Visualisierung Medizinischer Daten 2
5. Vorlesung
Blood Vessel Visualization

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Application Areas

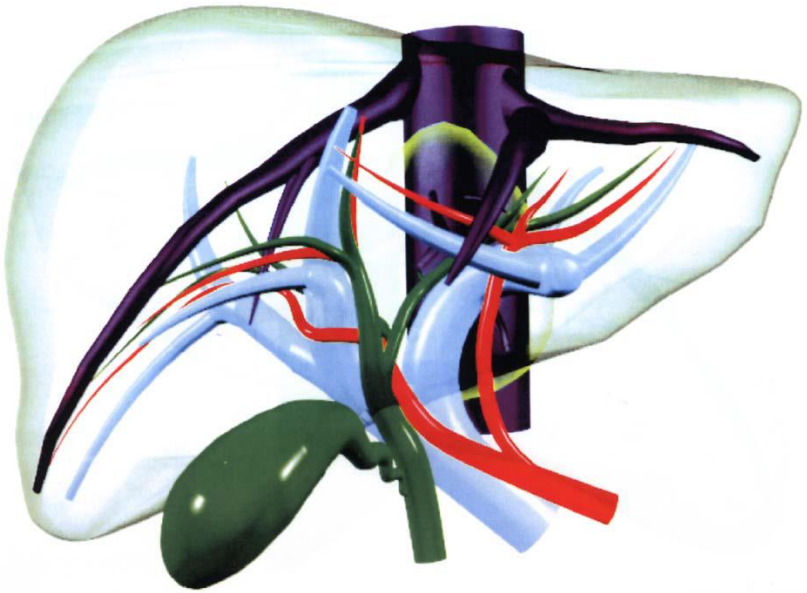
- Diagnosis of vascular diseases
- Therapy planning (e.g., tumor therapy)
- Endovascular surgery → minimally invasive

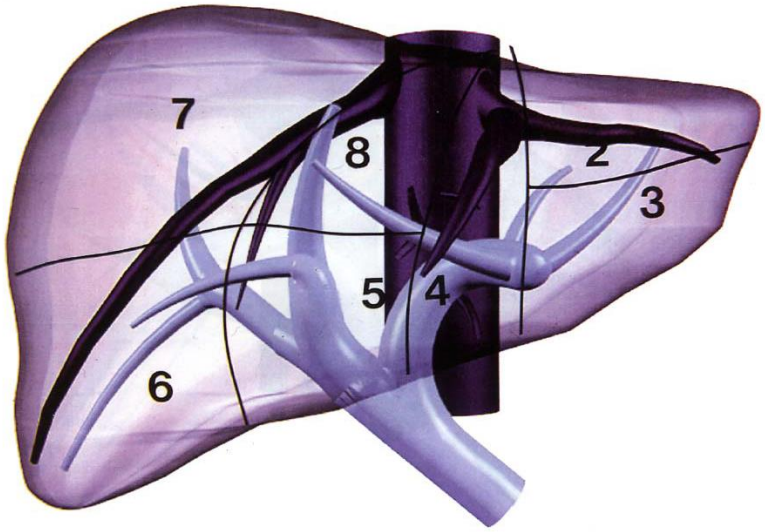
Goals of Vessel Visualization

- Vessel diameter
- Identification and treatment of vascular occlusions
- Identification of spatial positions, branching structure and resulting supply regions
- Data sources: CTA or MRA with small inter-slice distance

Requirements

- Exact representation of the underlying data
- Topology preserving (connectivity, branching)
- Intuitive visualization

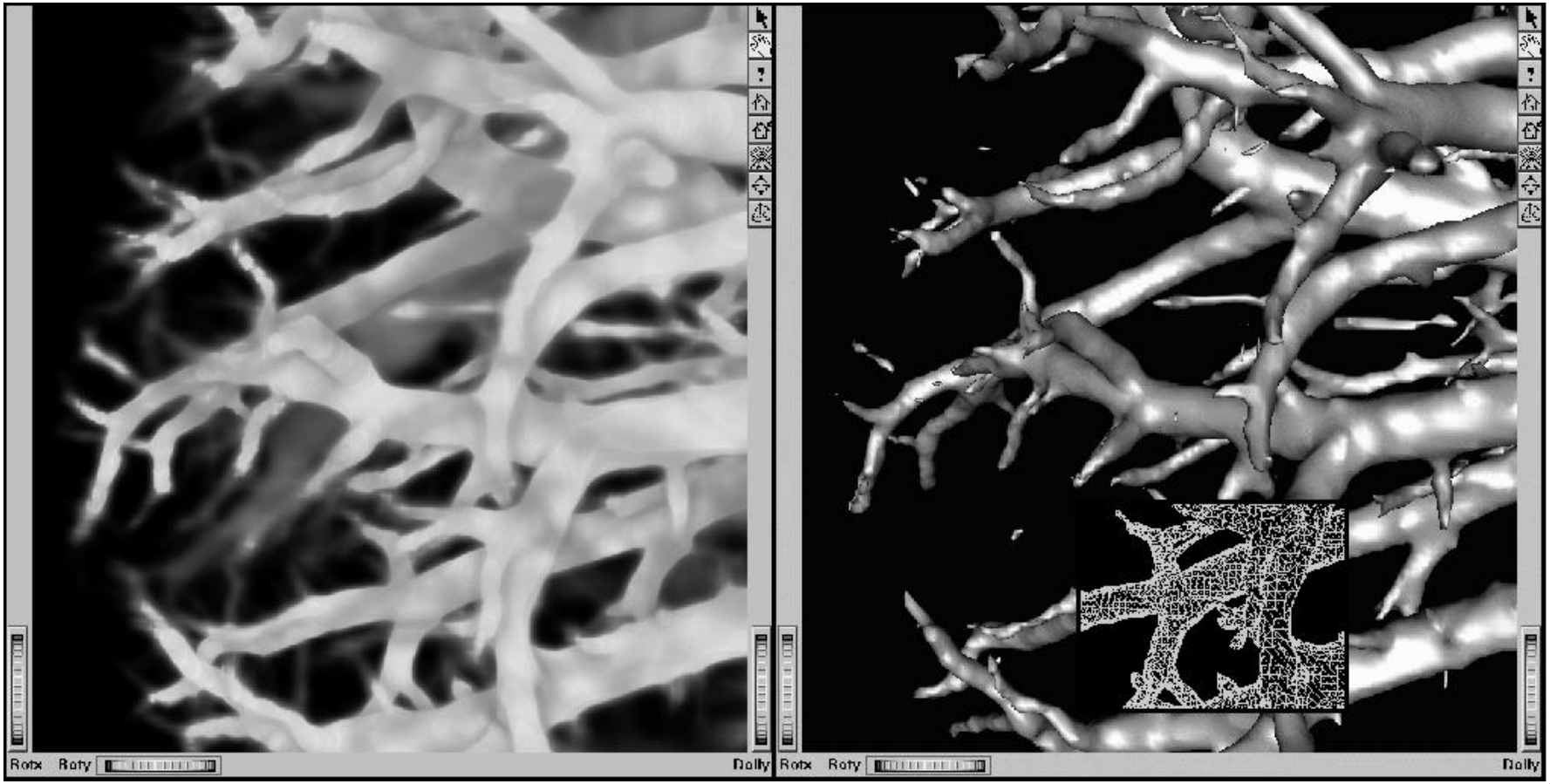




[Source: Bernhard Preim]

Conventional Techniques

- Direct Volume Rendering (DVR)
- Shaded Surface Display (SSD)



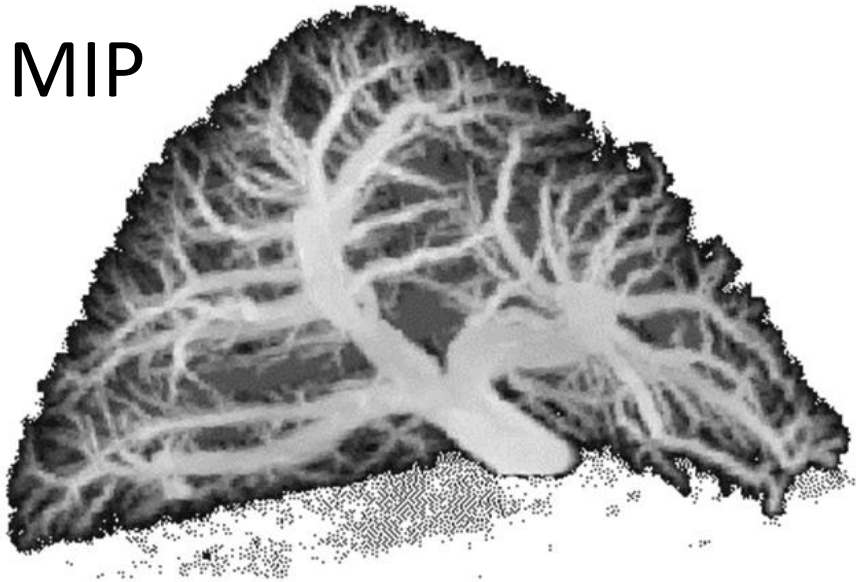
[Hahn et al. 2000]

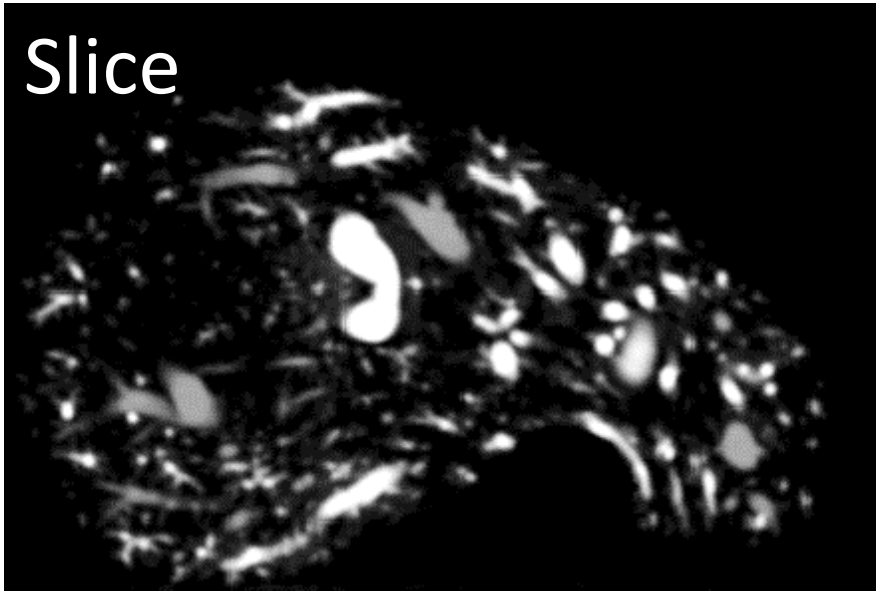
Conventional Techniques

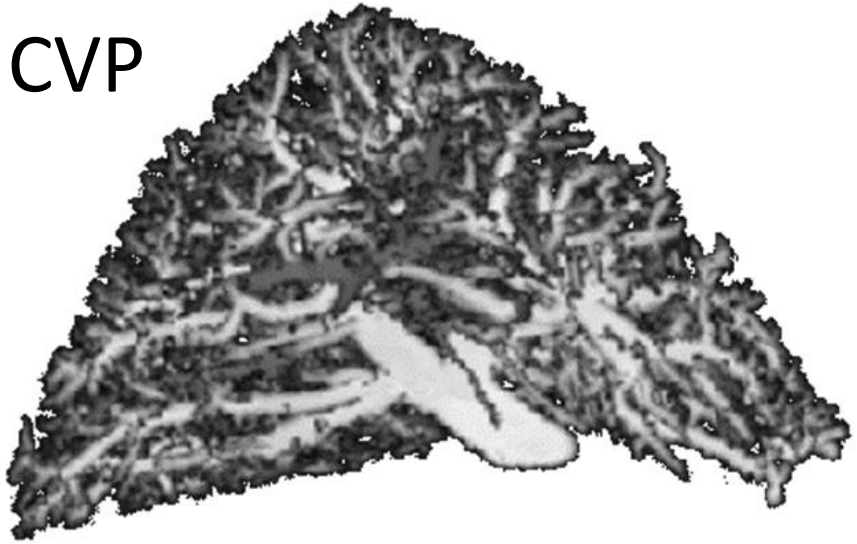
- Improved using Connected Component Analysis

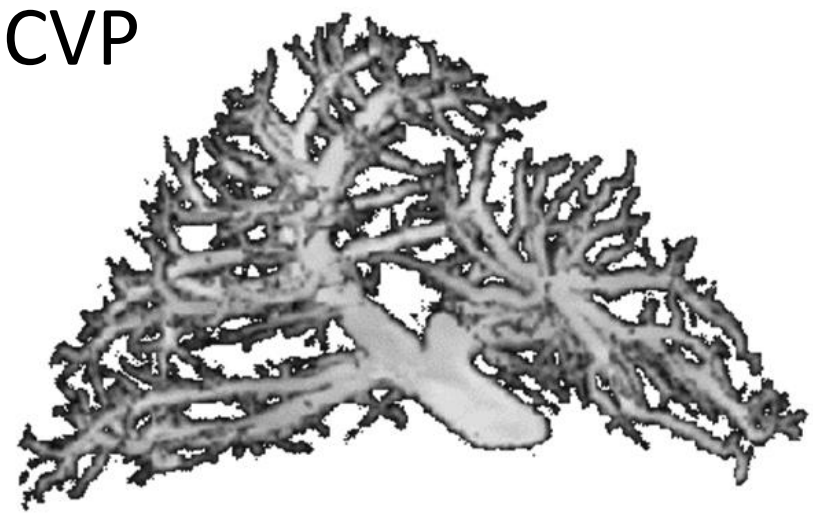
[Source: T. Mönch, B. Preim, Univ. Magdeburg]

Conventional Techniques









[Source: Bernhard Preim]

Model-based Visualization

Model-Based Vessel Visualization

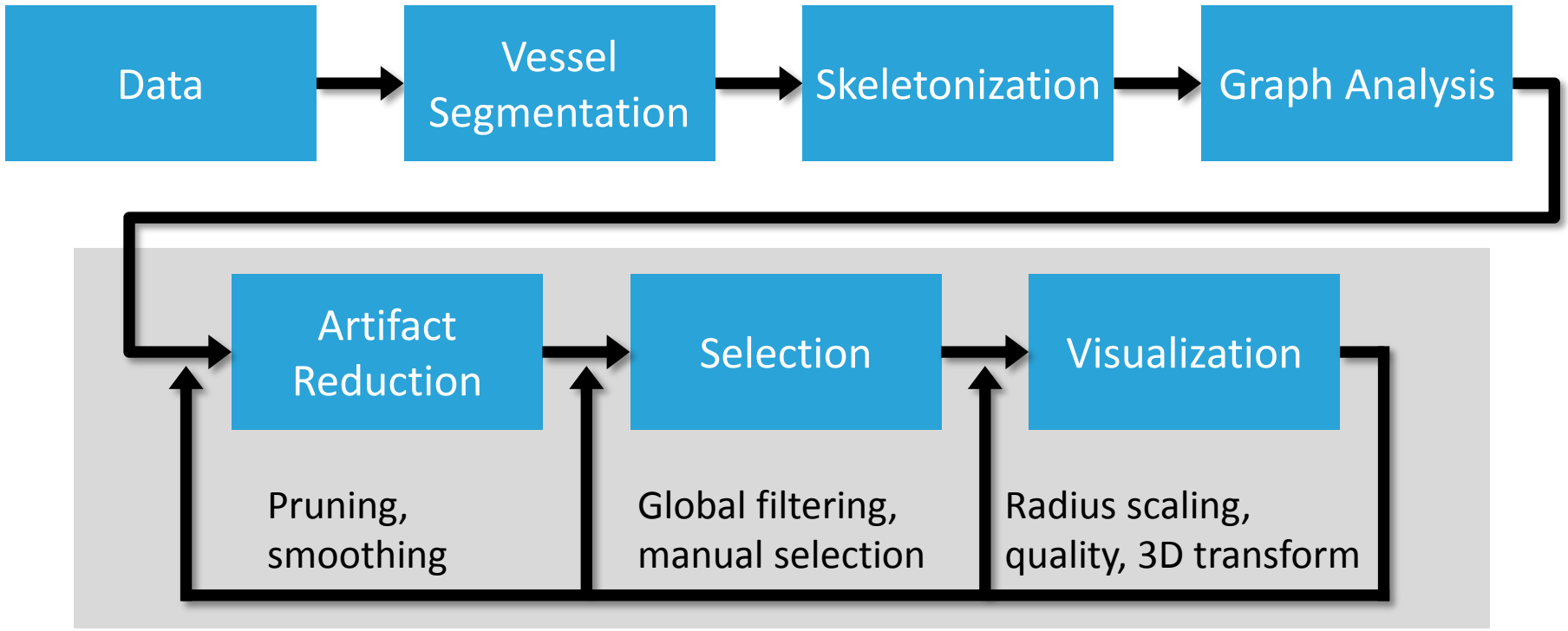
- Depiction of
  - Spatial position
  - Branching structure
  - Radius progression

- Model
  - Vascular system viewed as directed graph with its vertices as branching points
  - Circular or elliptical cross-section

Model-Based Vessel Visualization

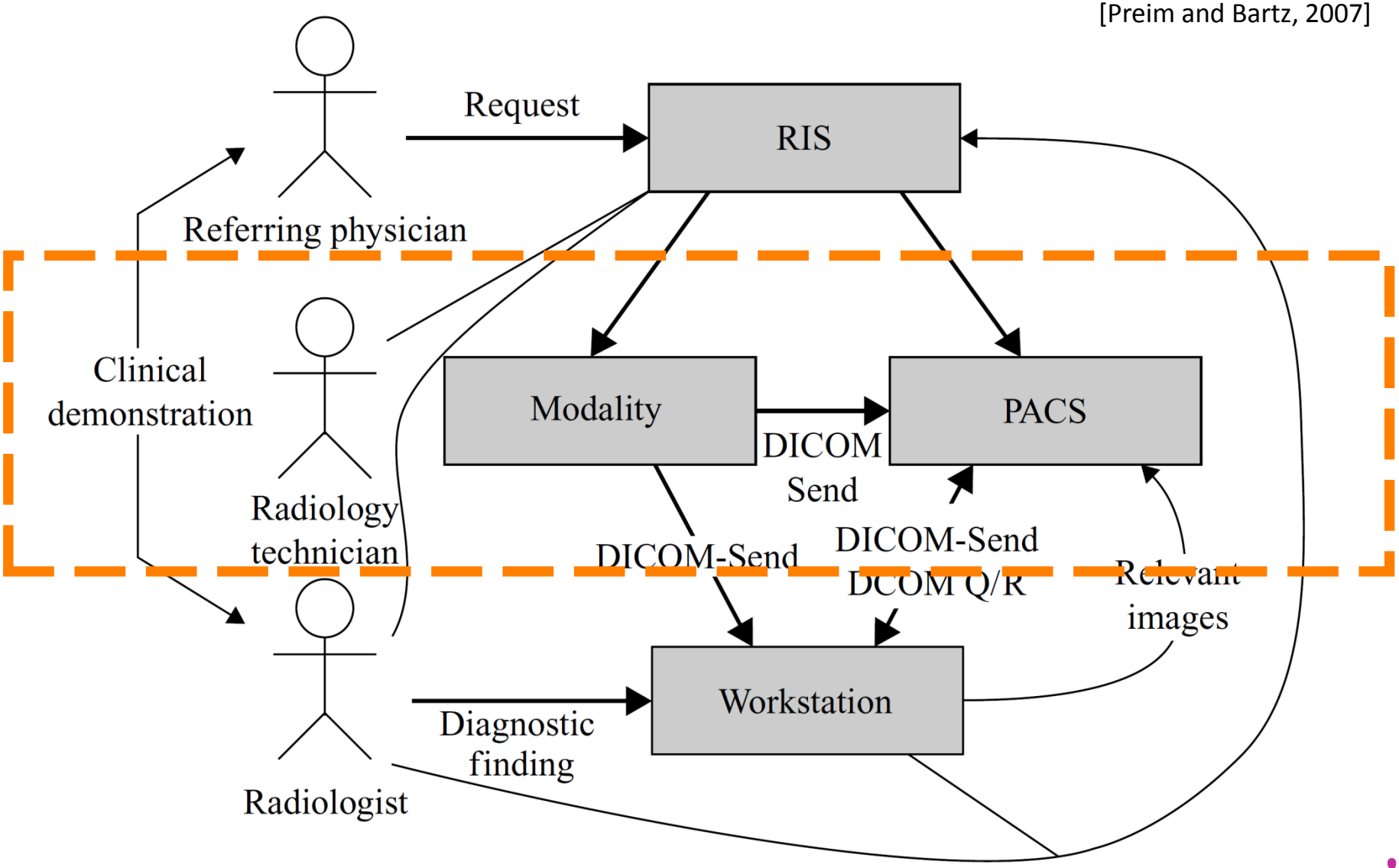
- Vessels visualized with connected graphics primitves
- Requirements: Voxels of vascular system with their structure (connectivity)

Model-Based Vessel Visualization – Pipeline



Pipeline – Workflow Integration

[Preim and Bartz, 2007]



Pipeline – Vesselness Filtering

- Based on the eigenvalues of the Hessian matrix (partial 2nd derivatives)
- Enhancement of elongated objects (such as vessels) if $\lambda_1 \gg \lambda_2$ and $\lambda_1 \gg \lambda_3$
- Problems at bifurcations

