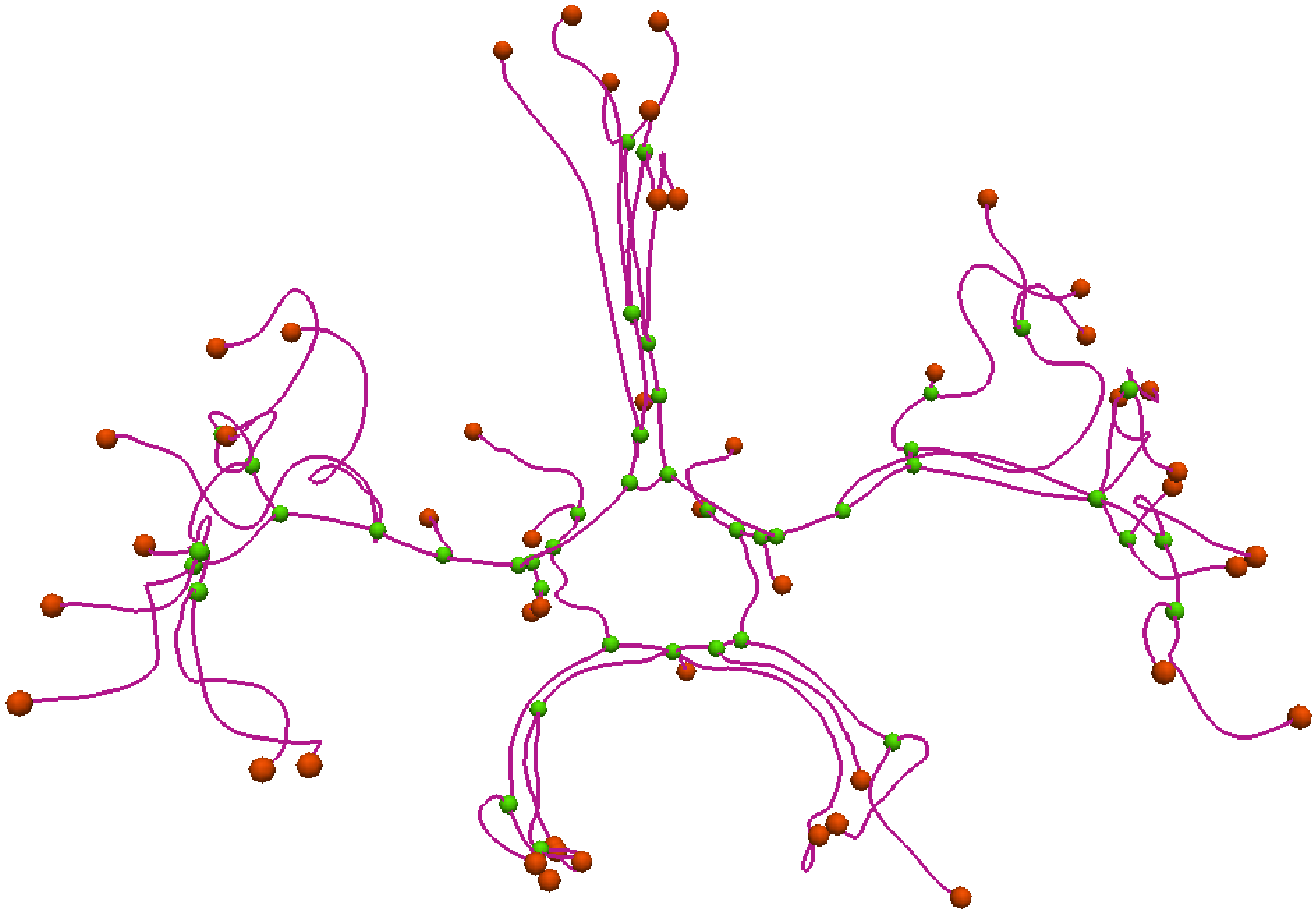
- Objective: Establish anatomical correspondence between subjects in the region of the Circle of Willis (CoW)
  - Enables subsequent geometric characterization and population analysis of the entire CoW
- Arteries form a graph containing a cycle with multiple roots
  - Unique to the CoW



Detection of
11 bifurcations of interest

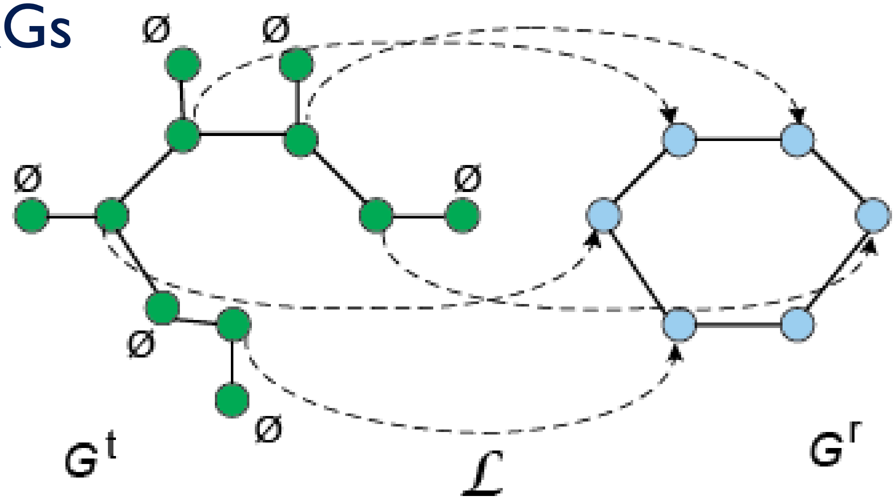


Segmentation and graph extraction



- Labeling as mapping between ARGs

$$\mathcal{L} : V^t \rightarrow V^r \cup \{\oslash\}$$



- Availability of a knowledge base (KB)
  - Set of reference graphs $\{V^r\}$
  - Sample vertex attributes $\{A^r\}$
  - Joint BoI configuration appearance $\{V^r\}$
- Maximum a posteriori probability $\mathcal{L}^* = \arg\max_{\mathcal{L}} P(\mathcal{L}|\hat{G}^{\mathrm{t}}, \mathrm{KB})$

$$P(\mathcal{L}|G^{\mathrm{t}}, A^{\mathrm{t}}, R^{\mathrm{t}}, \mathrm{KB}) \propto \underbrace{p(A^{\mathrm{t}}|\mathcal{L}, G^{\mathrm{t}}, R^{\mathrm{t}}, \mathrm{KB})}_{\text{likelihood}} \underbrace{P(\mathcal{L}|G^{\mathrm{t}}, R^{\mathrm{t}}, \mathrm{KB})}_{\text{prior}}$$