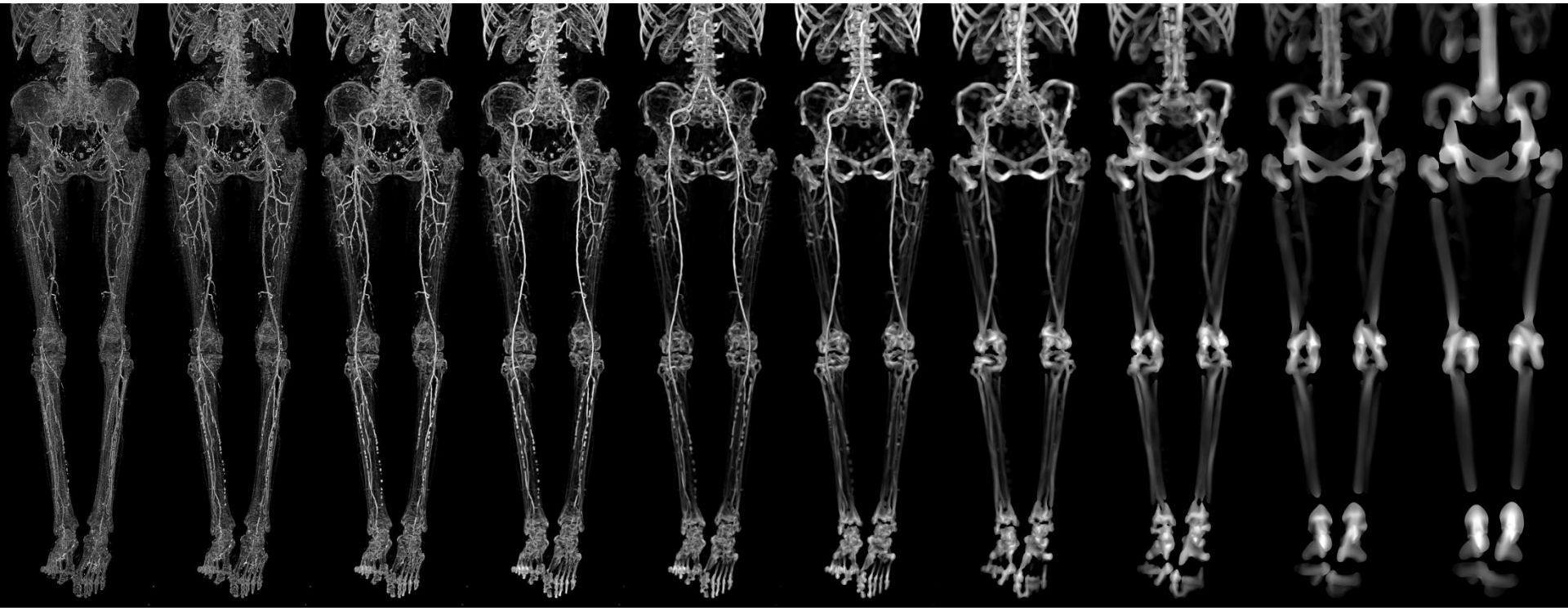
Pipeline – Vesselness Filtering

[Frangi 1998]

Pipeline – Multi-Scale Analysis

- Enhance differently sized objects with the data
  → Vessels of various sized enhanced
- Combine these into a single volume
  → Store maximum response
- Use for subsequent skeletonization
- Captures even small vessels

Pipeline – Multi-Scale Analysis



Increasing scale (vessel size)

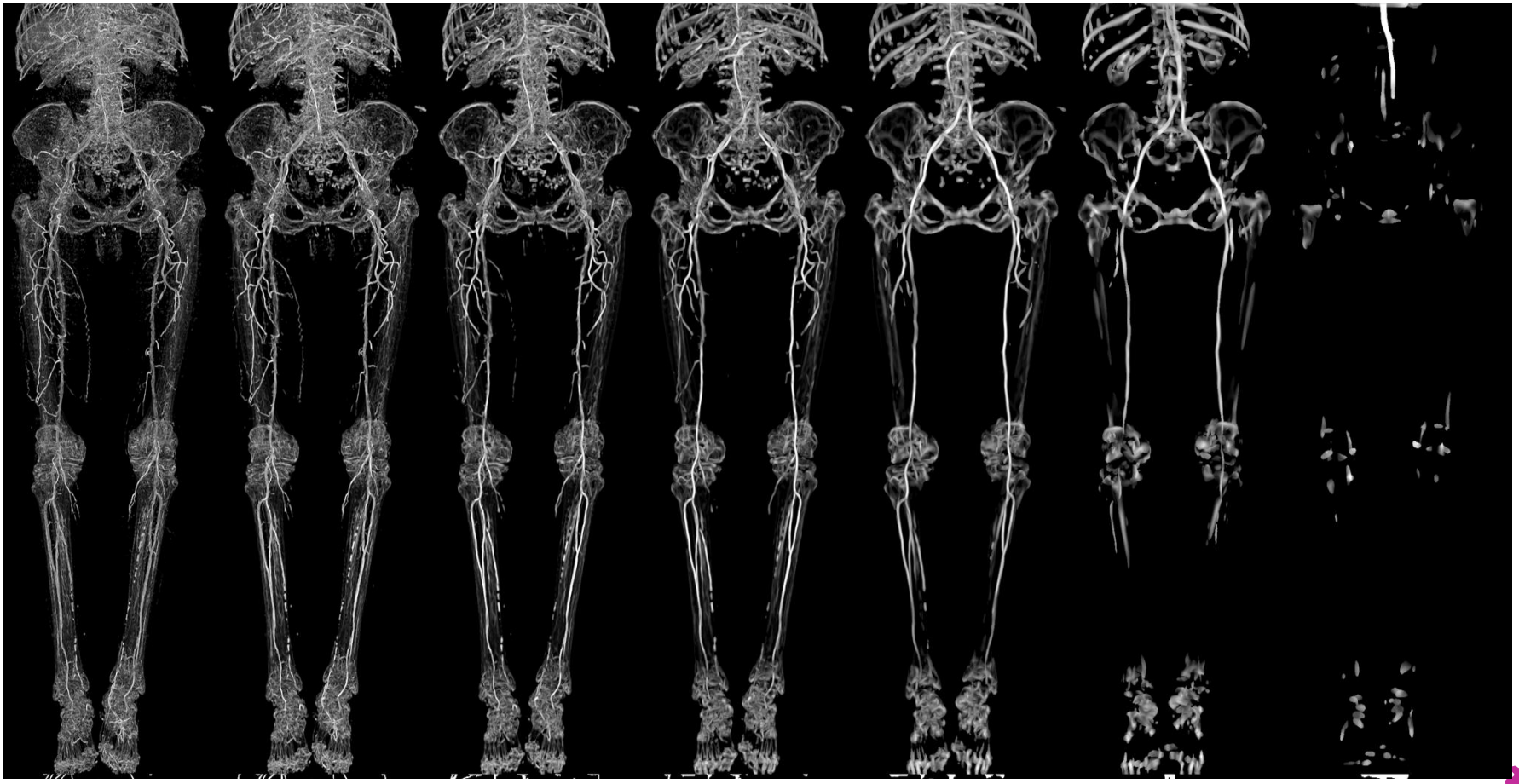
Pipeline – Multi-Scale Analysis

All scales combined into a single volume

Vessels color-coded according to their scale (= size)

Pipeline – Vessel Segmentation

- Threshold Hessian enhanced volume
- Hysteresis thresholding to remove small objects



Pipeline – Vessel Segmentation

- Threshold Hessian enhanced volume
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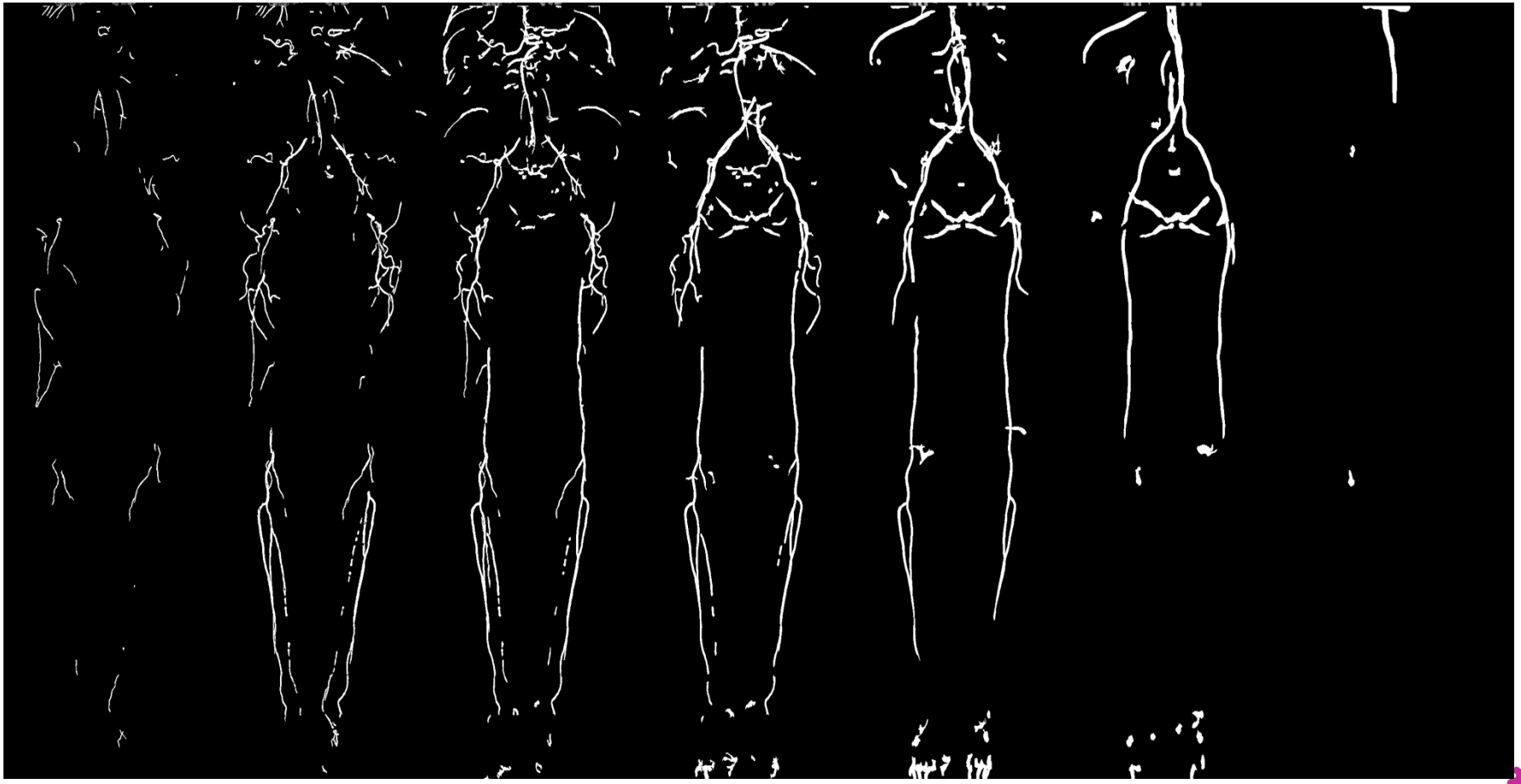
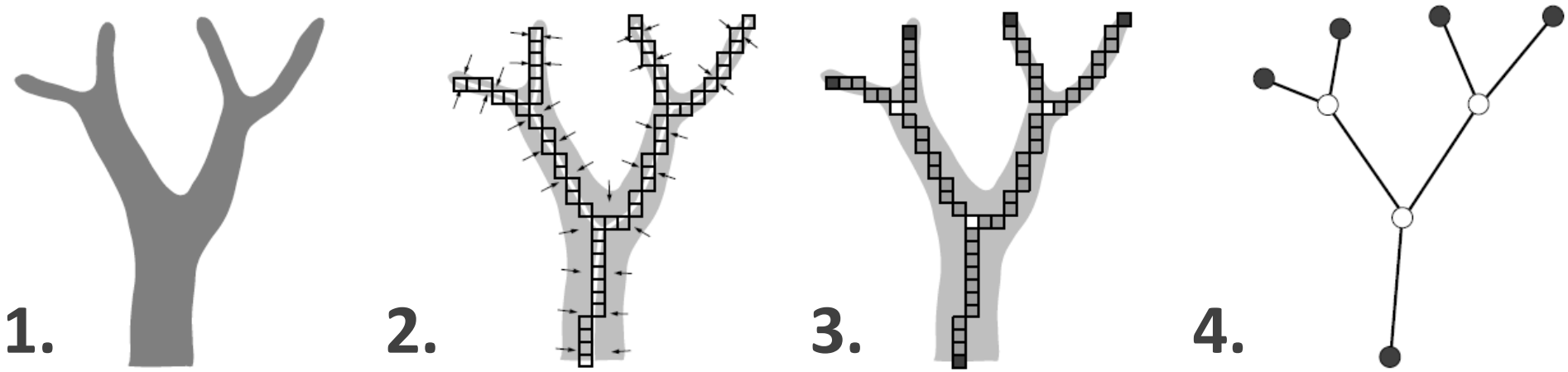


Pipeline – Vessel Segmentation

- Combine thresholded data sets into a single volume
- Additionally, store the max. response (size) in a second volume
- Skeletonize combined volume

Pipeline – Skeletonization

- Skeletonization
  - Thinning-based approaches
  - Medial axis transform
- → Graph representation of vessels



[Selle et al. 2002]

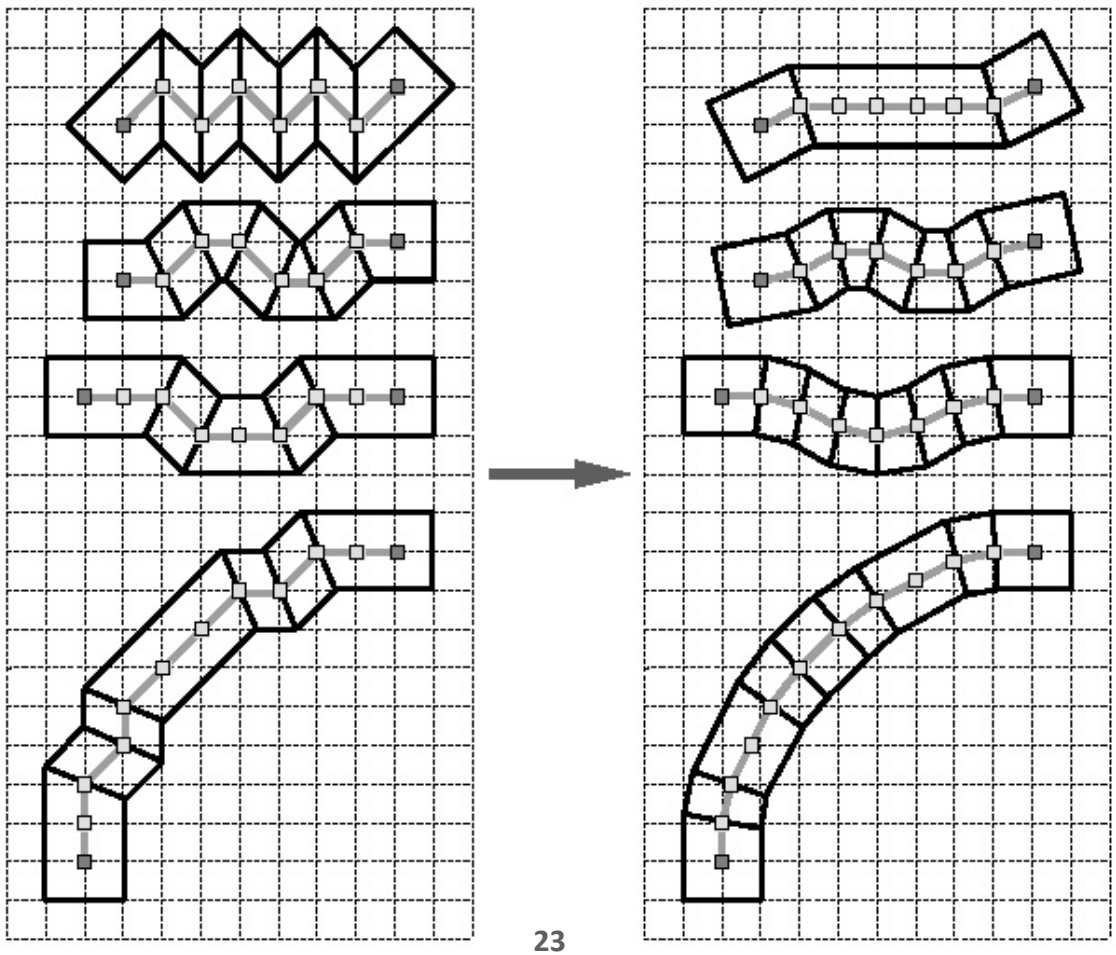
Pipeline – Graph Analysis

- Vessel tree consists of
  - Branching points
  - End points
  - Vessel segments (between branching and/or end points)

- Susceptible to noise on the object boundary
  → Many small segments
  → Analyze graph

Pipeline – Artifact Reduction

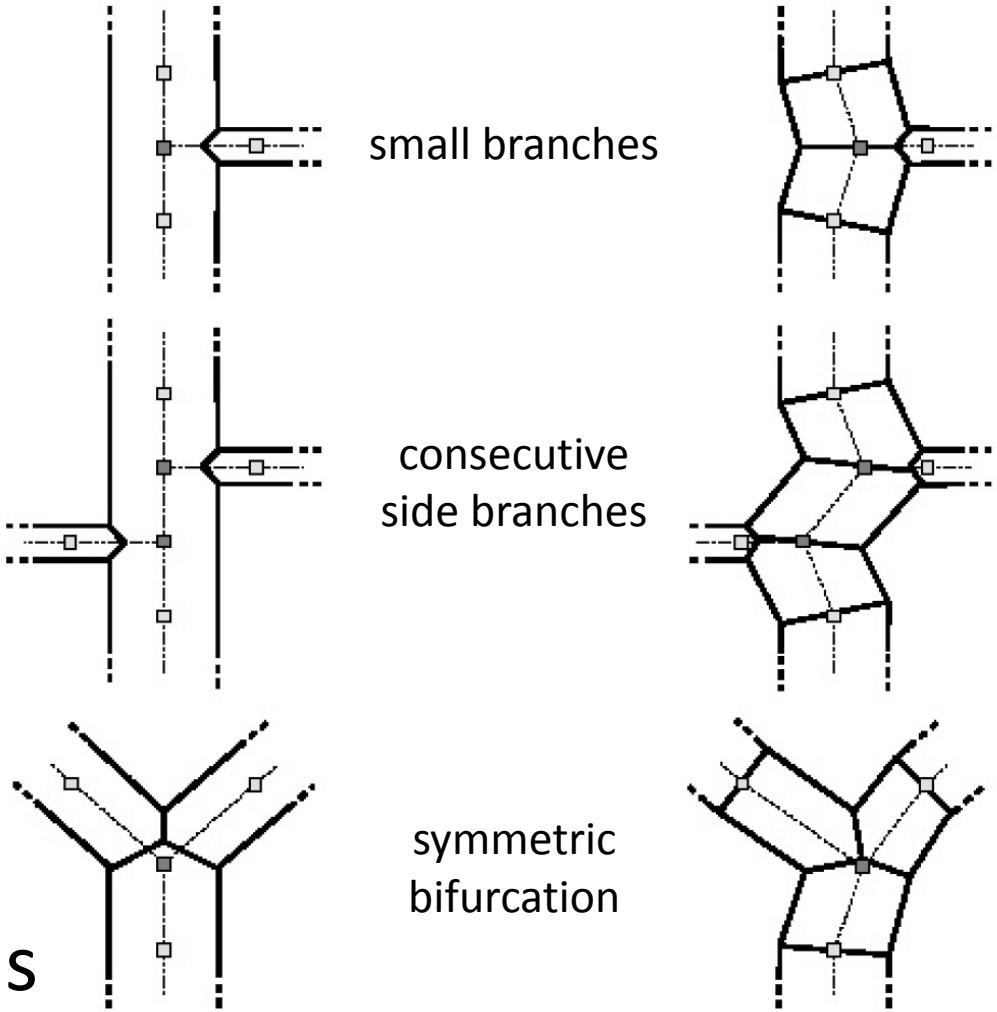
- Improvement of skeletonization results
- Smoothing using a binomial filter kernel



[Hahn et al. 2000]

Pipeline – Artifact Reduction

- Reduction of side branches, depending on the size ratio: side branch / main branch
- Avoid deformation in case of two side branches
- Center voxels at symmetric bifurcations



[Hahn et al. 2000]

Pipeline – Artifact Reduction

- Analyze vessel tree and develop solutions for every branching type

- Handle branches uniformly
  - If # skeleton voxels > 2 → branching point
  - Weight influence of neighbhors with the length of the respective skeleton

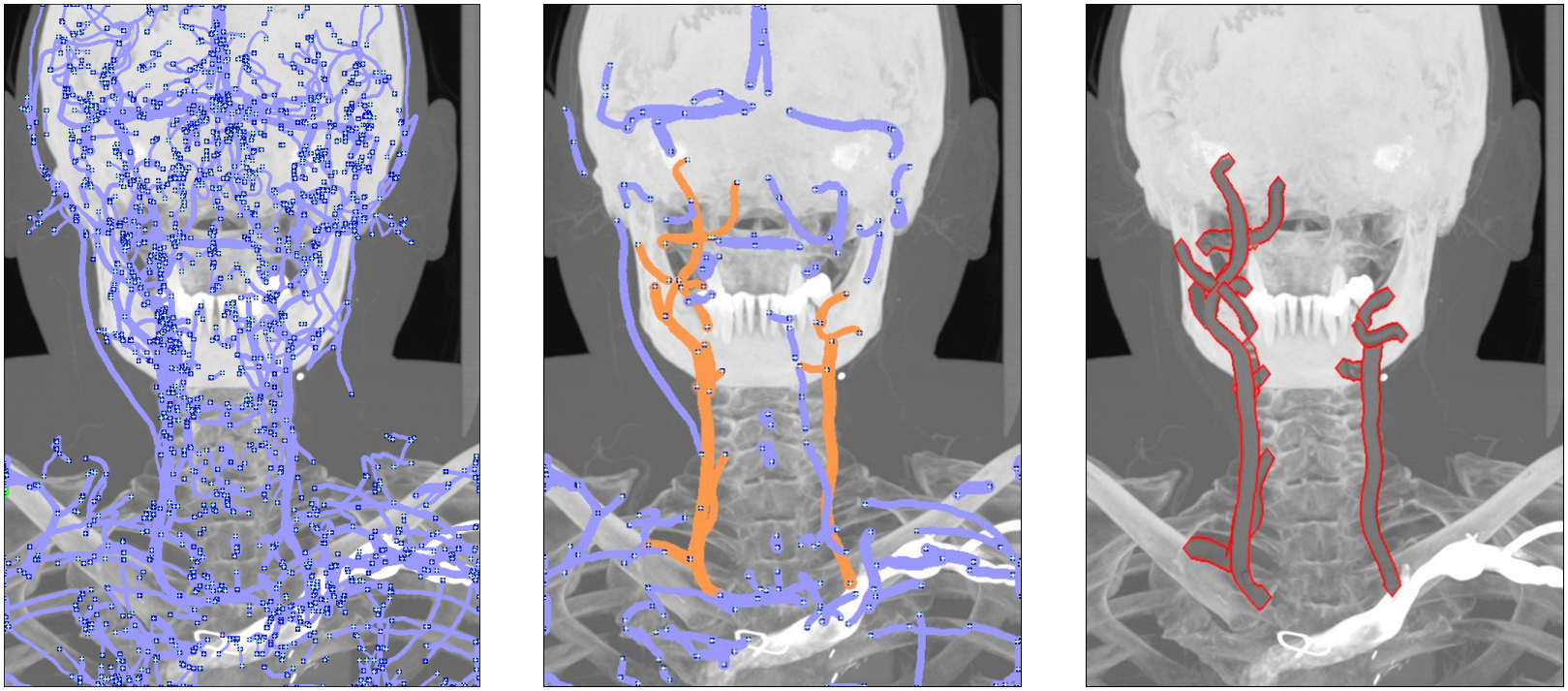
Pipeline – Artifact Reduction

- Relinking of disconnected segments

[Thomas Pock, 2004]

Pipeline – Selection

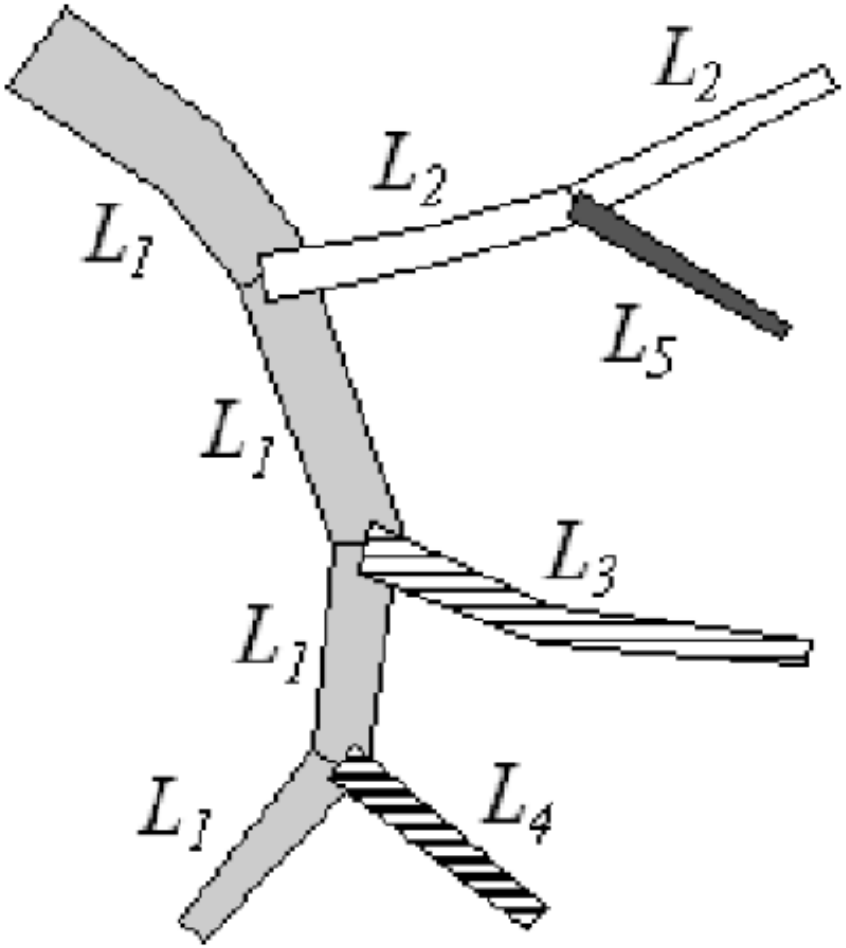
- Determine properties of vessel segments
  - Size / thickness
  - Length
- Used for exploration / filtering of the vessel tree



Pipeline – Visualization

- Connected vessels segments
- Avoid small or short segments
- Minimize discontinuities
- Extrude cones along segments

- Visualizationg using truncated cones



[Hahn et al. 2001]

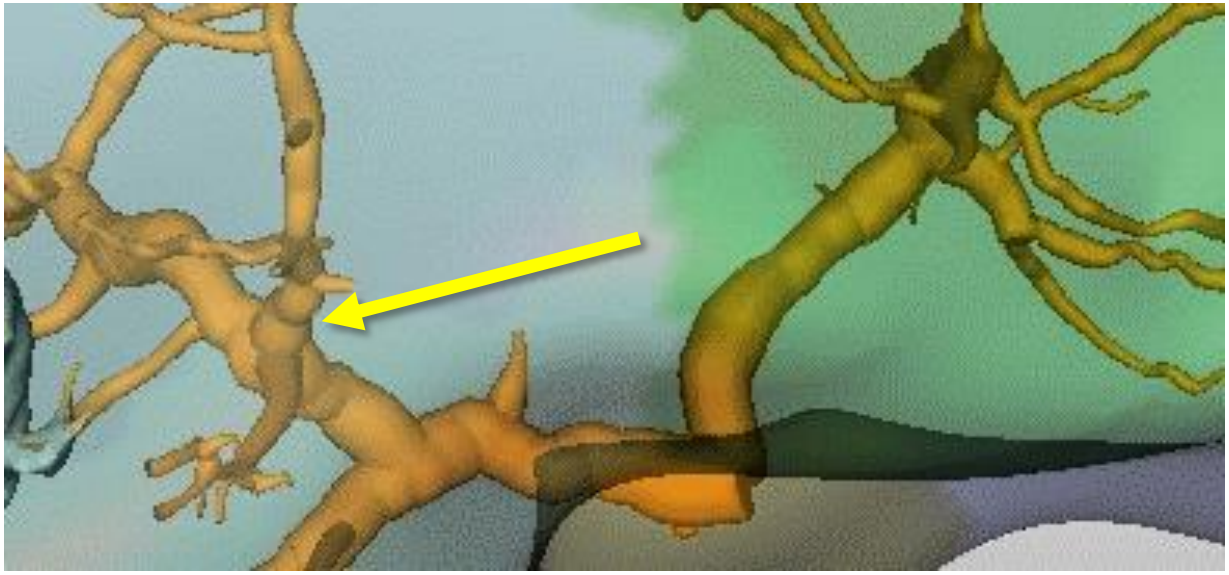
Truncated Cones

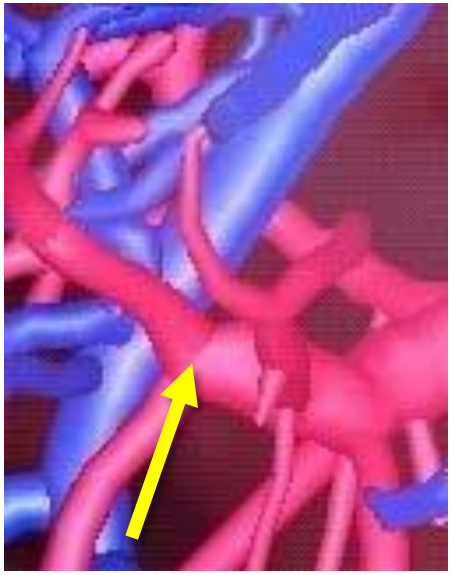
- Vessel segments represented as cones
- Half spheres added at end points
- Simple and fast techniques
- Widely used for surgery planning

[Hahn et al. 2001]

Truncated Cones

- Orientation discontinuities at branching points
- Cones with highly varying diameters connected

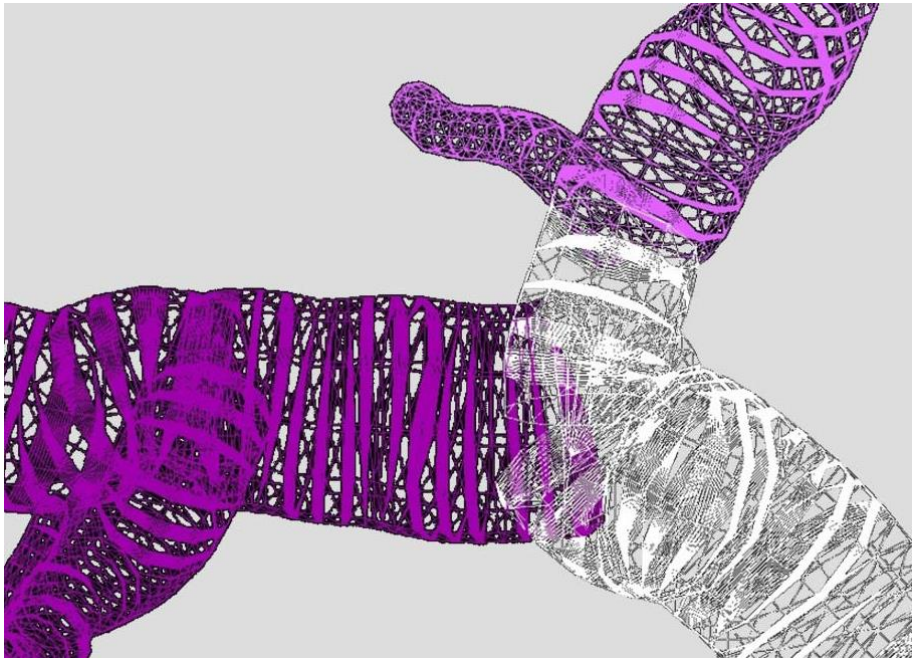




[Images: Bernhard Preim]

Truncated Cones

- Problems at regions with high curvature
- Refine geometry at regions with high curvature



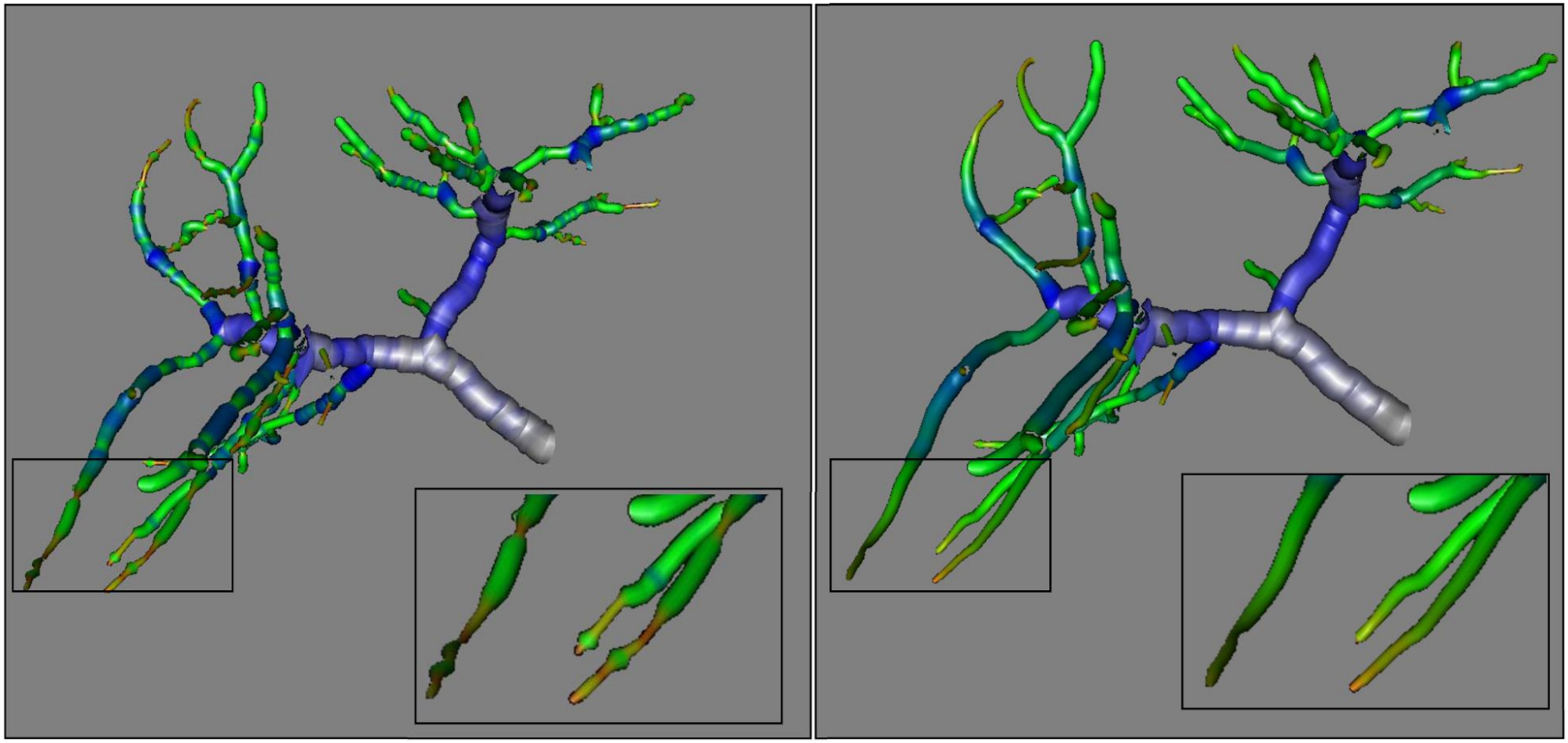
[Images: Bernhard. Preim]

Model-Based Vessel Visualization

- **Problem:** Radii not always reliable and accurate (worse in smaller, thinner vessels)
- **Possible reasons:**
  - Data resolution (especially in the lower legs, vessel approx. 1-2 voxels thick)
  - Vascular pathologies
- **Problem:** Hardly distinguishable if pathological or resolution is the problem
- Visualization of unsmoothed radii undesired
  → Smooth vessel radii

Model-Based Vessel Visualization

- Visualization of vessel radii, color-coded
- Without (left) and with (right) radius smoothing



[Images: Bernhard Preim]

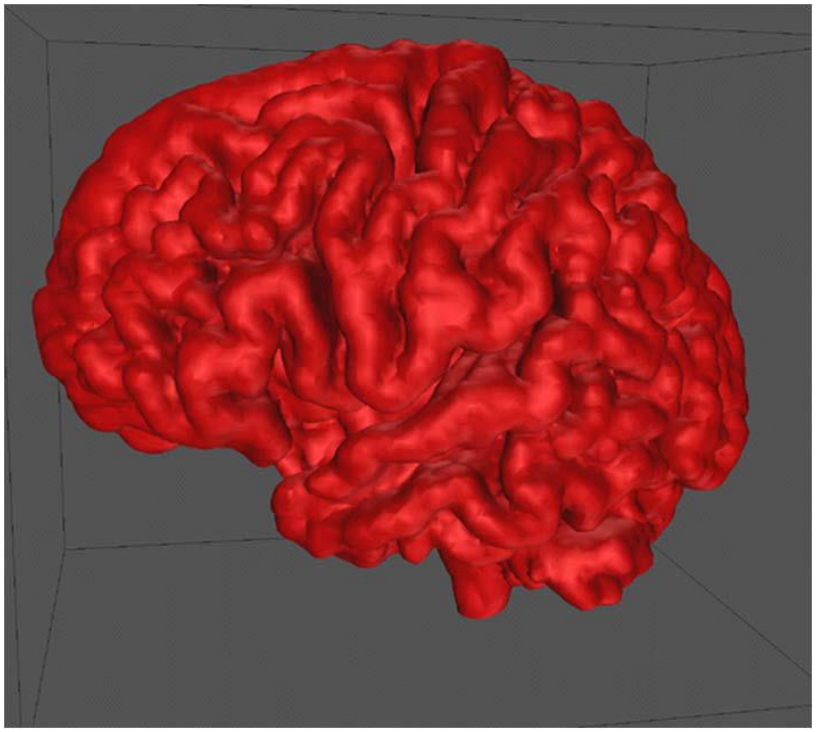
Comparison of Methods

	Symbolic Representation	Truncated Cones	Shaded Surface Display (SSD)	DVR / MIP
Degree of abstraction	High (radius ignored)	Medium (circular vessel model)	Low	Very low
Memory consumption	Low (~10^2 ... 10^3 coordinates)	Medium (~10^3... 10^4 coordinates and radii)	High (~10^5 triangles)	Very high (~10^6 voxels)
Branching structure	Optimal	High	Problematic	Very problematic
Interaction (filtering and highlighting of parts)	Possible, regarding the hierarchy	Possible, regarding the hierarchy and radii	Problematic, clipping planes required	Problematic, clipping planes required

Implicit Methods

- **Advantages:**
  - Smooth and organic looking surfaces
  - Smooth bifurcations
- **Disadvantages:**
  - Merging of branches

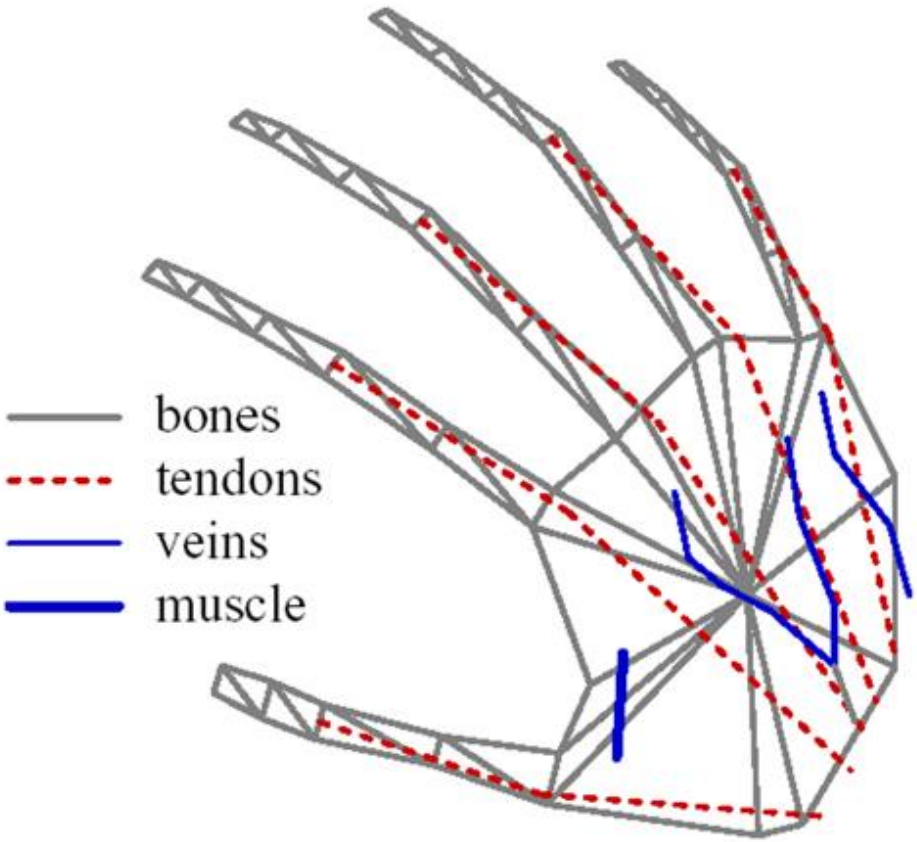
[Source: Bernhard. Preim]



Implicit visualization of the brain

Implicit Methods

- Different properties for various types of tissue



[Images: Bernhard. Preim]

Implicit Methods

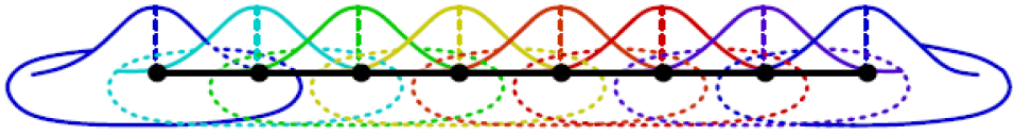
- Uses implicit functions: $F(x, y, z) - Iso = 0$
- Used in computer graphics for rendering of electric fields with blobby molecules (objects)