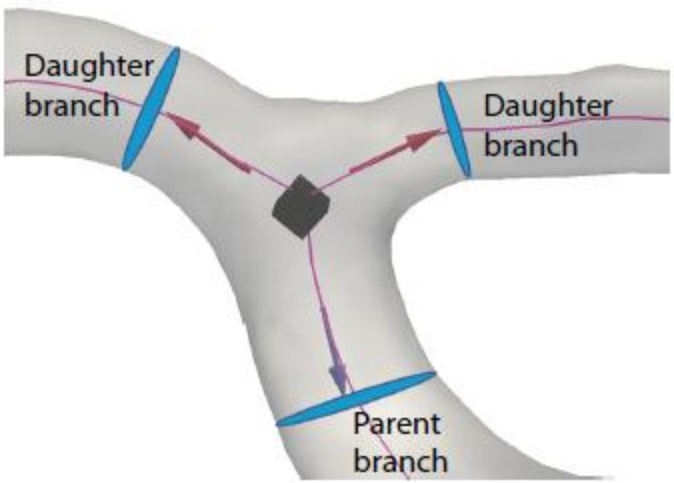
Likelihood term $p(A^{\mathrm{t}}|\mathcal{L}, G^{\mathrm{t}}, R^{\mathrm{t}}, \mathrm{KB})$

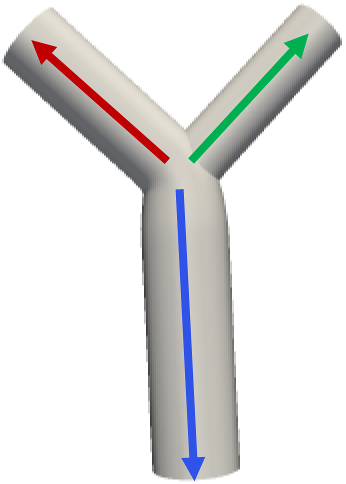
- Independency of attributes assumed

$$p(A^{\mathrm{t}}|\mathcal{L}, G^{\mathrm{t}}, R^{\mathrm{t}}) = p(A^{\mathrm{t}}|\mathcal{L}, V^{\mathrm{t}}) = \prod_{i=1}^{N} p(a_i^{\mathrm{t}}|\mathcal{L}(v_i^{\mathrm{t}}))$$

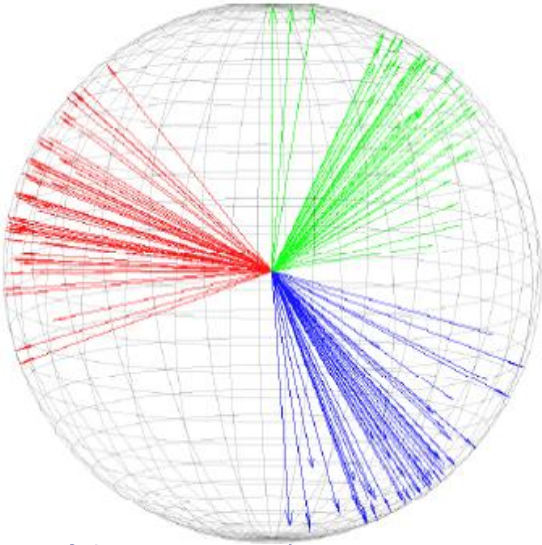
- Each bifurcation a 7-tuple.
  - Element of Riemannian manifold

$$a = (\mathbf{x}, \mathbf{n}_0, r_0, \mathbf{n}_1, r_1, \mathbf{n}_2, r_2) \in \mathcal{M} = \mathbb{R}^3 \times S^2 \times \mathbb{R}^+ \times S^2 \times \mathbb{R}^+ \times S^2 \times \mathbb{R}^+$$





Cylindrical model



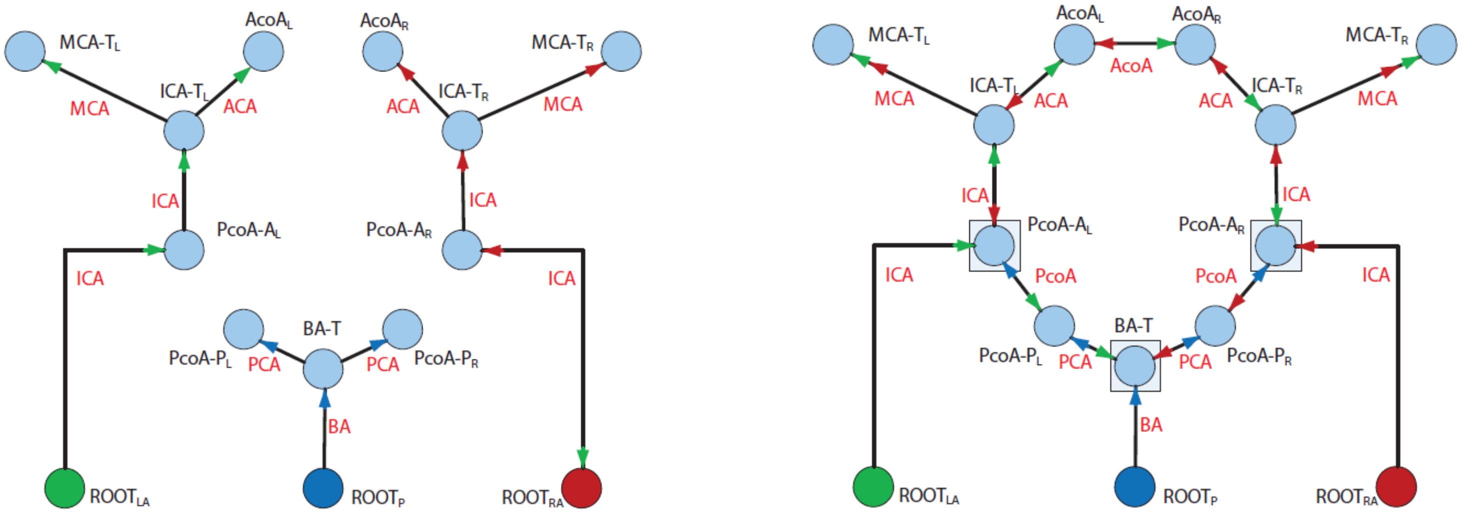
ICA terminal bifurcation
Population distribution