- Use for visualization of tree-like structures
- Skeleton points as enery sources
- Skeleton points define spherical iso-surfaces
- **Problem:** Smooth surfaces on line segments
- **Solution:** Convolution Surfaces [Jules Bloomenthal]

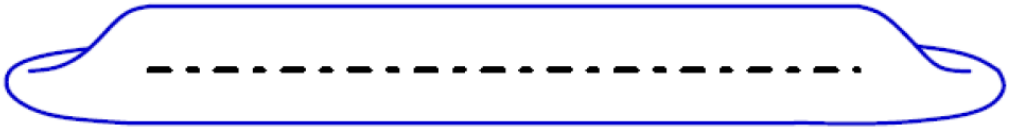
Convolution Surfaces

- Convolve a signal with a filter
- Convolution of a line segment with a lowpass filter, e.g., a Gaussian filter
- Polygonization of the implicit function with an iso-value depending on the applied filter (e.g., marching cubes version of Bloomenthal)
- **Goal:** Visual effects, precision subsidiary

Sum of lowpass filter



Resulting convolution surface



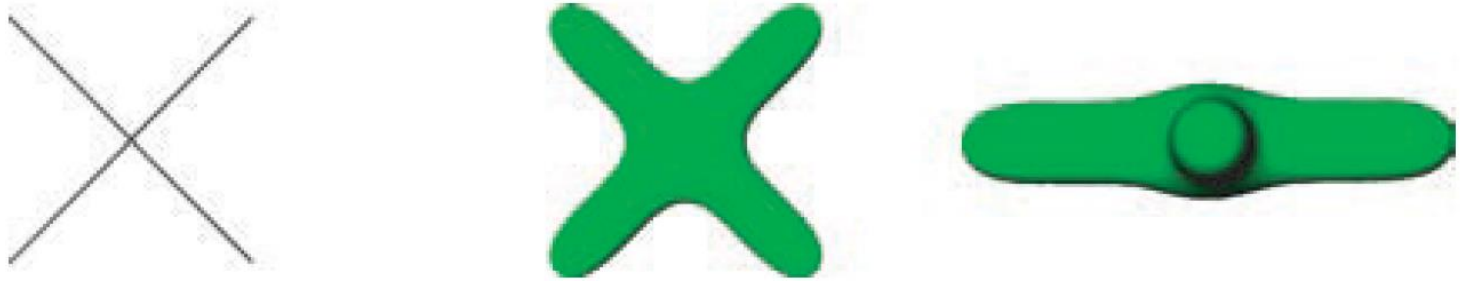
[Source: Bloomenthal, J.: Skeletal Design of Natural Forms, Dissertation, 1995]

Convolution Surfaces

- **Problems:**
  - <u>Bulging:</u> Interfering scalar field at bifurcations → Undesired thickening

[Oeltze and Preim, 2005]

  - <u>Blending strength:</u> Merging of neighboring segments



[Oeltze and Preim, 2005]

Convolution Surfaces

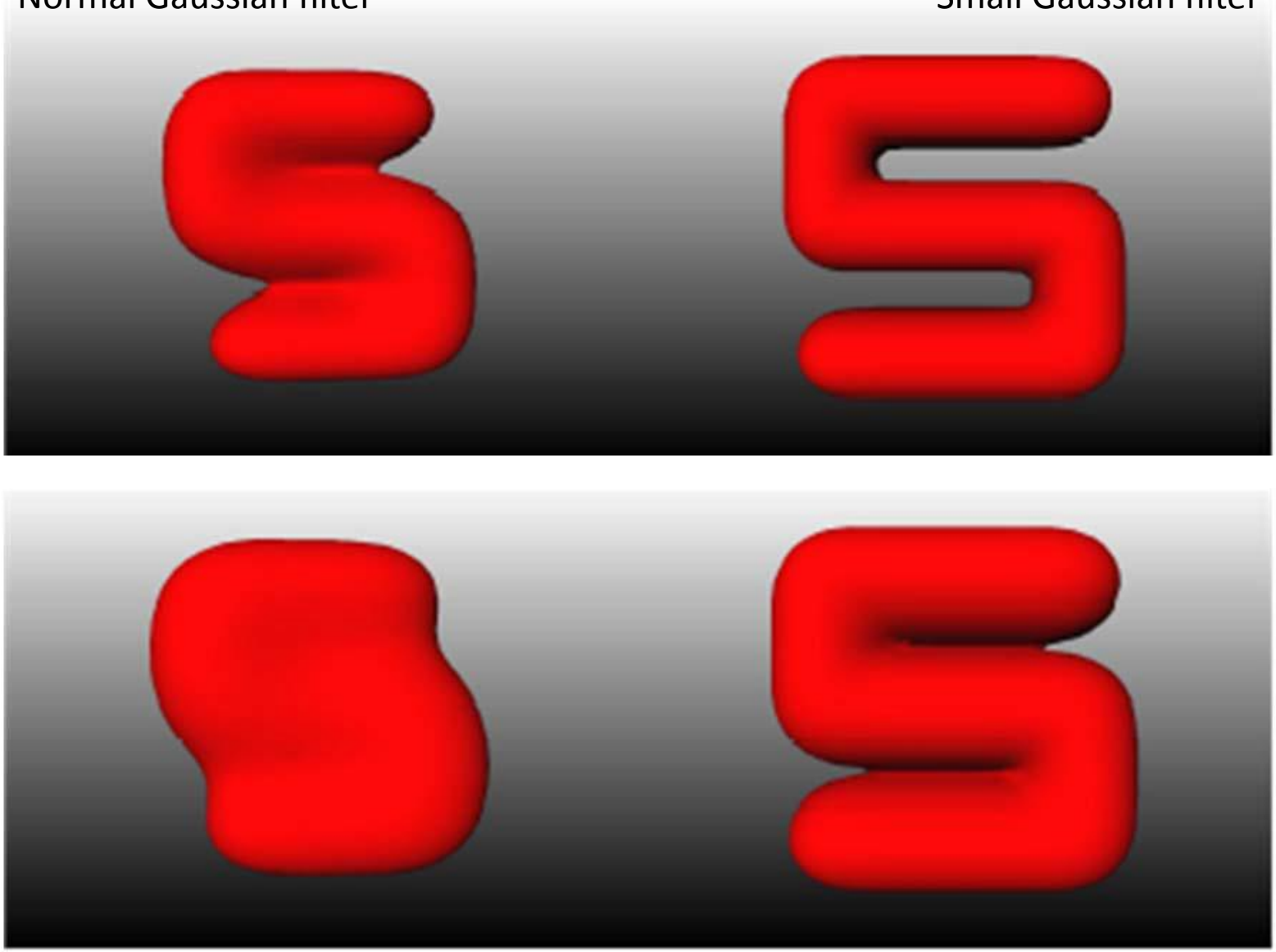
- Restrict blending to certain parts of the model
- Smart selection of filter parameters
- Small Gaussian filter:
  - Reduces bulging significantly
  - Correct representation the radius
  - Empirically determined: $\sigma = 5\ ln\ 2$ fits best

[Bloomenthal (1997): Bulge elimination in convolution surfaces. *Computer Graphics Forum* (1997), 16:31–42]

Convolution Surfaces

Normal Gaussian filter

Small Gaussian filter



[Oeltze et al. 2004]

Convolution Surfaces

- Trifurcation
  - Bulging

[Oeltze et al. 2004]

  - Blending strength

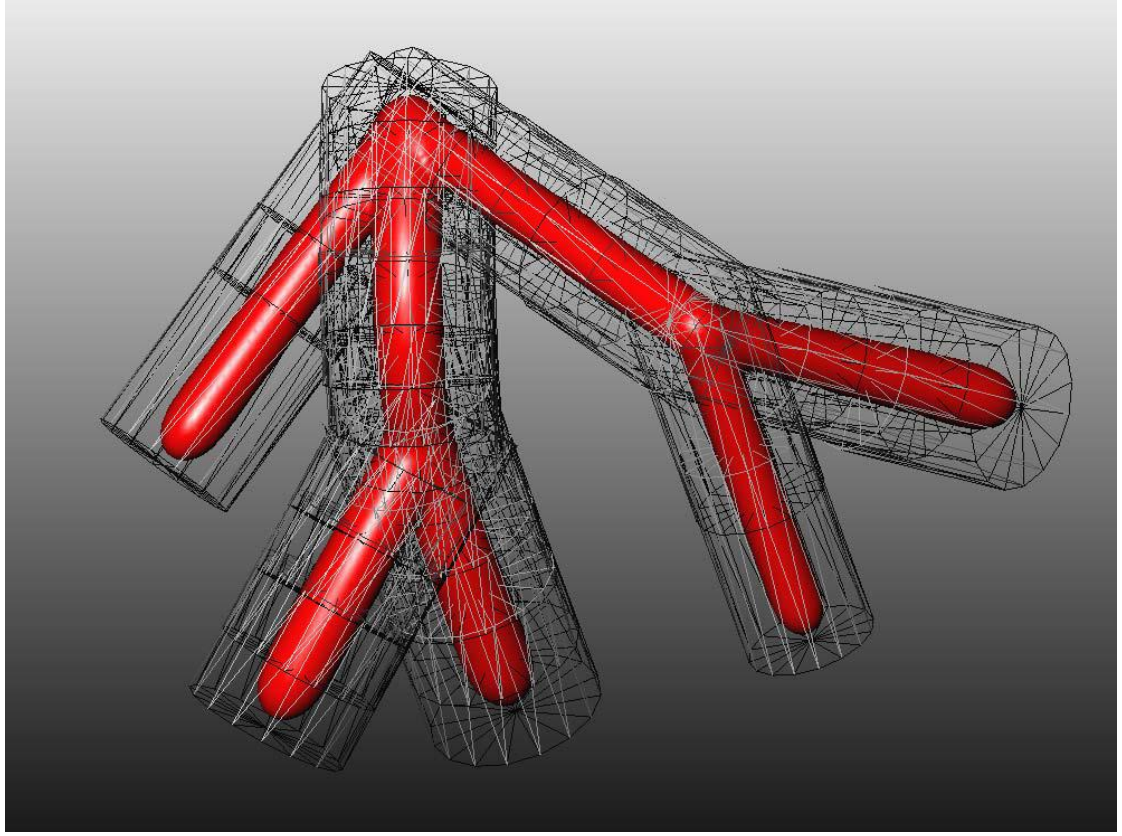
[Oeltze et al. 2004]

Efficient Computation of Scalar Fields

- Computing a scalar field is time-intensive
- Possible improvements:
  - Preprocessing
  - Generation of bounding object around line segments → computation of scalar field is reduced to its inside
  - Bounding object as tight as possible (e.g., cylinders per line segment)

Efficient Computation of Scalar Fields

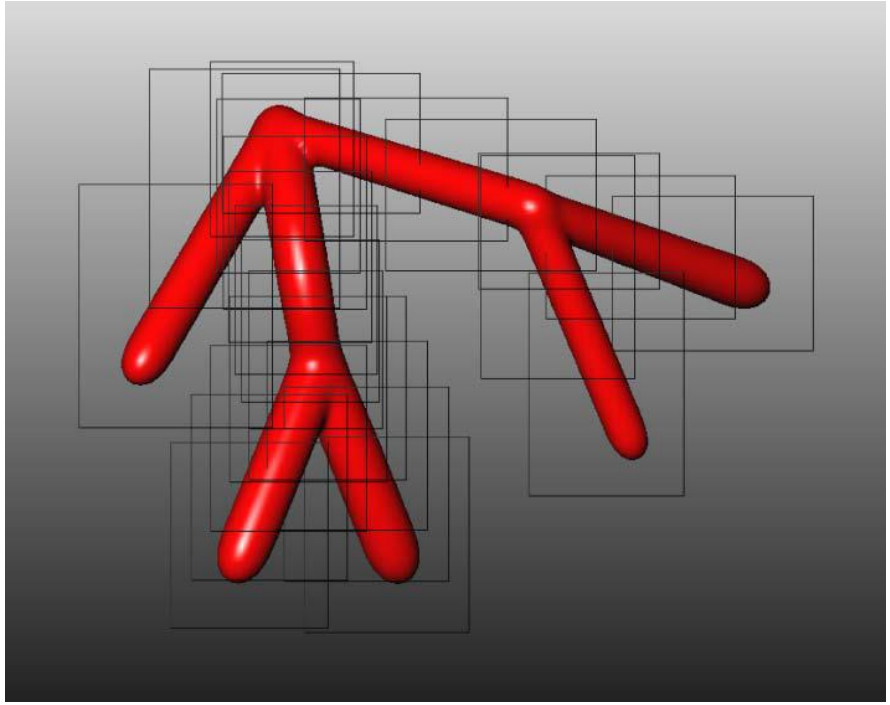
- Investigate only points inside cylinders (cylinder radius = 1.5x max. radius of segment)
- Use implicit equation of cylinders



[Oeltze et al. 2004]

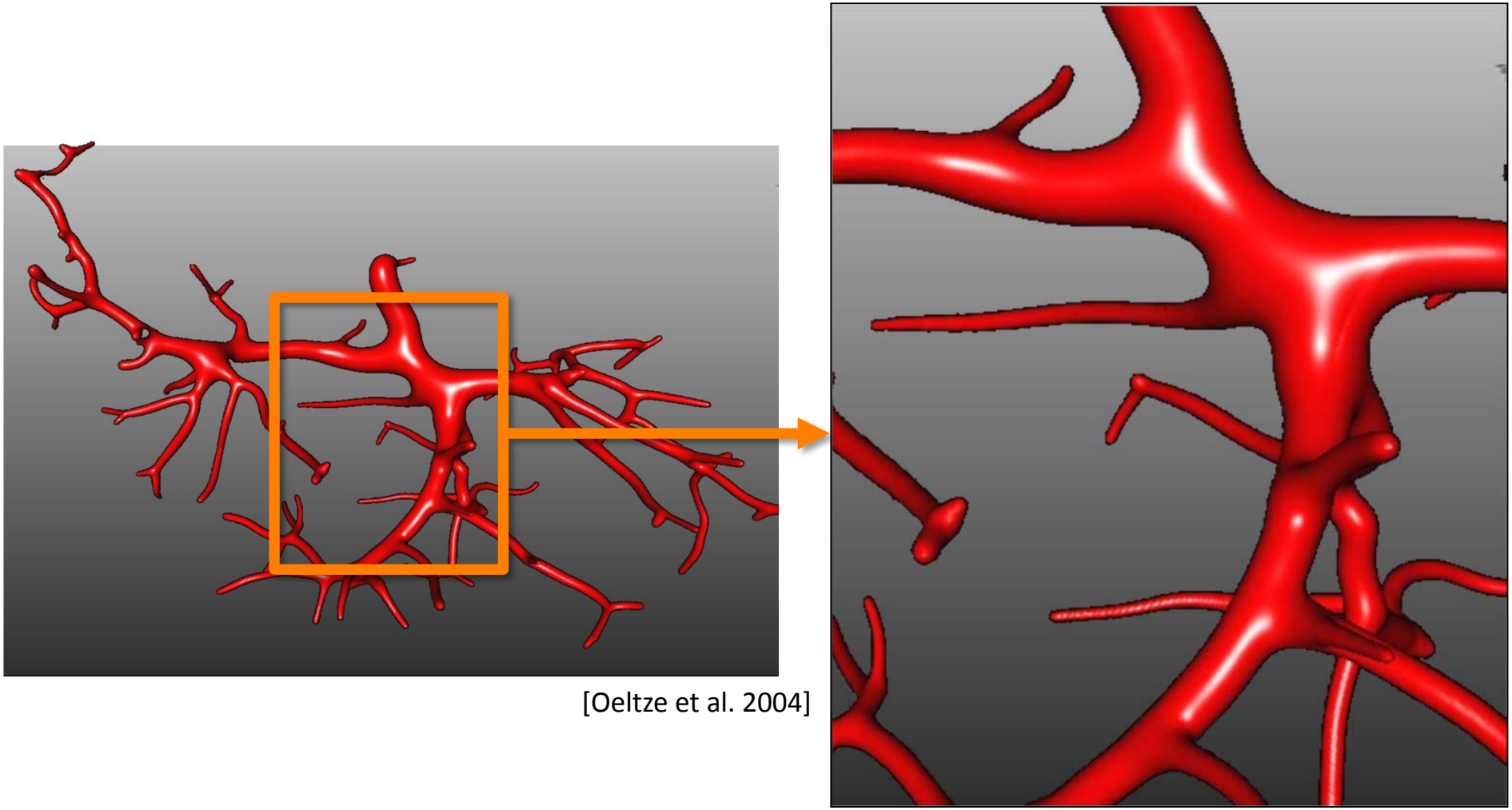
Efficient Computation of Scalar Fields

- Not all voxels should be tested
- Investigate only voxels inside the axis-aligned bounding boxes (AABB) of line segments
- Computed in a pre-processing step



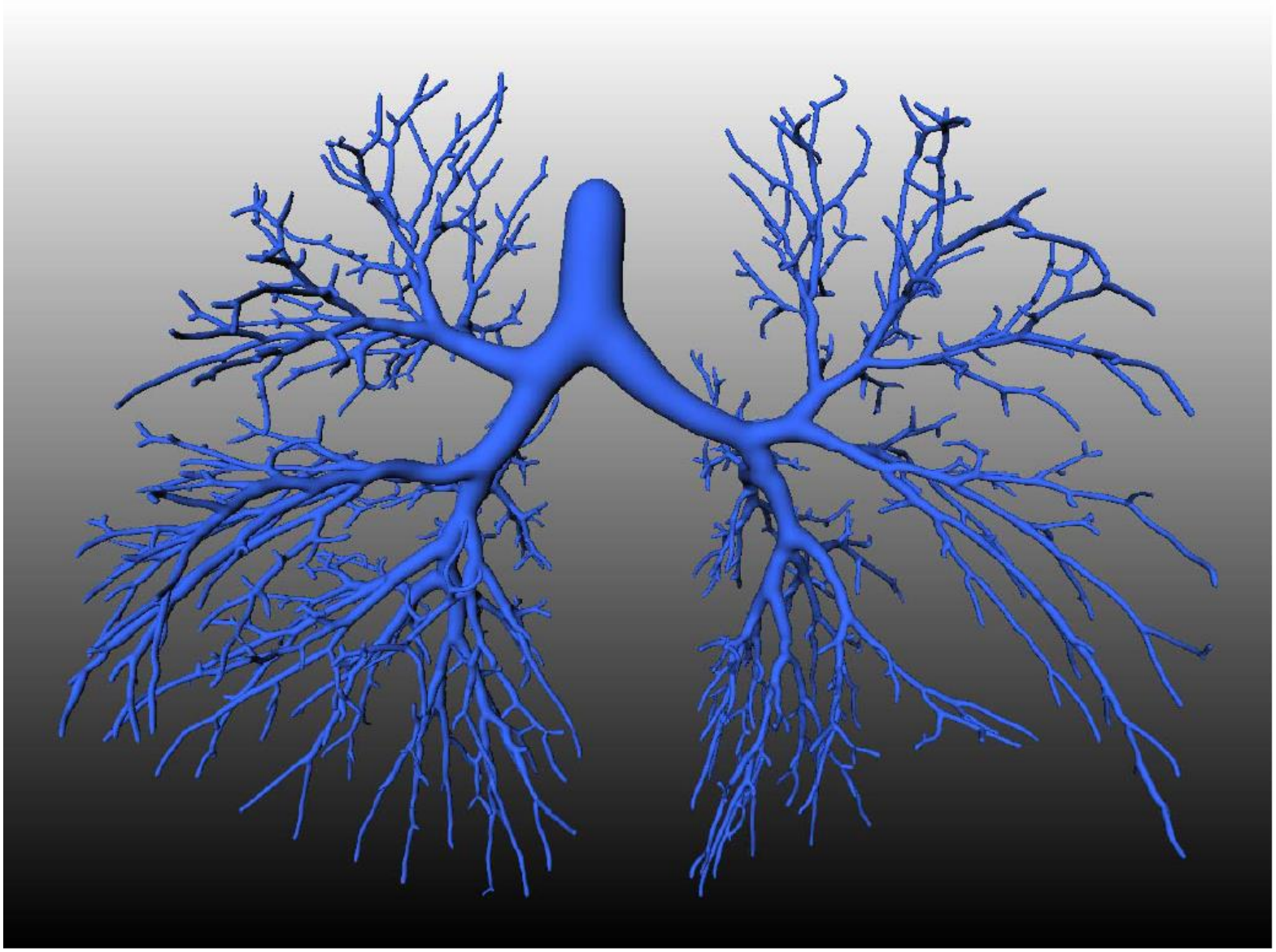
[Oeltze et al. 2004]

Efficient Computation of Scalar Fields



[Oeltze et al. 2004]

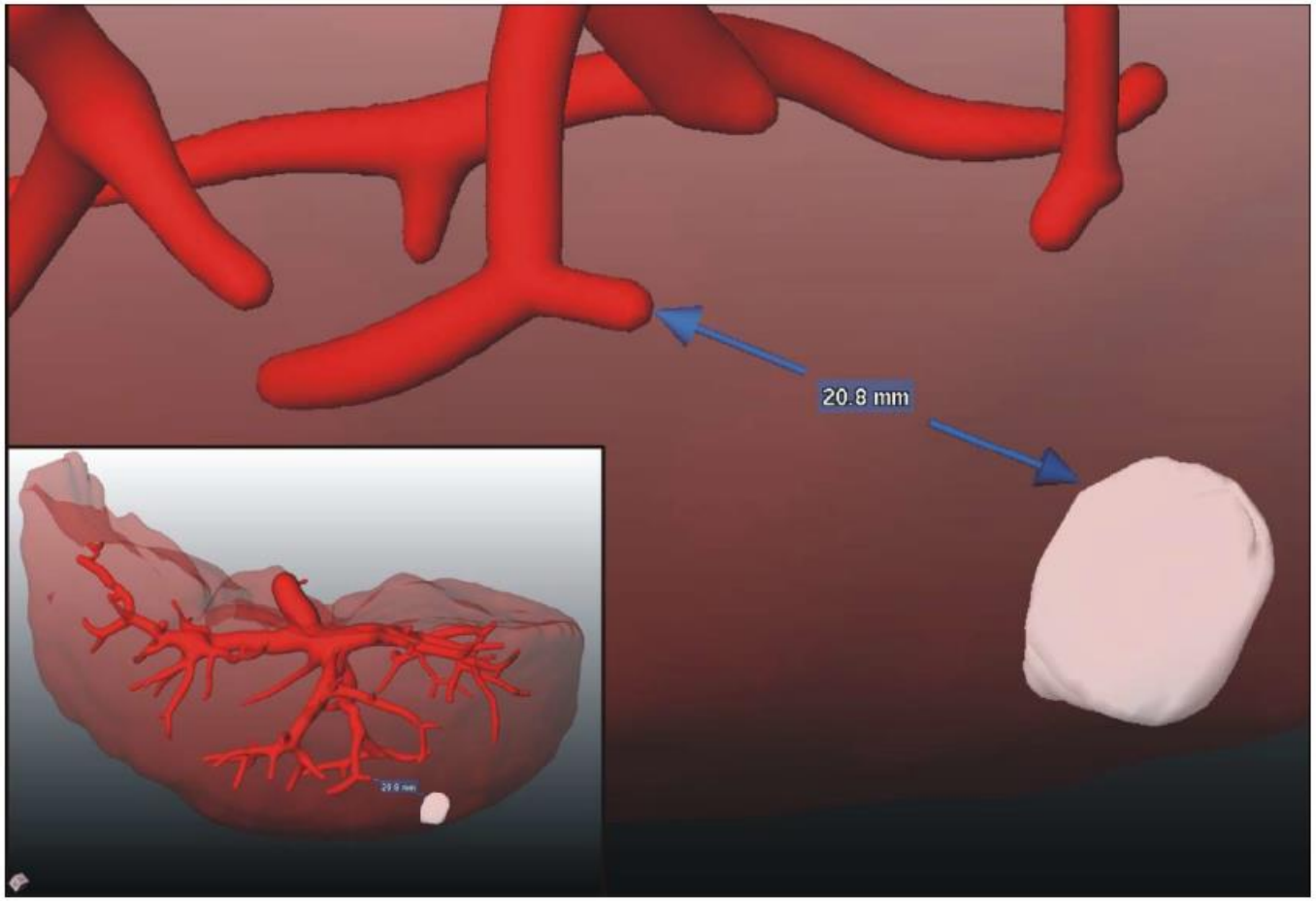
Efficient Computation of Scalar Fields



[Oeltze and Preim 2005]

Convolution Surfaces

- Visualization and measurements for tumor surgery planning

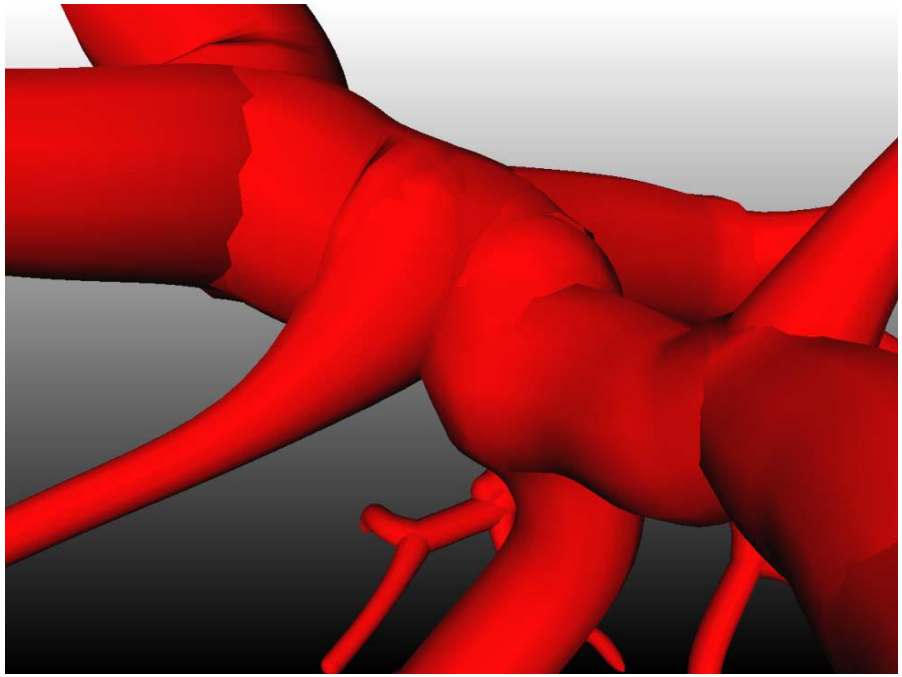


[Oeltze et al. 2004]

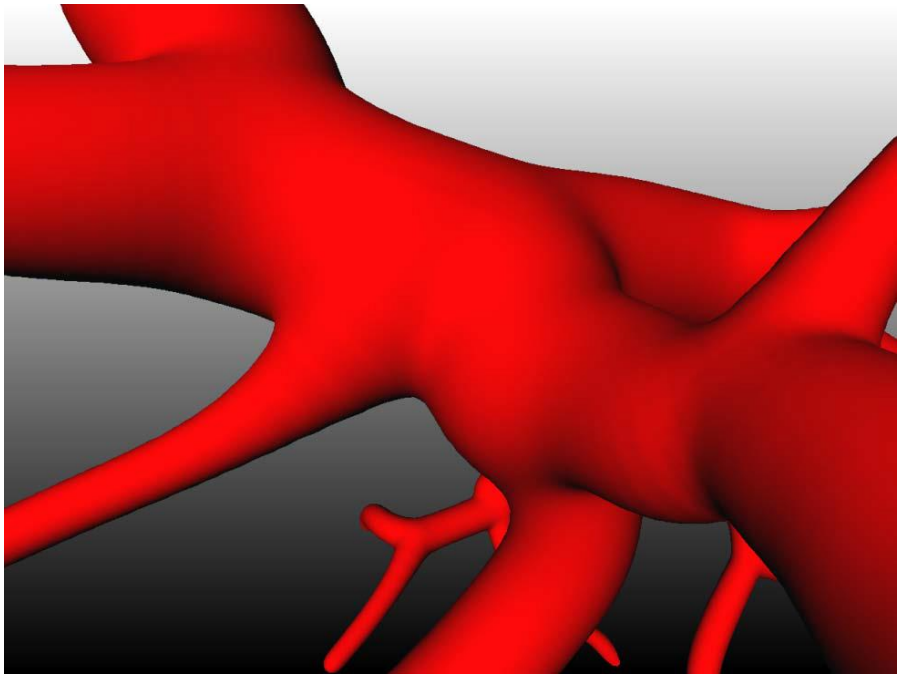
Qualitative Validation

- Comparision of truncated cones and implicit methods (convolution surfaces)

[Images: Oeltze et al. 2004]



Truncated cones

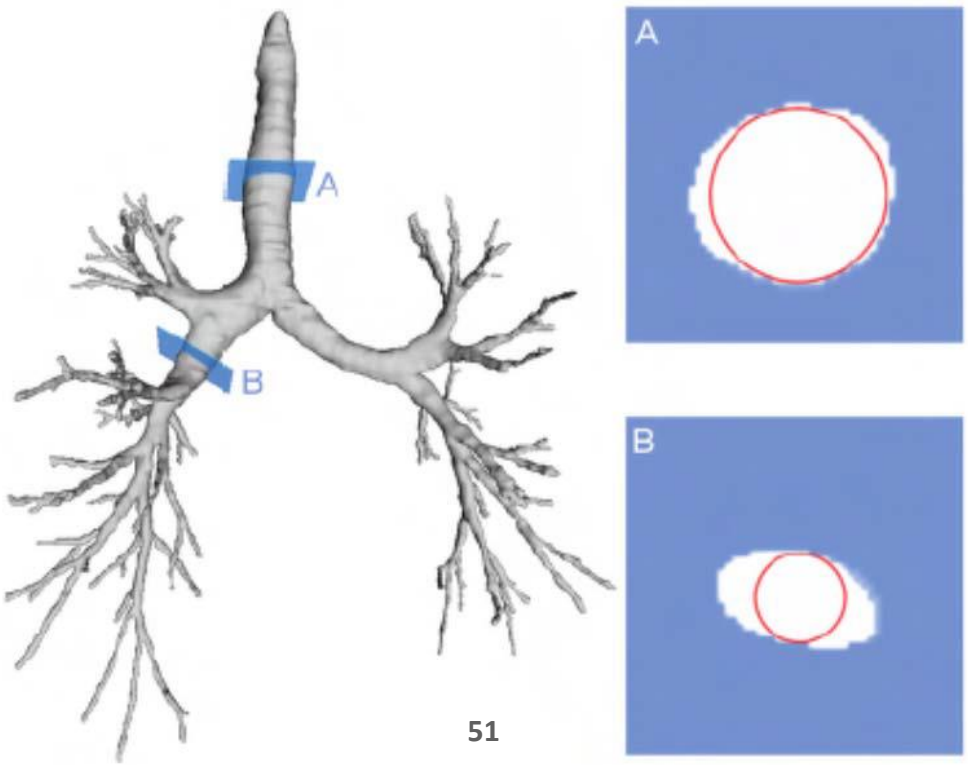


Convolution surfaces

Model-free Visualization

Model-free Vessel Visualization

- Simplified assumption of circular vessel model violated in case of pathological conditions
- Examples: Stenoses, aneurysms
- Even healthy vessels not „perfect“ circles



[Schumann, 2006]

Multi-level Partition of Unity Implicits

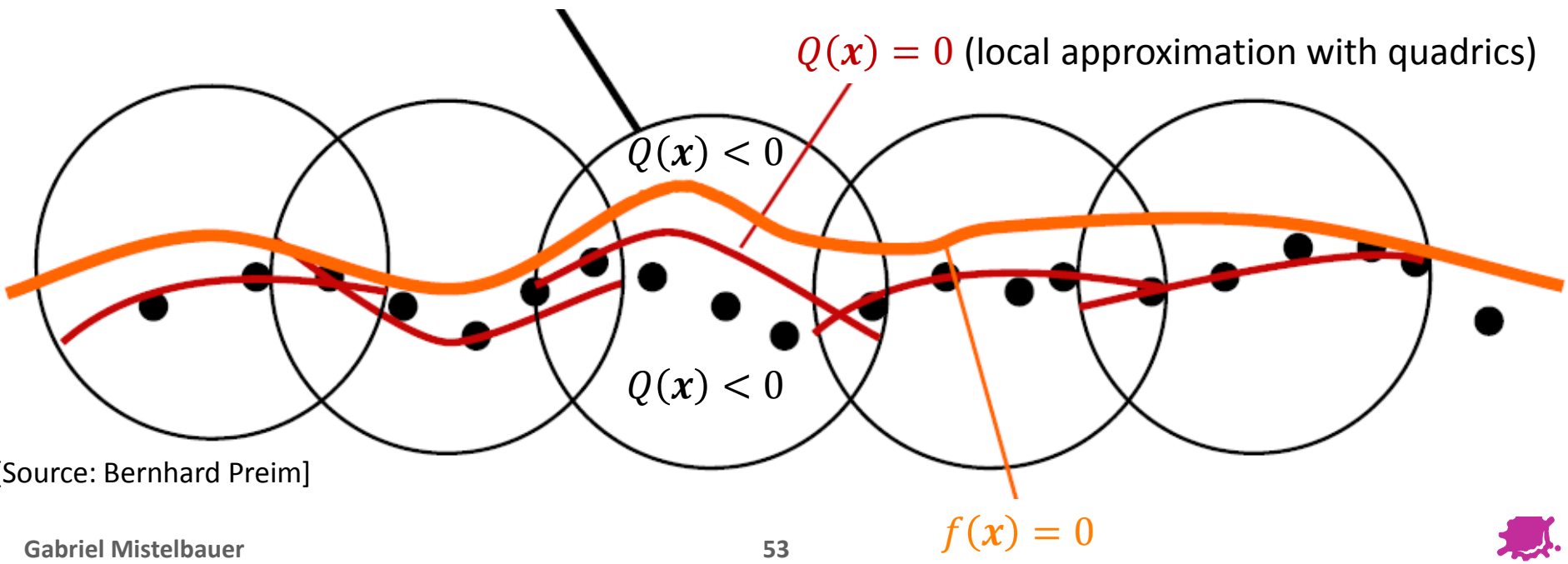
- Approximation of a point cloud with a surface
- Based on postprocessing of segmentation results
- Points placed in boundary voxels
- Able to construct arbitrary cross-sections
- Suitable for vessel analysis
- **Algorithm:**
  - Use octree for space subdivision
  - Locally approximate with the surface
  - Blending of local approx. → global approx.

Multi-level Partition of Unity Implicits

- Local approximation with quadrics
- Weighted average of local approximations

$$f(\boldsymbol{x}) = \frac{\sum w_i(\boldsymbol{x}) Q_i(\boldsymbol{x})}{\sum w_i(\boldsymbol{x})}$$

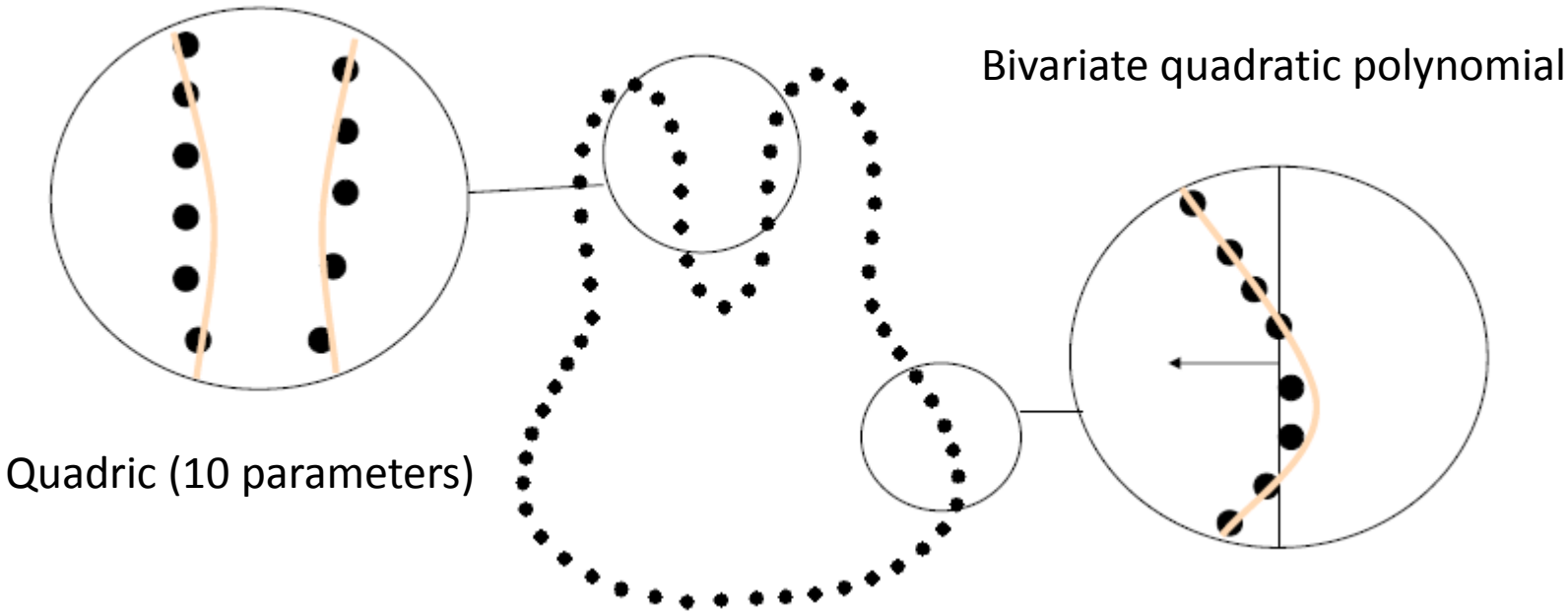
Support of $Q(\boldsymbol{x})$ using, e.g., a Gaussian weighting



[Source: Bernhard Preim]

Multi-level Partition of Unity Implicits

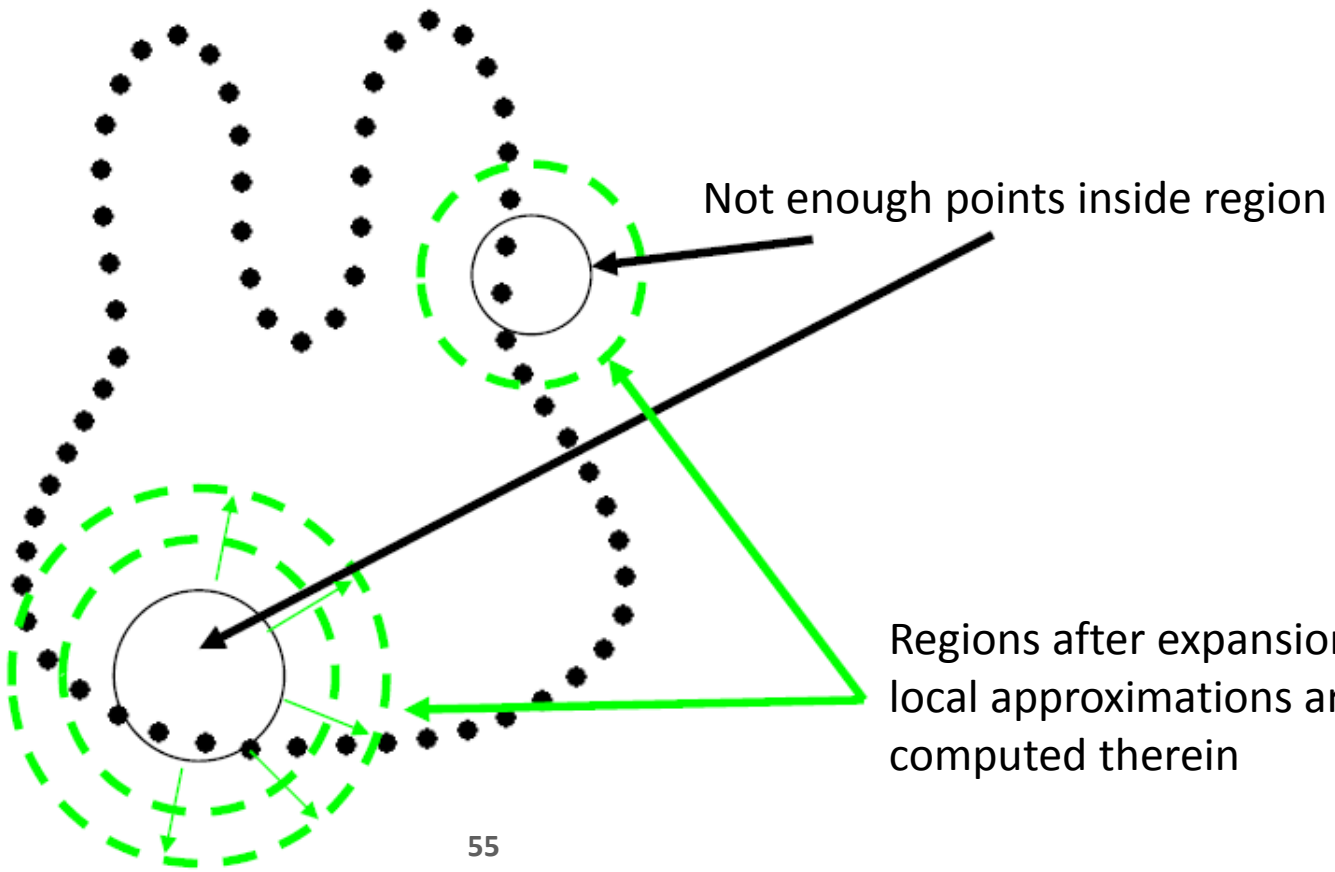
- Polynomial approximation (quadric) using the least-square method
- Adaptive subdivision according to the distributions of the normals



[Source: Bernhard Preim]