Prior term $P(\mathcal{L}|G^{\mathrm{t}}, R^{\mathrm{t}}, \mathrm{KB})$

- Assures the labels follow the ordering of the reference graph
  - Only compatible labelings ($L^{\mathrm{t}}_{\mathrm{c}}$) allowed

$$P(\mathcal{L}|G^{\mathrm{t}}, R^{\mathrm{t}}) = \begin{cases} 0 & \text{if } \mathcal{L} \notin L^{\mathrm{t}}_{\mathrm{c}} \\ P(V^{\mathrm{r}}_{\mathcal{L}}) & \text{if } \mathcal{L} \in L^{\mathrm{t}}_{\mathrm{c}}; \end{cases}$$

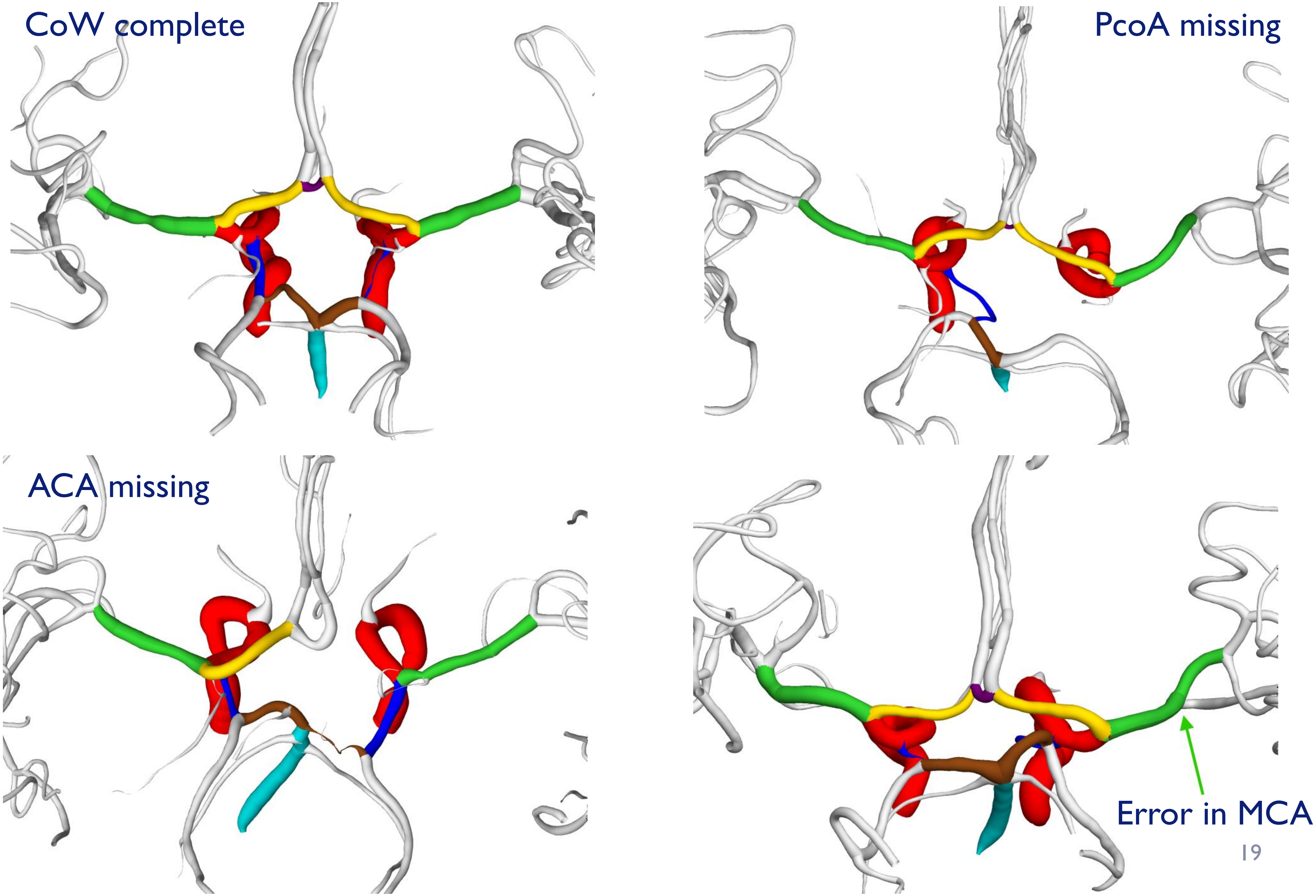
- L_c : Labelings compatible with a reference graph