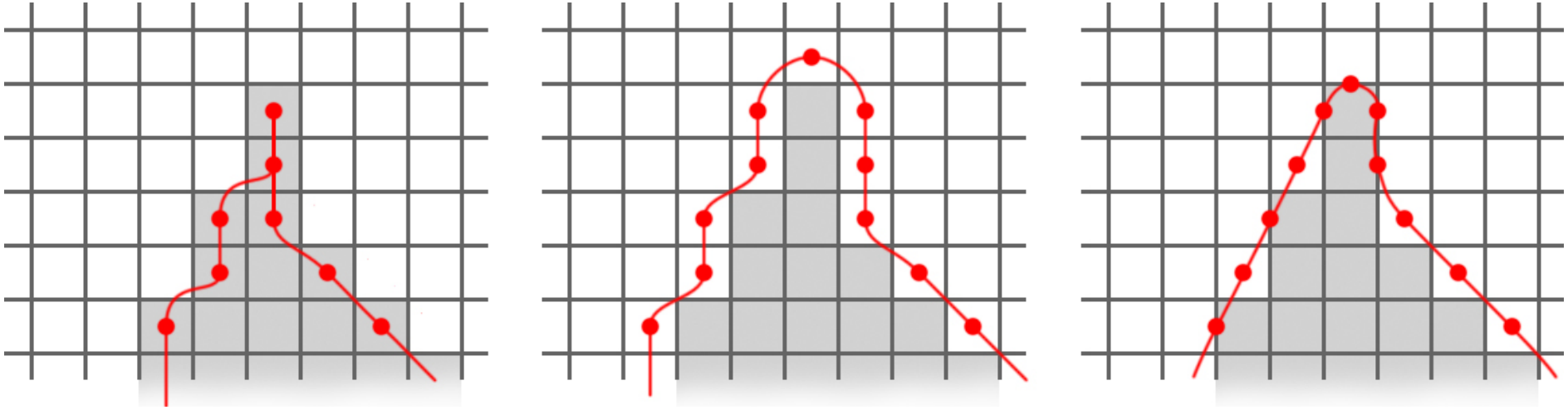
Multi-level Partition of Unity Implicits

- If not enough points inside local region → expand
- Parameters: Max. octree depth, initial size of region, region expansion rate



Model-Free Vessel Visualization: Special Cases

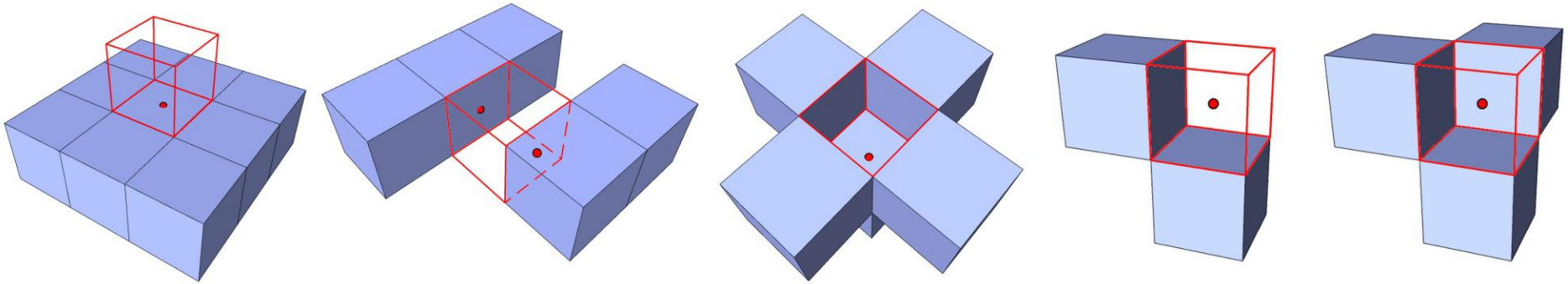
- **Problem:** Degeneration of thin vessels [Schumann et al., 2007]



Boundary voxels as initial positions for surface points

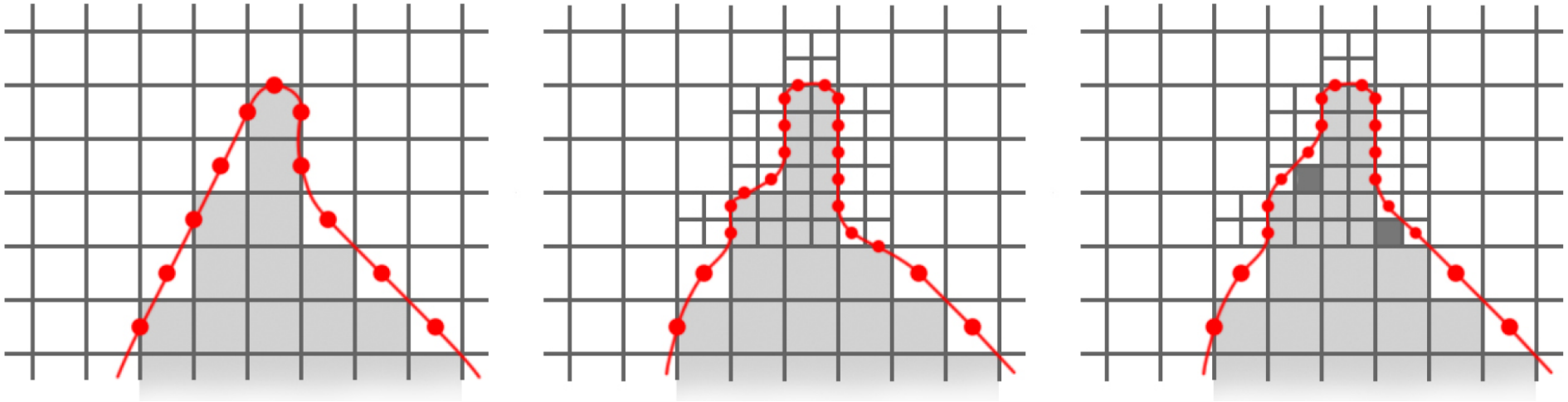
Ideal point distribution

- Several cases for point placement [Schumann et al., 2007]

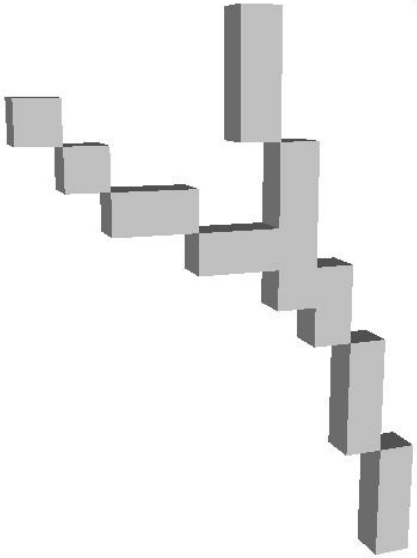


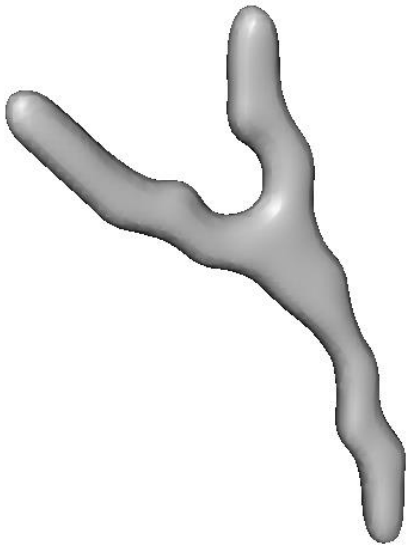
Model-Free Vessel Visualization: Special Cases

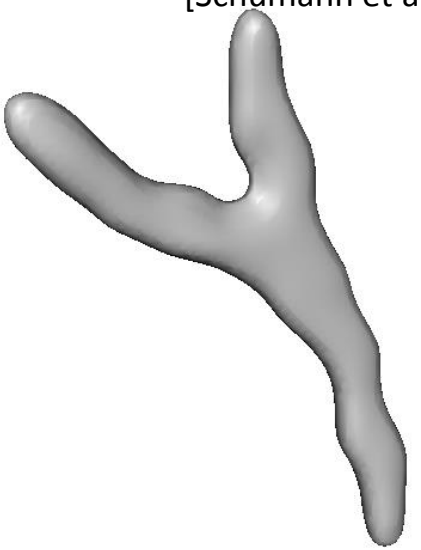
- **Solution:** Adaptive supersampling



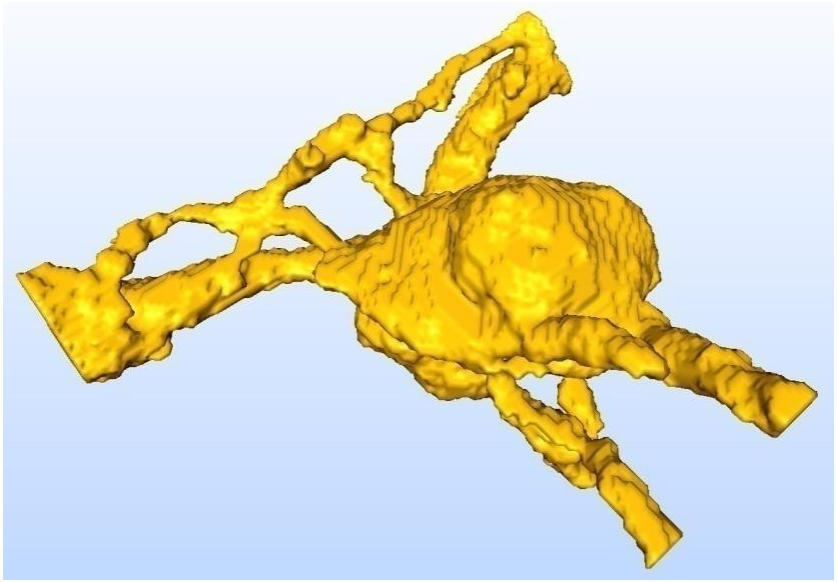
[Schumann et al., 2007]



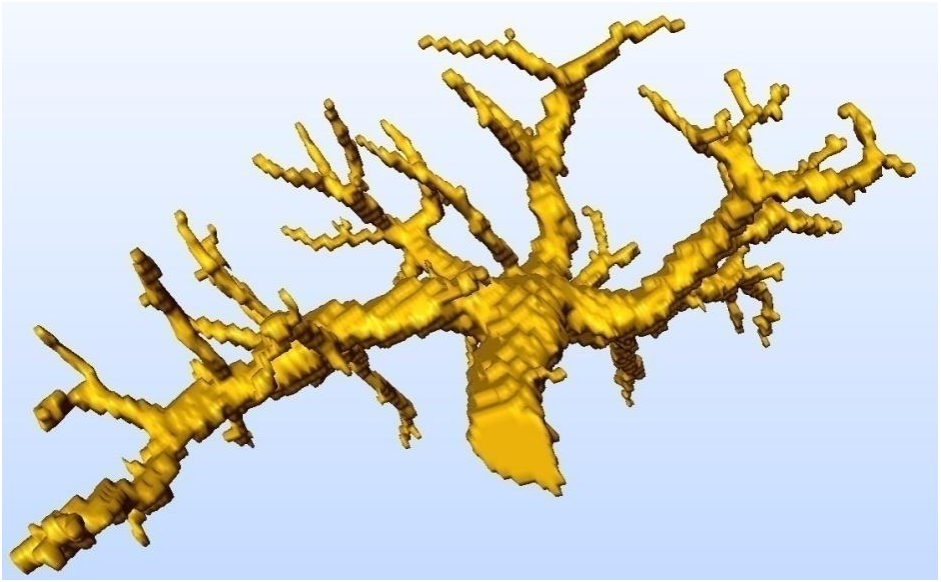


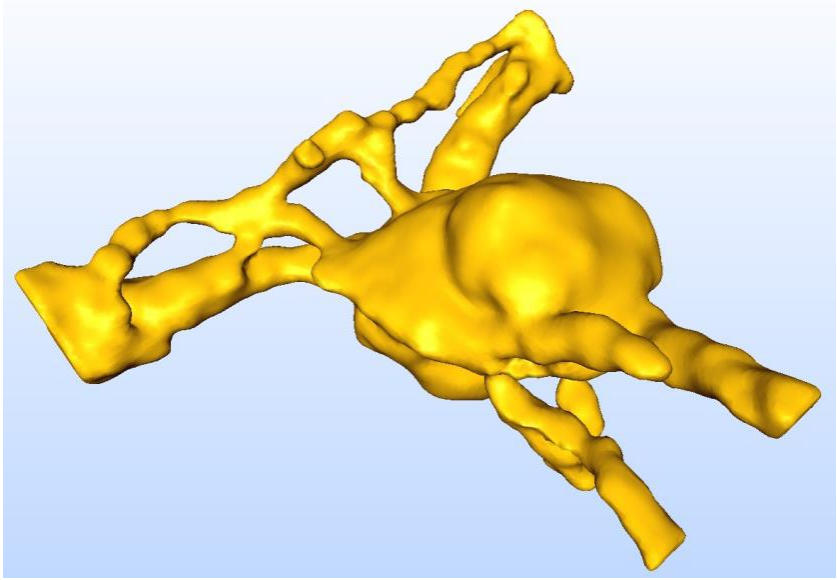


Model-Free Vessel Visualization – Results

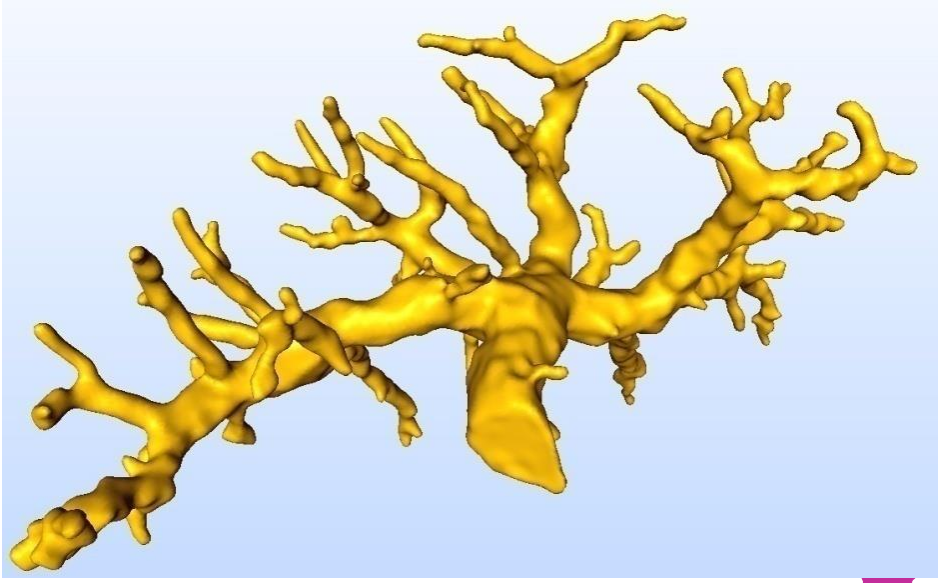


MC



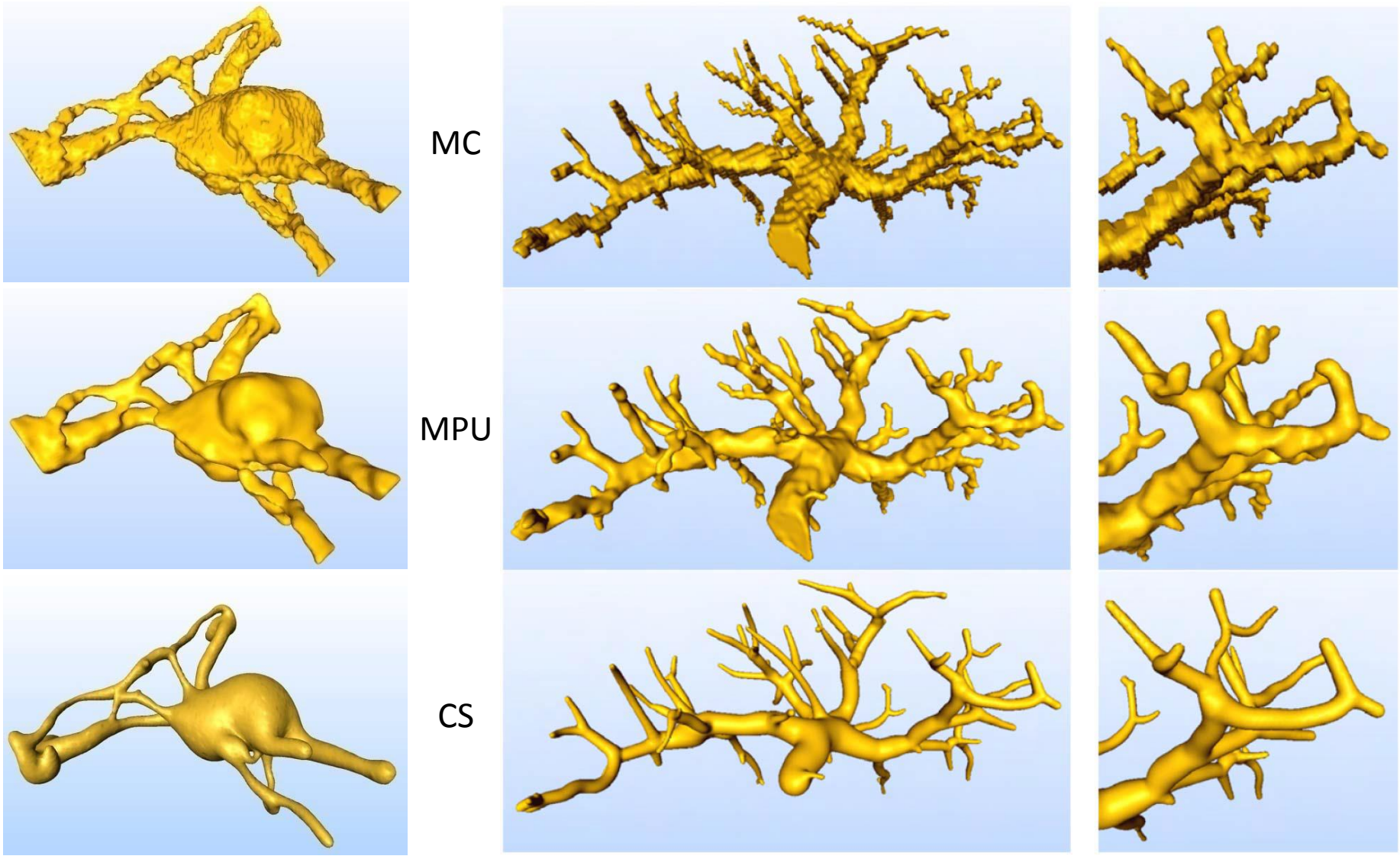


MPU



[Schumann, 2006, 2007]

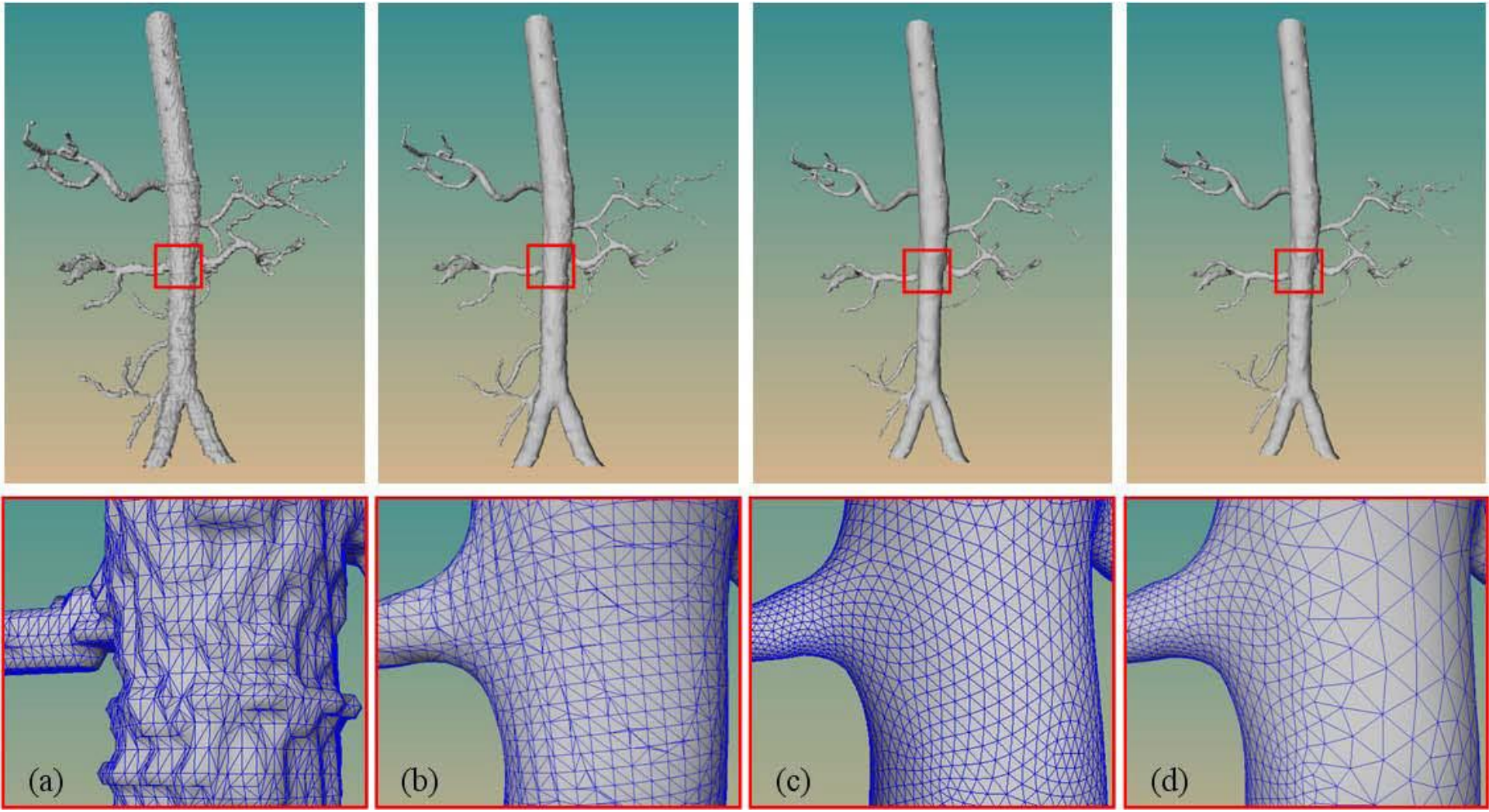
Model-Free Vessel Visualization – Results



[Schumann, 2006, 2007]

Curvature-Dependent Surface Visualization

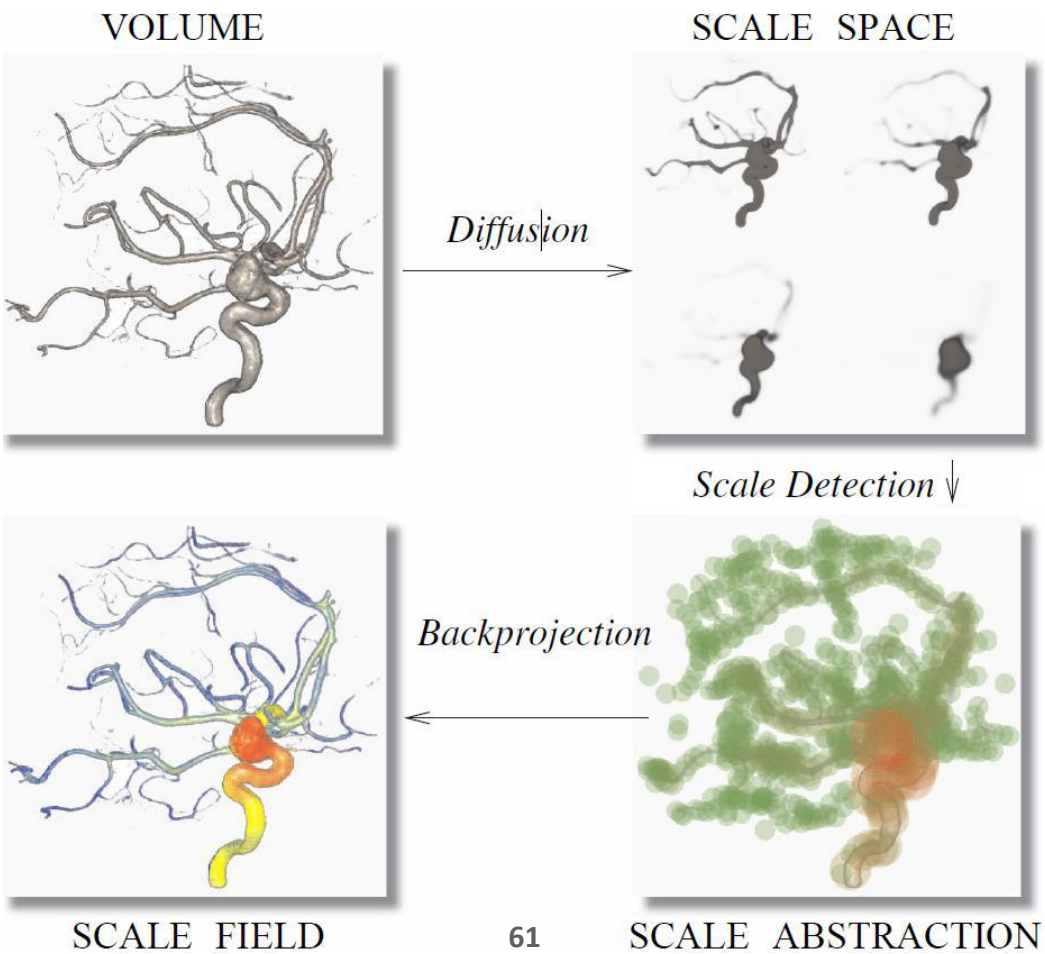
[Images: Bernhard Preim]



MC MPU CS [Wu, 2010]

Size-based Transfer Functions

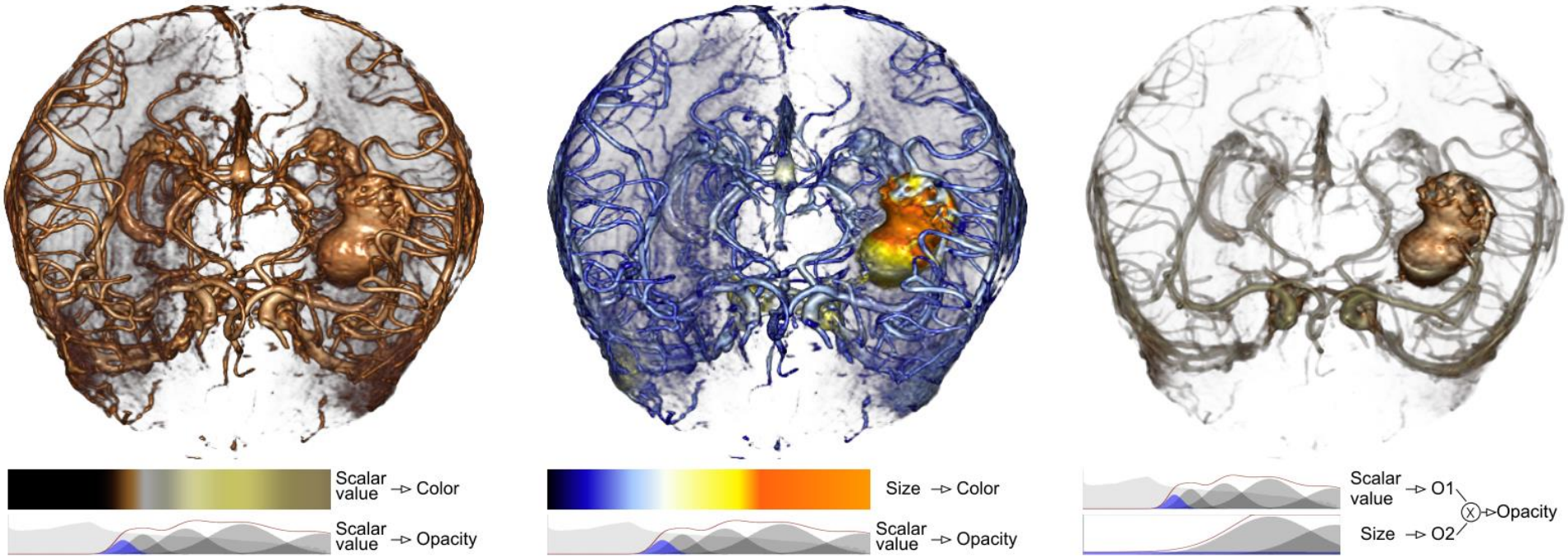
- Map color and opacity to the size of a feature
- Use multi-scale analysis to determine the size



[Correa and Ma 2008]

Size-based Transfer Functions

- Incorporate the size into the transfer function
- Color-code features according their size
- Opacity modulate using the size

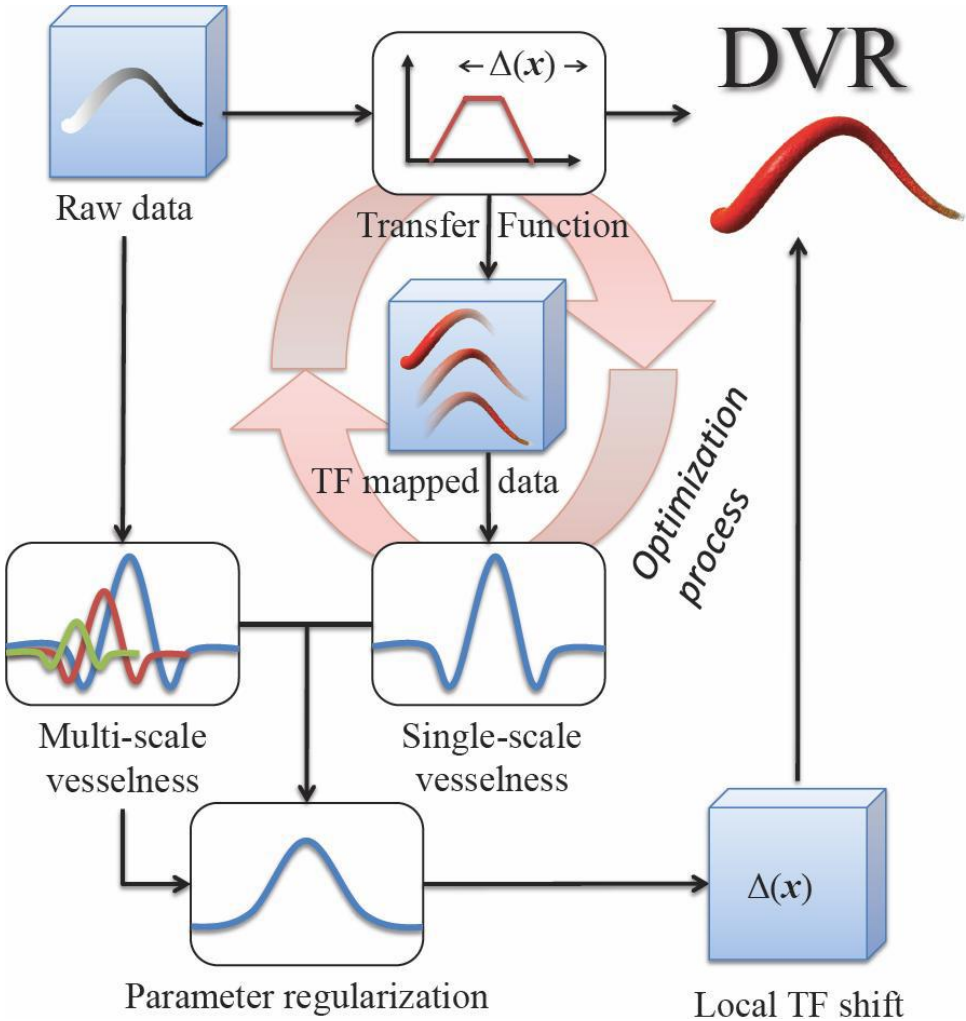


[Correa and Ma 2008]

Spatially Varying Transfer Funtions

- Vessels not uniformly enhanced (by contrast agent)
  → Partially rendered

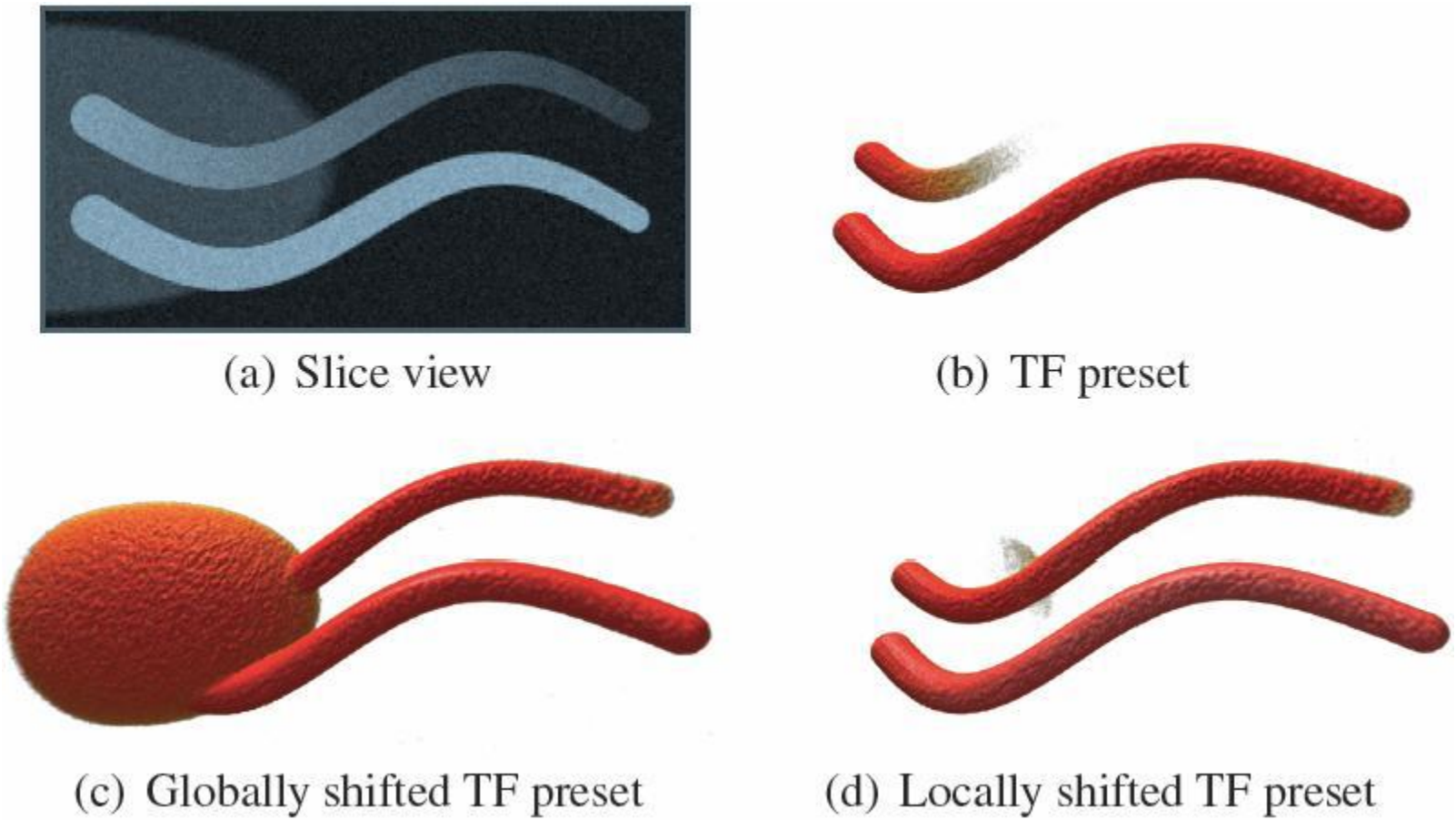
- Shift tranfer function according to the vesselness



[Laethen et al. 2012]

Spatially Varying Transfer Funtions

- Global vs. local transfer function shifting



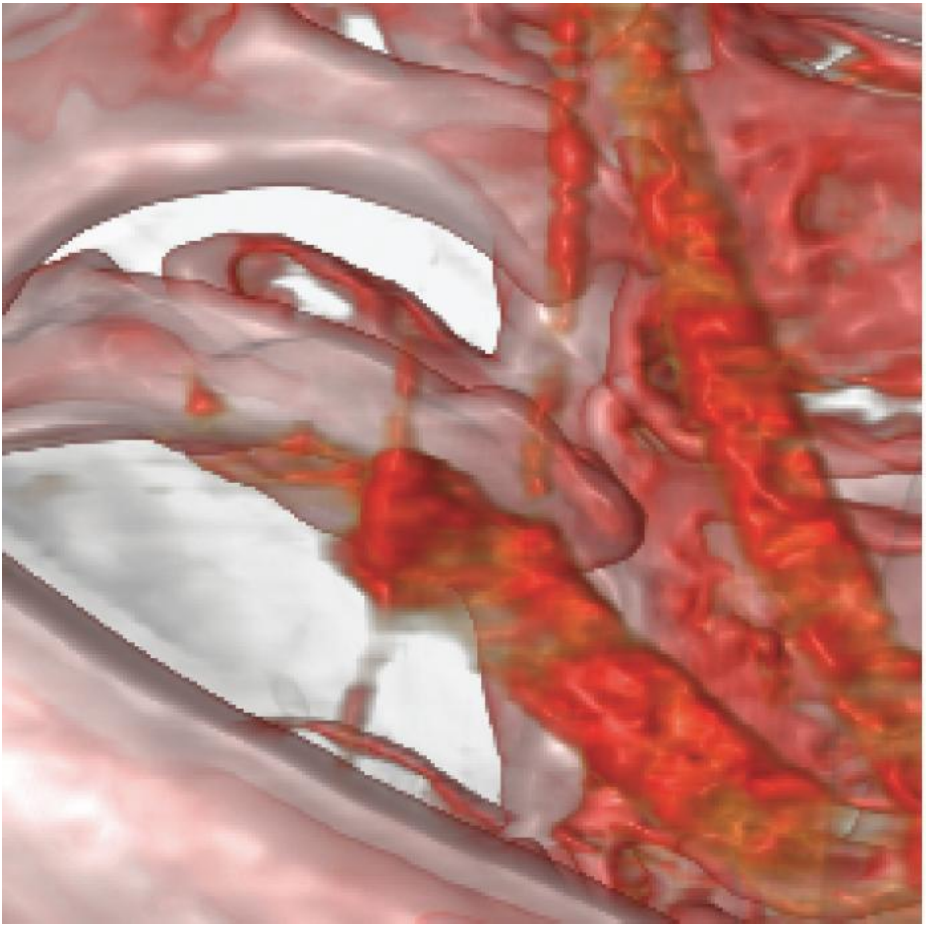
(a) Slice view (b) TF preset

(c) Globally shifted TF preset (d) Locally shifted TF preset

[Laethen et al. 2012]

Spatially Varying Transfer Funtions

[Laethen et al. 2012]



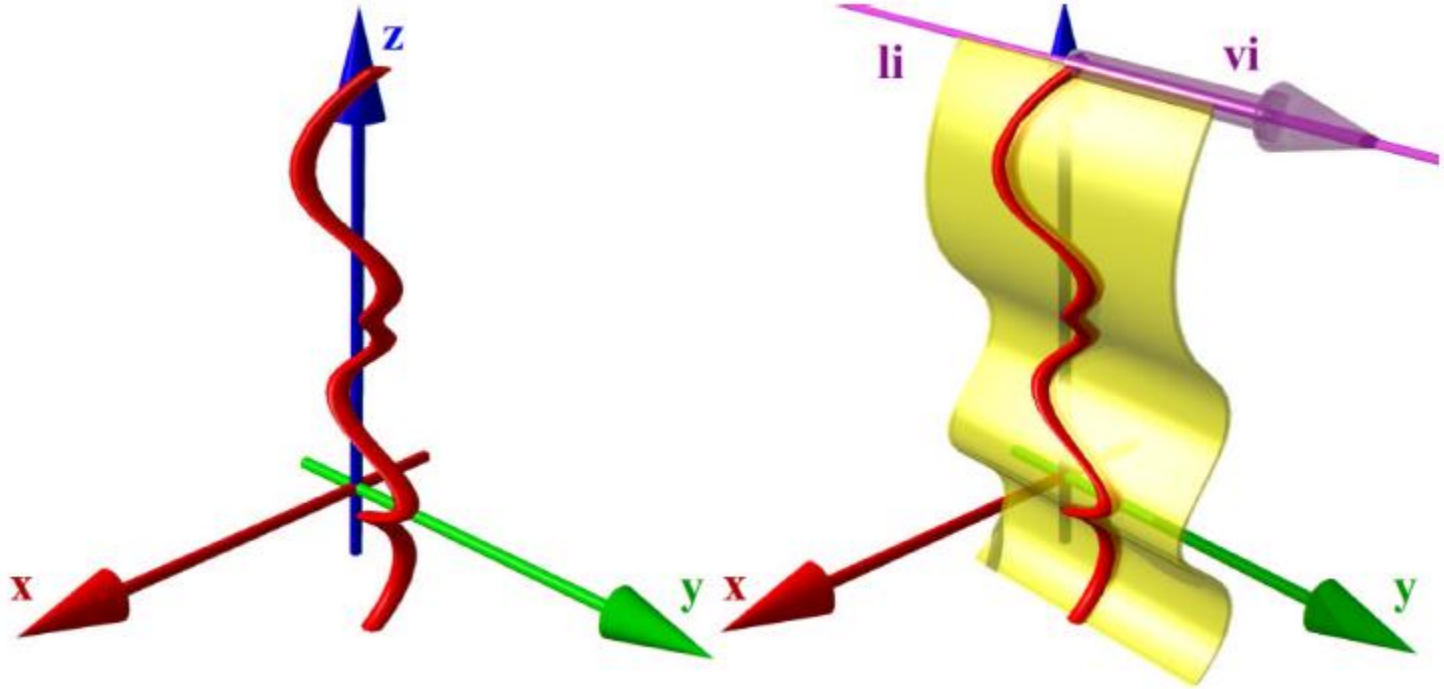
Original

Shifted transfer function

Diagnostic Visualization

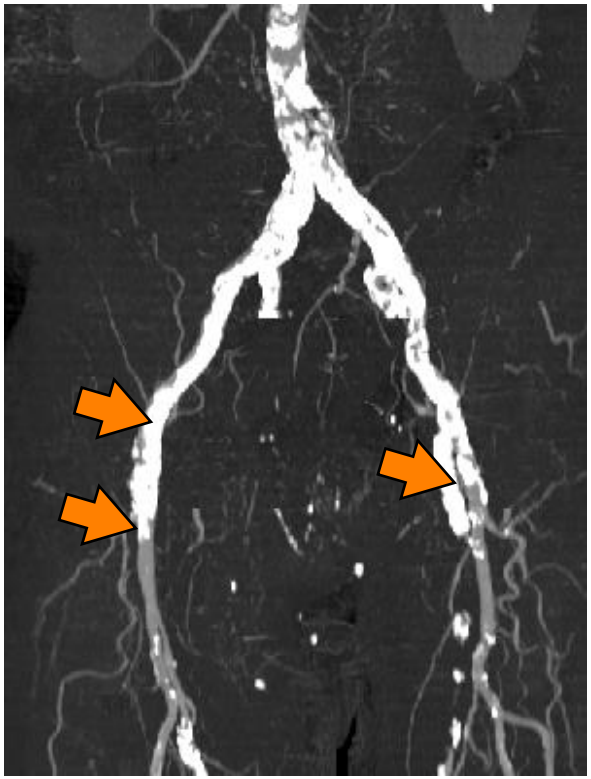
Curved Planar Reformation

- **Goal:** Investigate the vessel interior (= lumen)
- Cut surface along the vessel centerline
- Rotation around one predominant direction