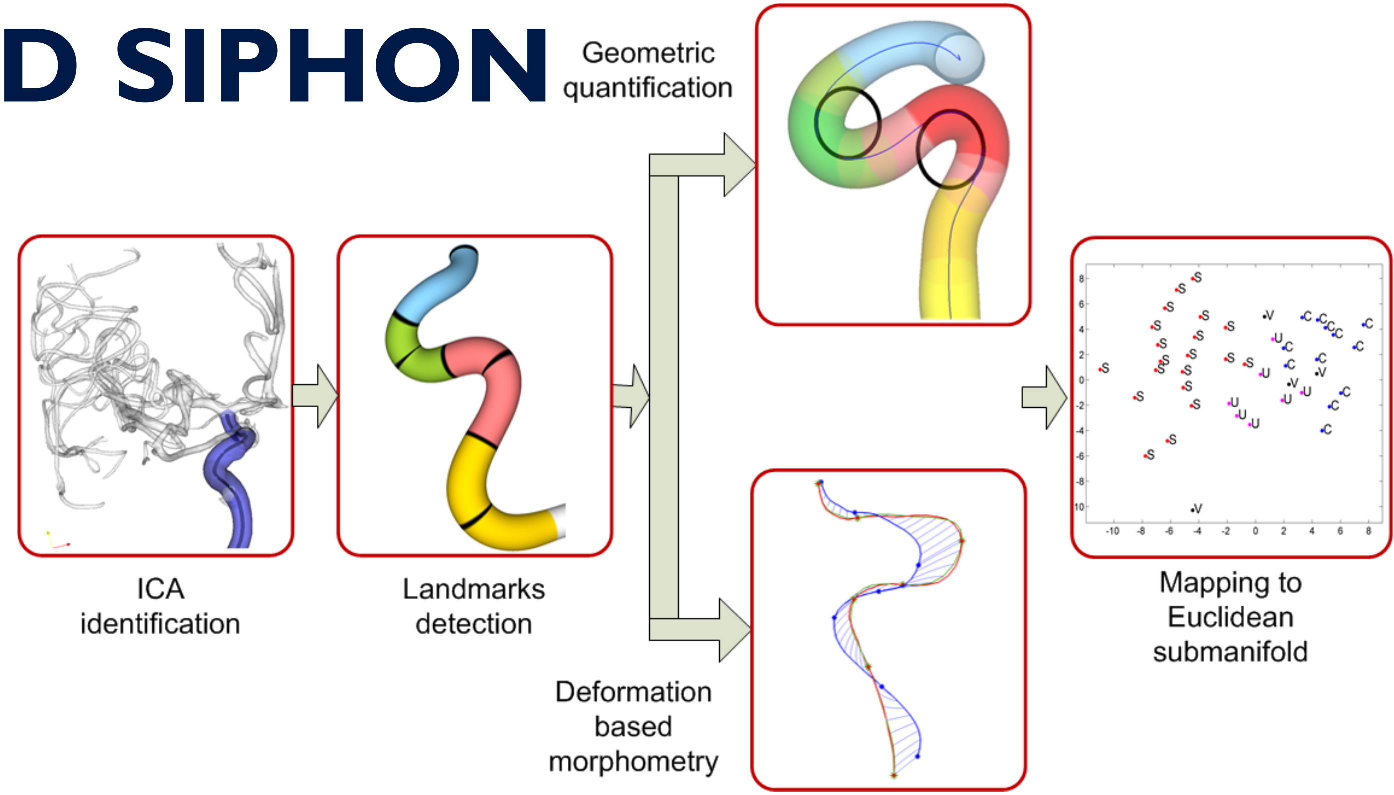
(a) ST1: Three isolated trees (h) ST8: Complete CoW

T2: Anatom. Labeling

Results



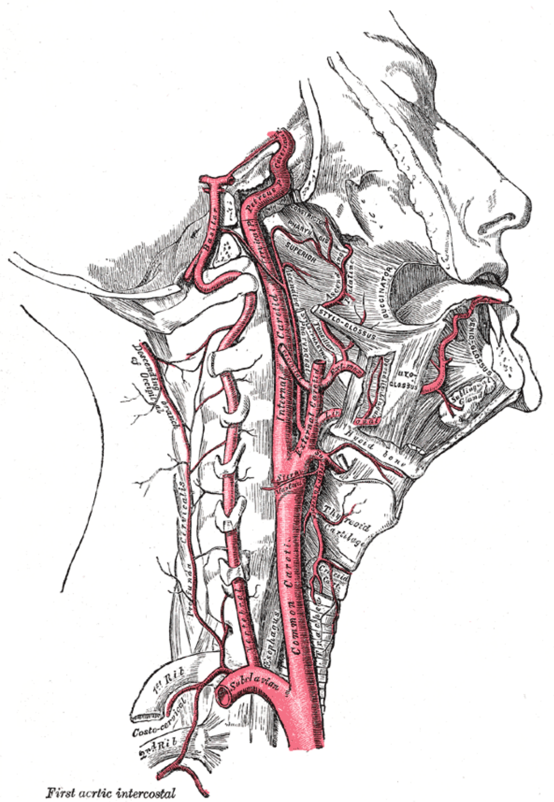
T3: GEOMETRIC CHARACTERIZATION OF THE CAROTID SIPHON



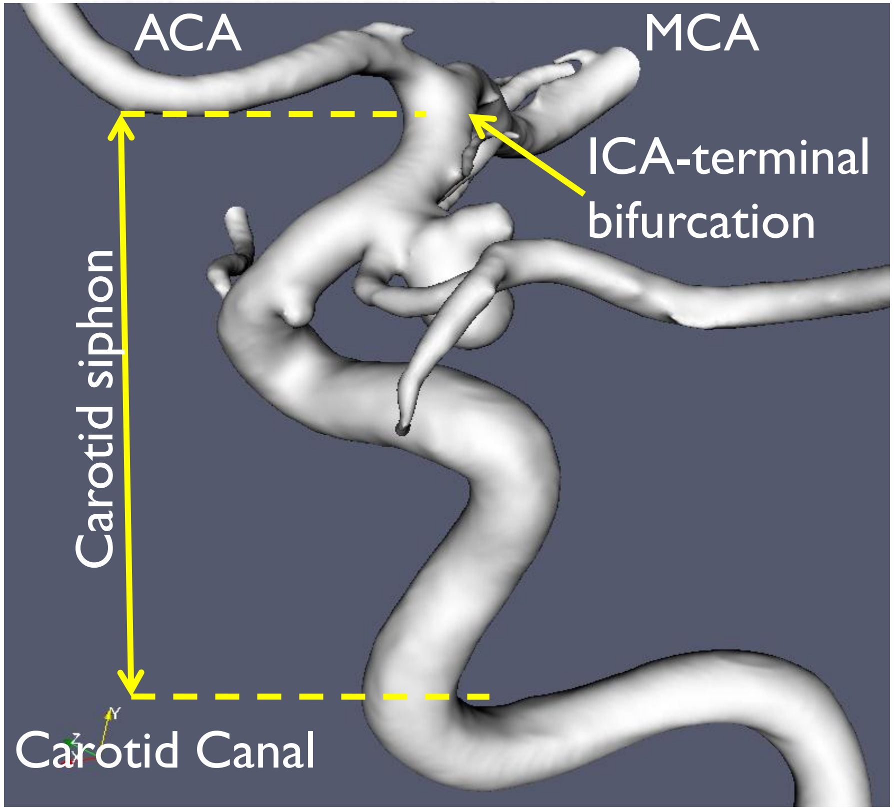
H. Bogunović, J. M. Pozo, R. Cardenes, M. C. Villa-Uriol, R. Blanc, M. Piotin, and A. F. Frangi: Automated landmarking and geometric characterization of the carotid siphon. *Medical Image Analysis*, vol. 16(4), May 2012, pp. 889-903.

T3: Carotid Siphon

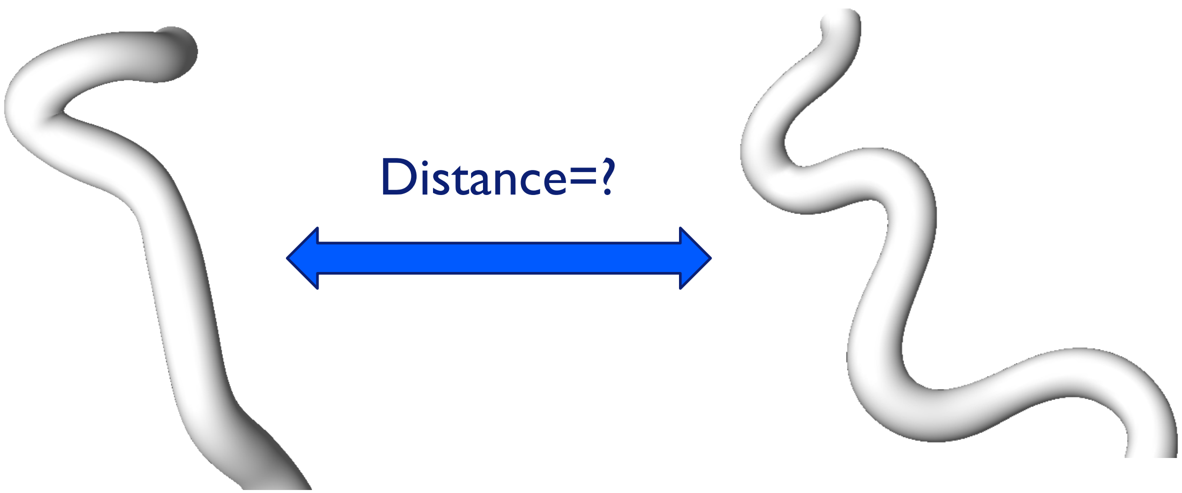
- Objective: Describe geometric variability of carotid siphon
  - Large geometric variability prerequisite for being a risk factors
    - 30% of aneurysms occur there
  - Important for stent fitness, endovascular accessibility



Henry Gray's *Anatomy of the Human Body*

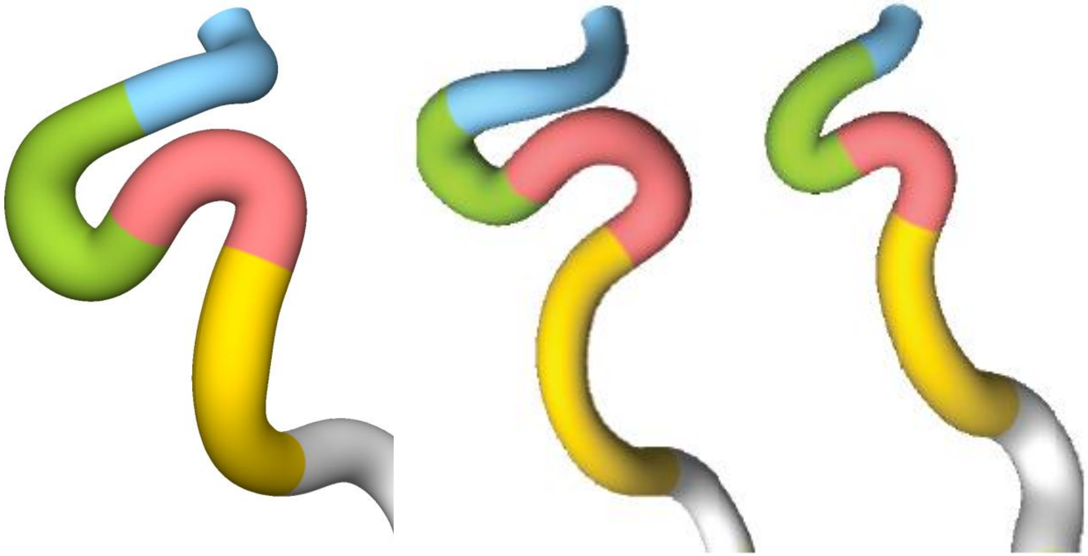


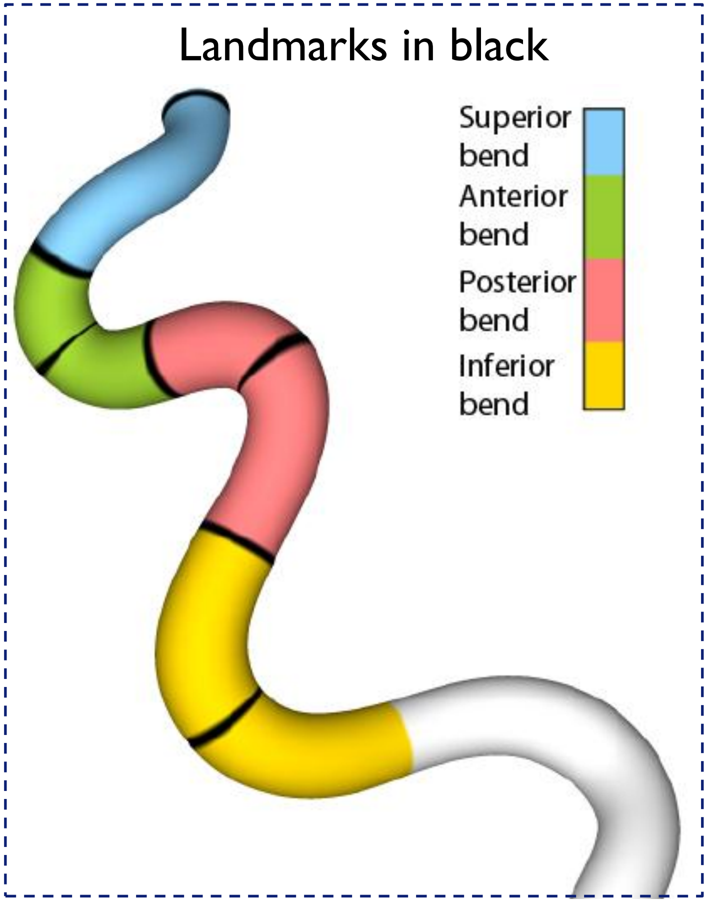
- Carotid siphon shape space
  - Finding a suitable representation and metric
  - Statistical analysis



- Option 1: Shape described as a vector of geometric features
  - Principal component analysis
- Option 2: Deformation based morphometry
  - Pairwise distance matrix + mapping to Euclidean submanifold

Four bend model



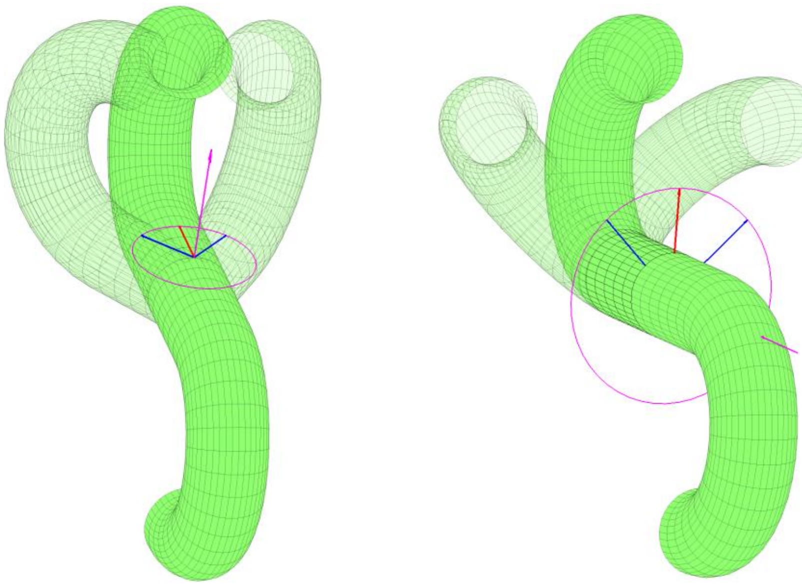


- Landmarks as points of correspondence
  - Define region of interest

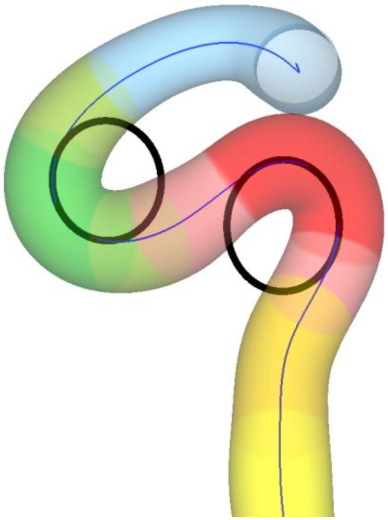
Geometric quantification

- Geometric feature vector (scale invariant)

Change of osculating planes

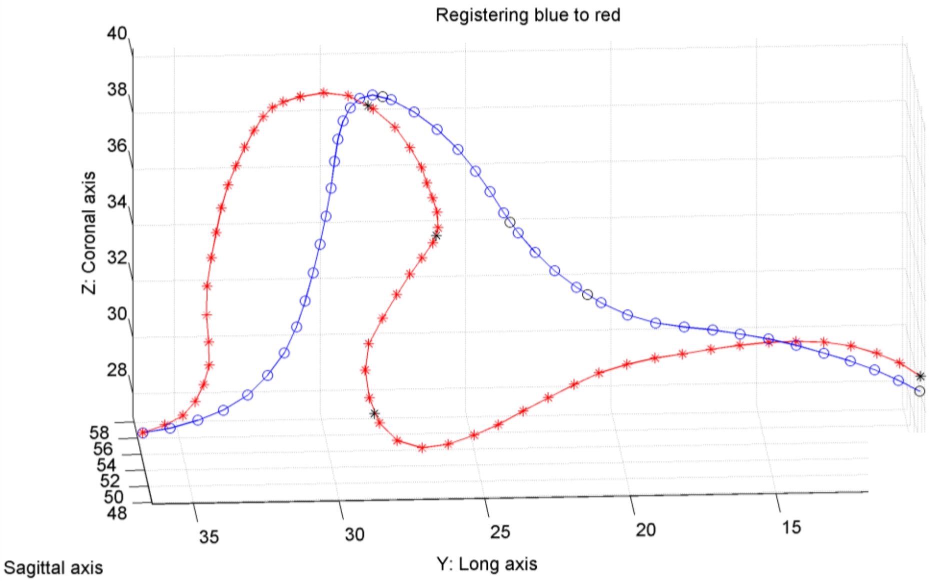


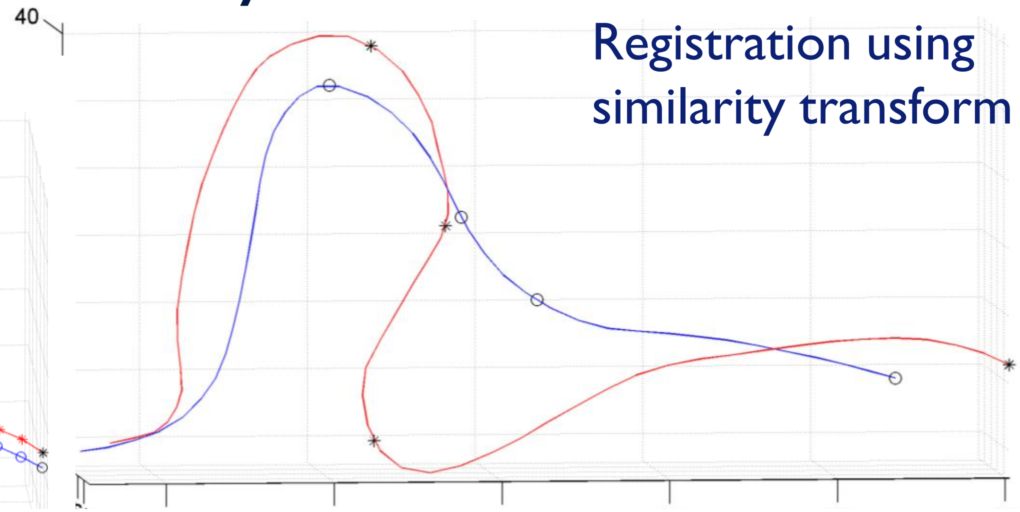
Bending radii



- + global features
  - Tortuosity
  - Bending and twisting energy
  - Curvature and torsion ratio

Deformation based morphometry - LDDMCM

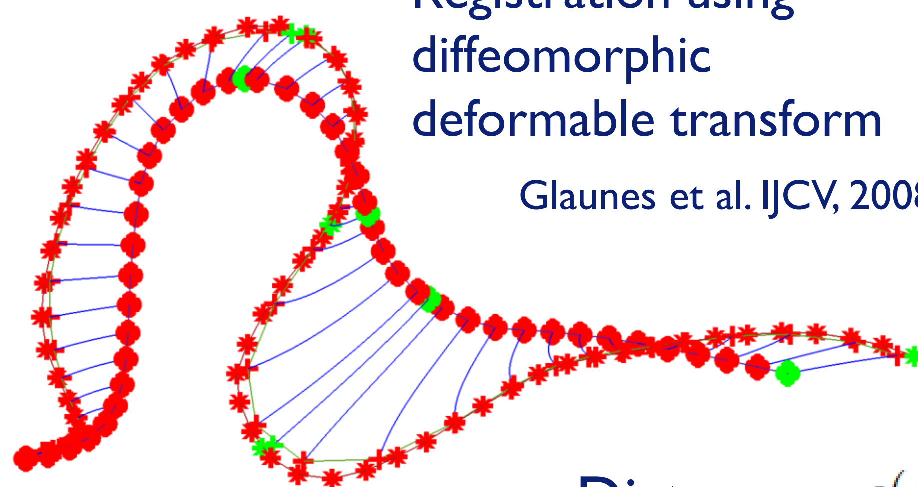




Registration using similarity transform

$$J_{C,S}(\phi_t) = \gamma \rho(\phi_t)^2 + E(\phi_1(C), S)$$

$$J_{C,S,\vec{x},\vec{y}}(\phi_t) = \gamma \rho(\phi_t)^2 + \gamma_{\mathrm{cr}} E_{\mathrm{cr}}(\phi_1(C), S) + \gamma_{\mathrm{lm}} E_{\mathrm{lm}}(\phi_1(\vec{x}), \vec{y})$$



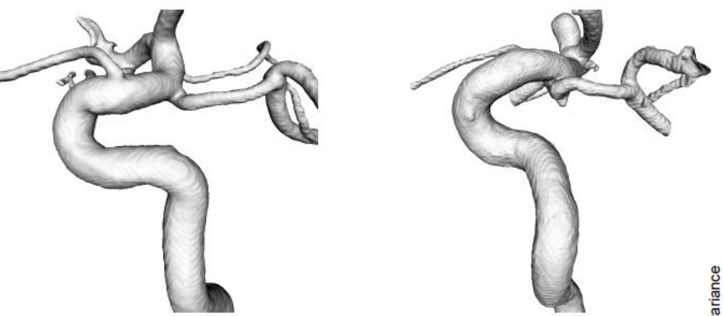
Registration using diffeomorphic deformable transform

Glaunes et al. IJCV, 2008

Distance = $\rho(\phi_t)$

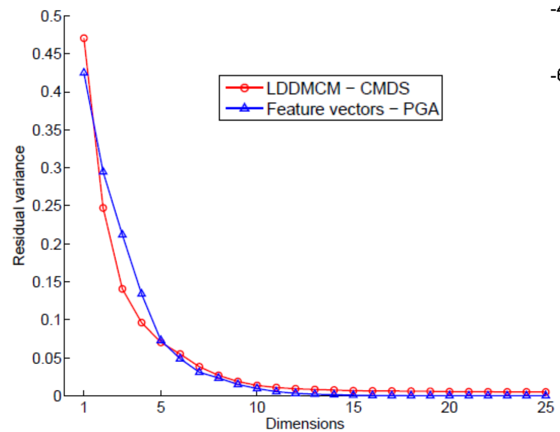
Shape prototypes

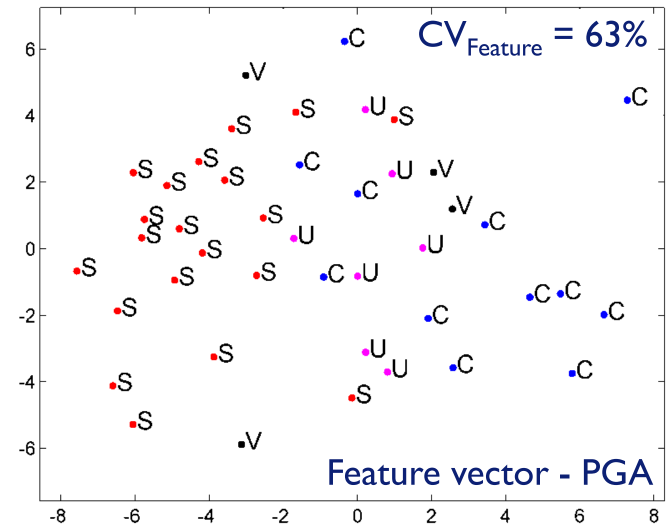
- Characterization evaluation
- Related to treatment difficulty

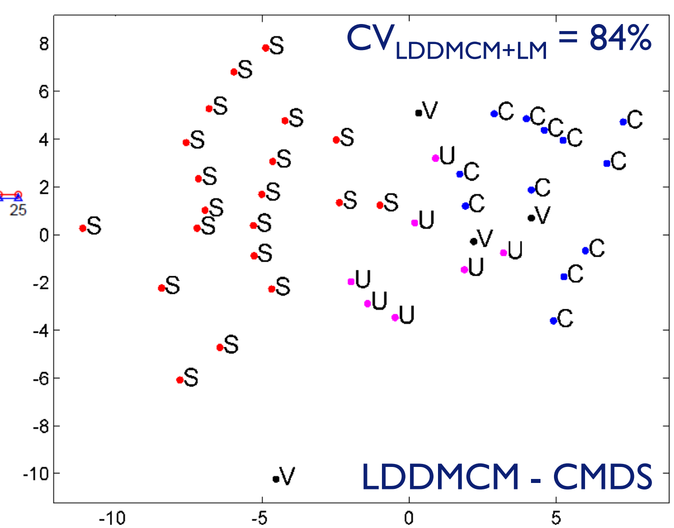


(a) U-type (b) C-type (c) V-type (d) S-type

Embedding in 2D Euclidean space



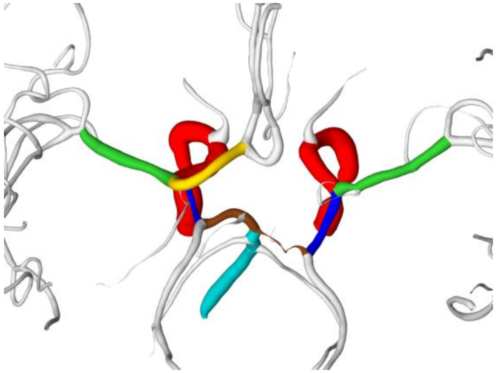




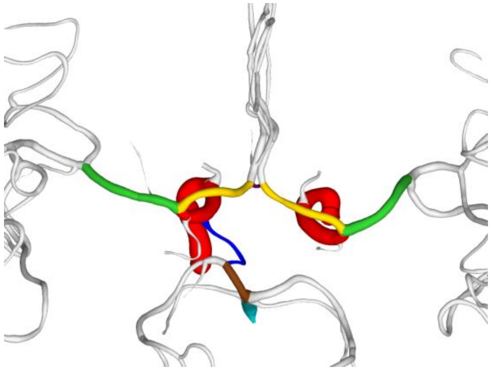
CONCLUSIONS

Still open problems:

- Are two vasculatures effectively the same or are they different? (pairwise statistics)
  - Finding a metric in the space of vasculatures (CoWs).
  - Measures that are closely clustered for similar vasculatures and are markedly different otherwise.
- How to model graph/tree-like structures and their variations? (groupwise statistics)
  - Atlas: mean and principal modes of variation (PCA)
  - Change of topology: Data space is strongly non-Euclidean

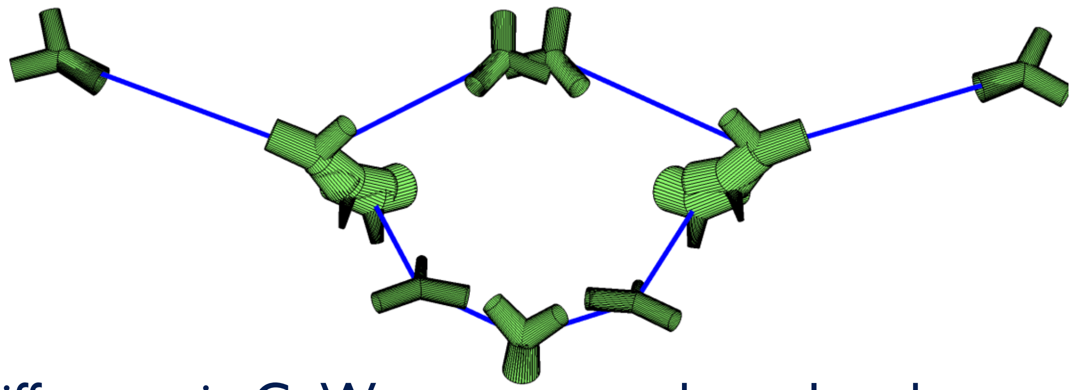


Distance =?



Start answering questions:

- How does the average CoW looks like and what are its principal variations?



- Is there any difference in CoW geometry and topology between men and women?
  - Prevalence of aneurysms is larger in women, could it be due to different CoW geometry between them?
- Is the difference in handedness reflected in the CoW?
- Does the CoW change with aging and how?
- What would be considered normal variability of the CoW and what would be deviations associated with the risk of developing a pathology?
- Can we predict or estimate a risk of aneurysm rupture, from the CoW?

Acknowledgments

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Agència de Gestió d'Ajuts Universitaris i de Recerca

Generalitat de Catalunya

aneurIST
Integrated biomedical informatics for the management of cerebral aneurysms

Unión Europea
Fondo Europeo de Desarrollo Regional

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