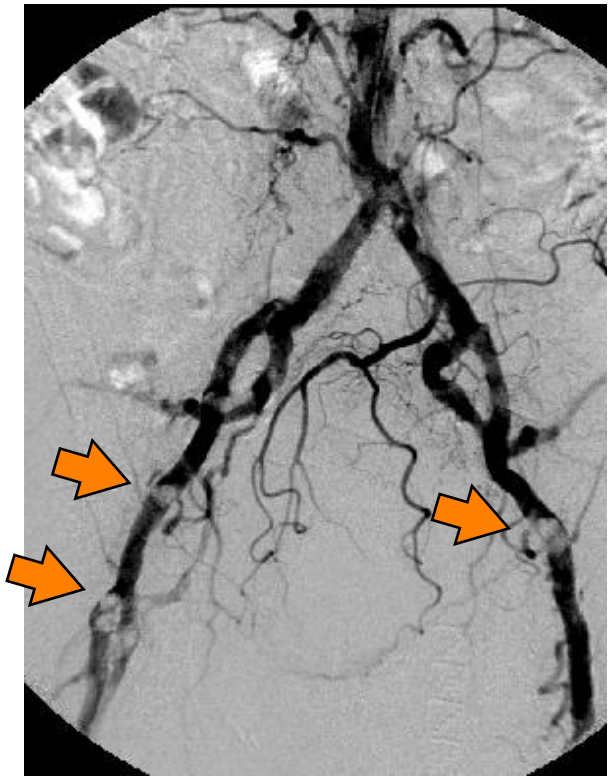


[Kanitsar et al. 2002]

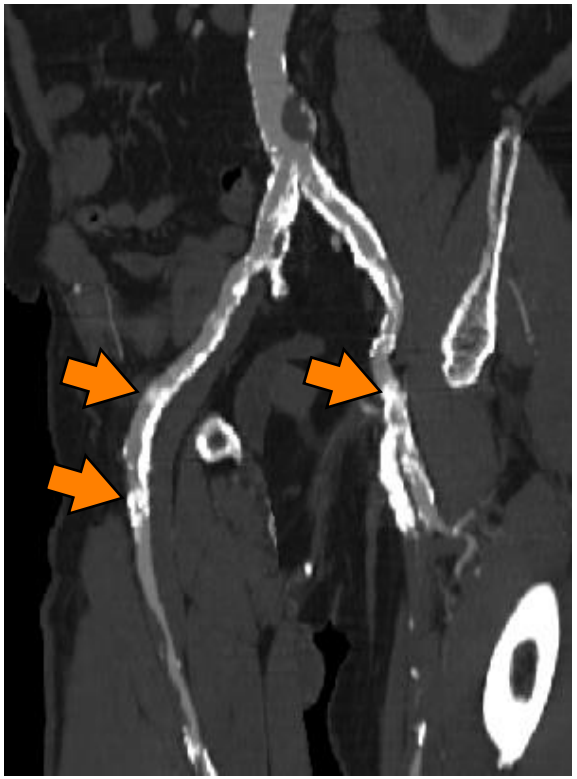
Curved Planar Reformation



MIP



DSA

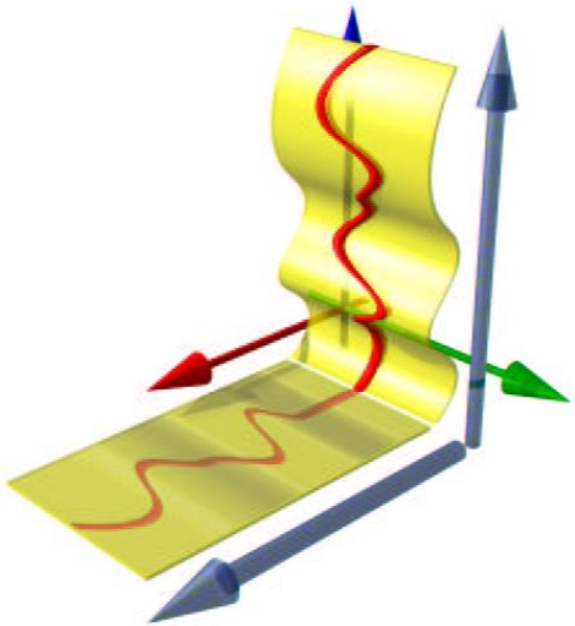


CPR

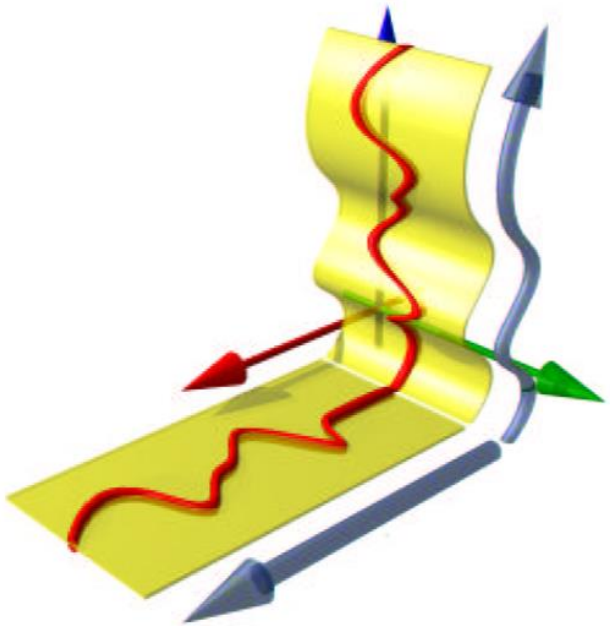
Curved Planar Reformation

- Different types

[Kanitsar et al. 2002]

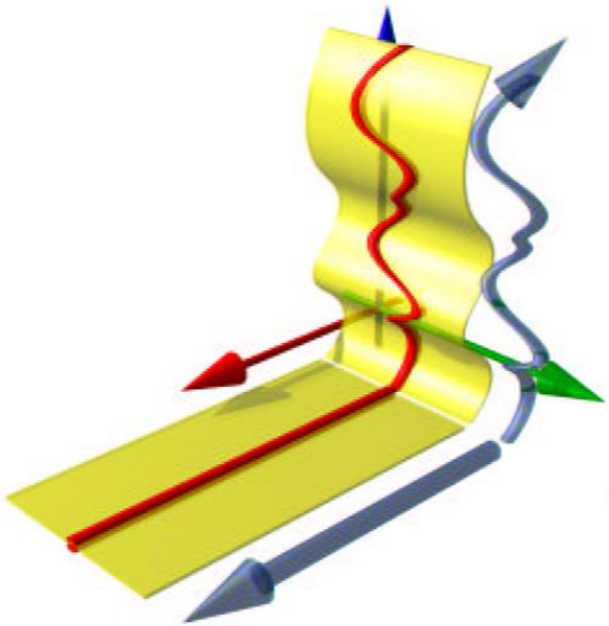


Projected CPR



Stretched CPR

No occlusions



Straightened CPR

Vessel straightened to a line

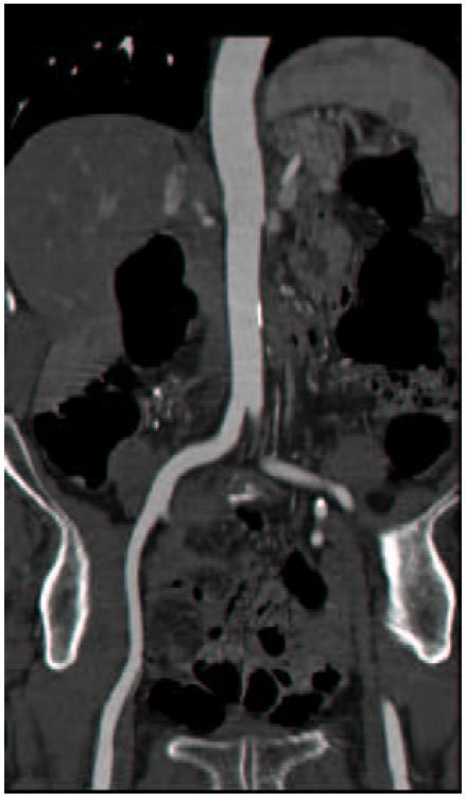
No occlusion

Curved Planar Reformation

[Images: Kanitsar et al. 2002]

Projected CPR 0°

Projected CPR 90°

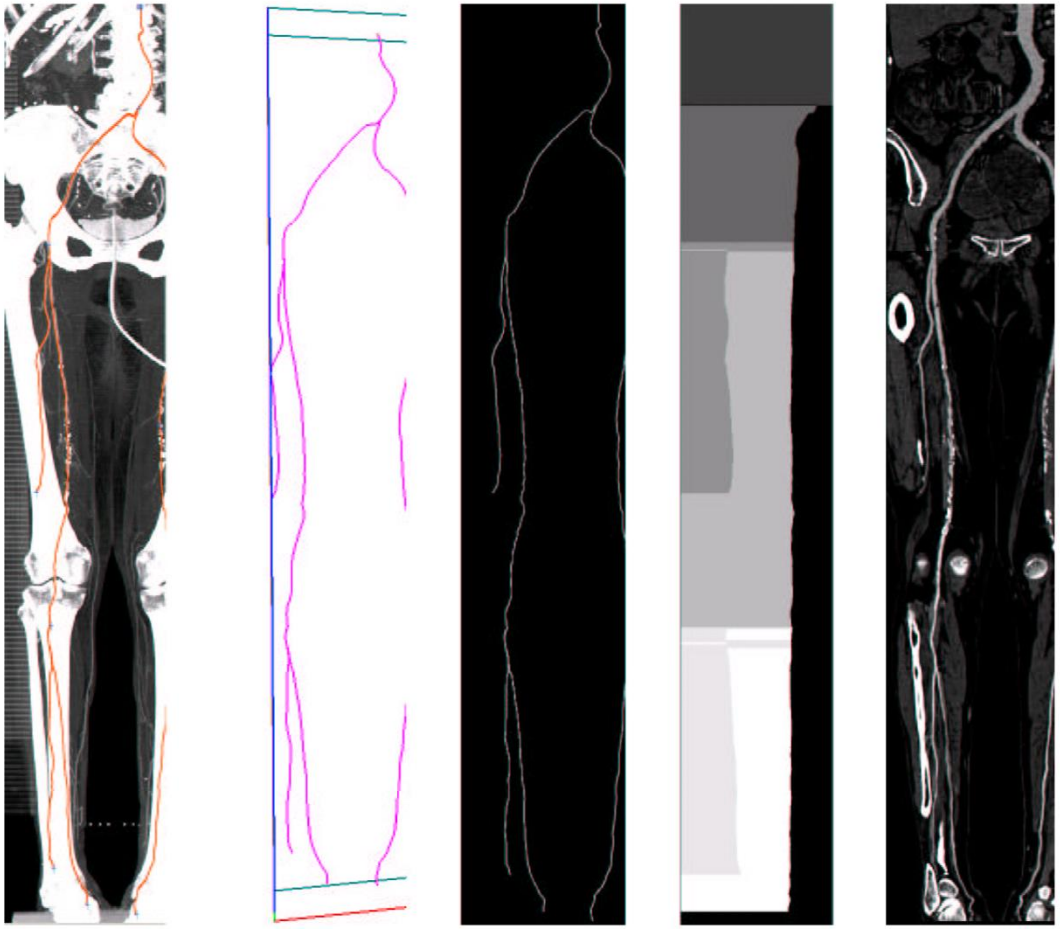


Stretched CPR 0°

Stretched CPR 90°

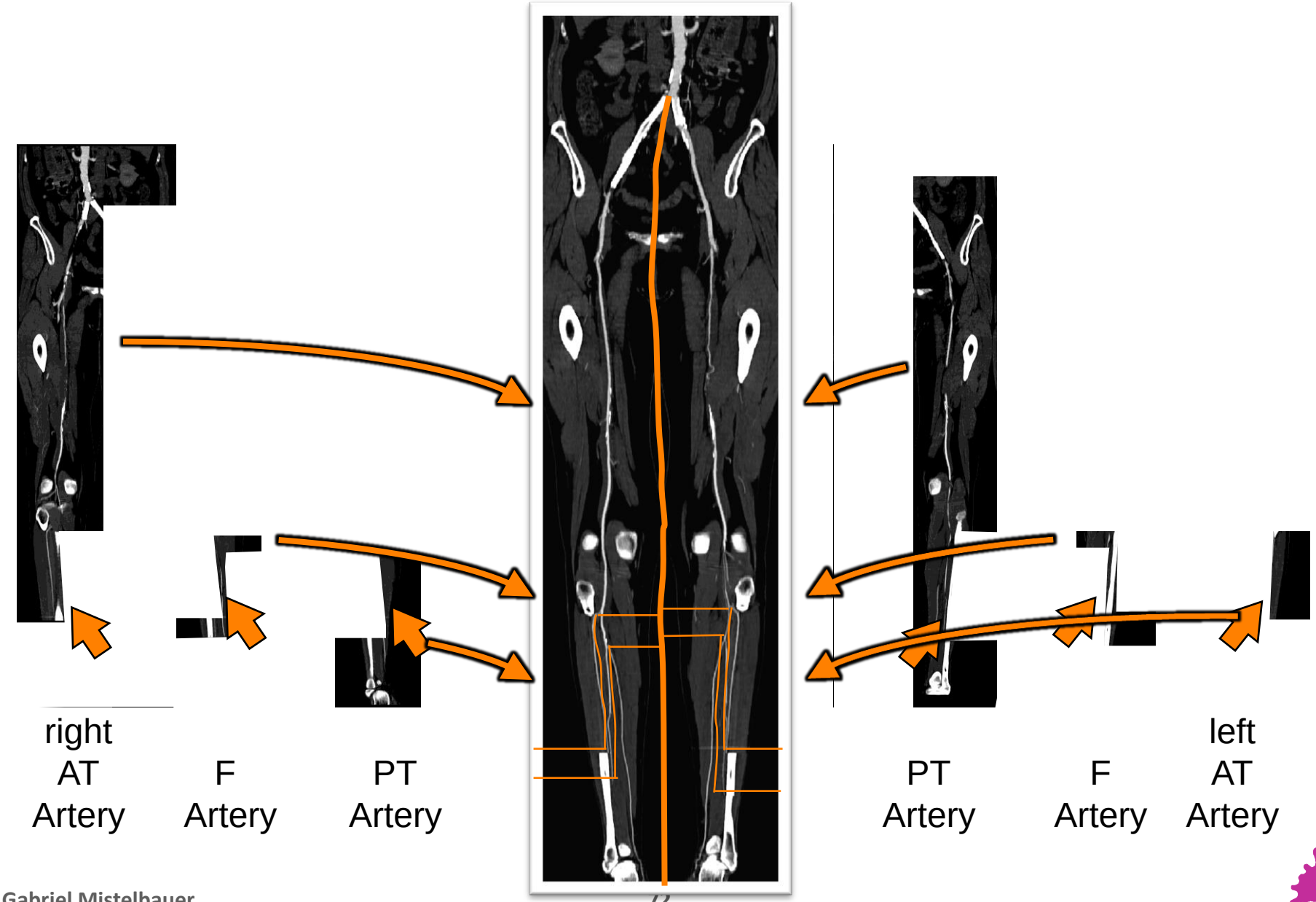
Multi-path Curved Planar Reformation

- Computes CPR for every vessel segments
- Combined into one image in image-space



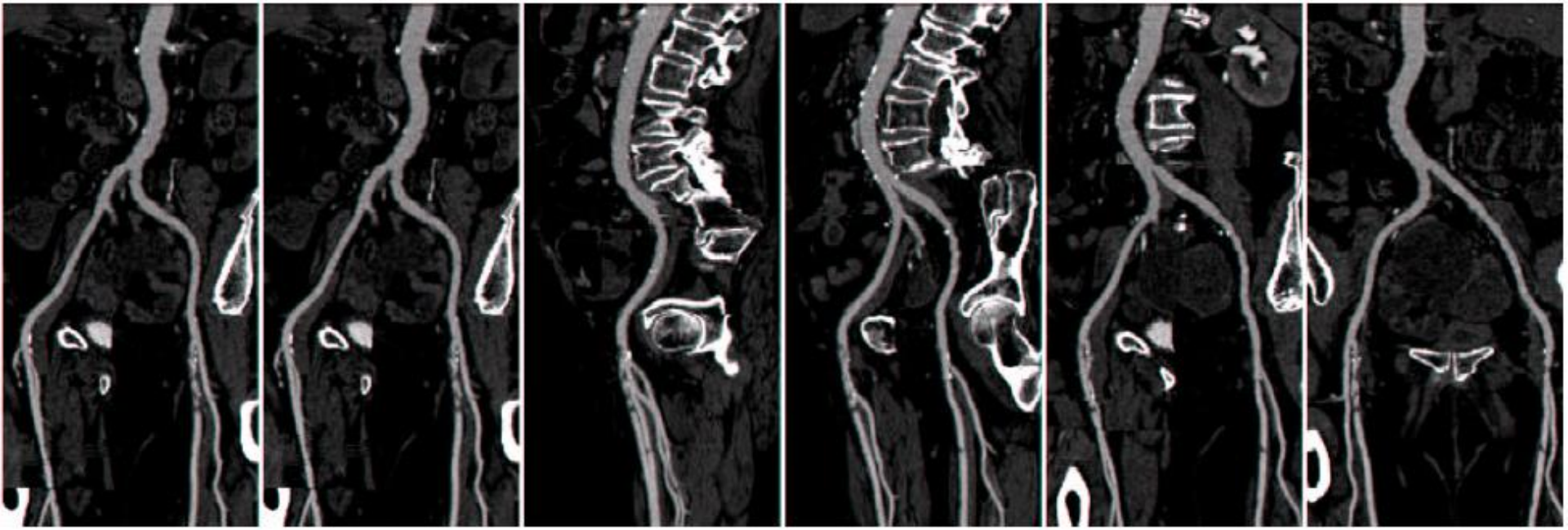
[Kanitsar et al. 2002]

Multi-path Curved Planar Reformation



Multi-path Curved Planar Reformation

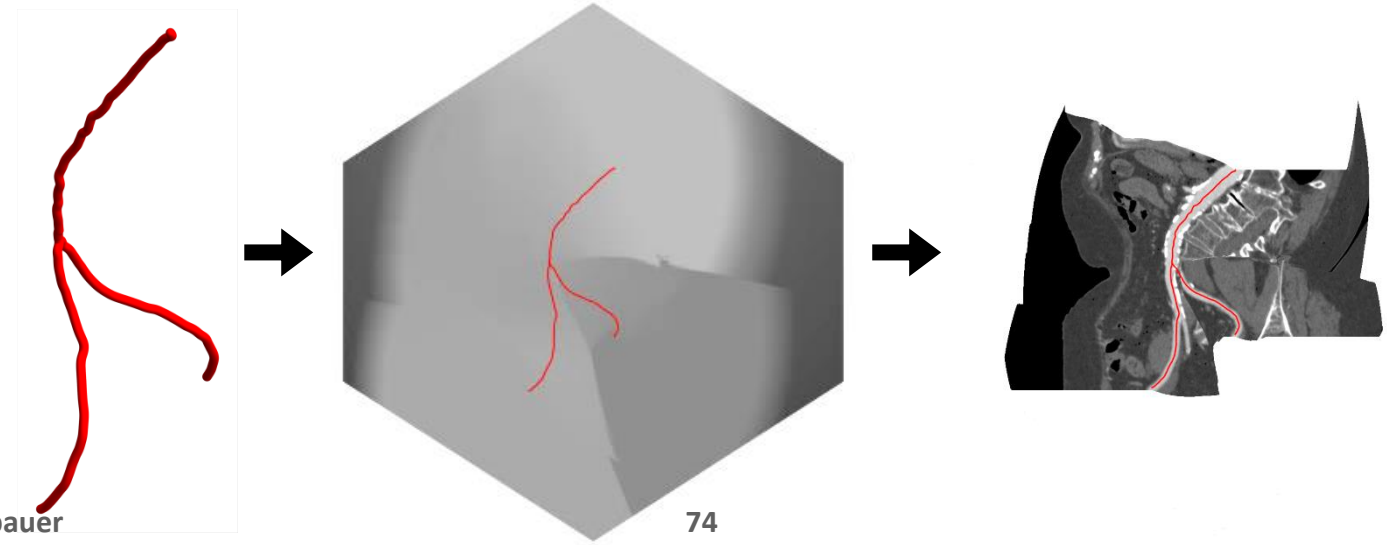
- Either projected or stretched
- Example of projected mpCPR at 30°, 60°, 90°, 120°, 150°, 180°:



[Kanitsar et al. 2002]

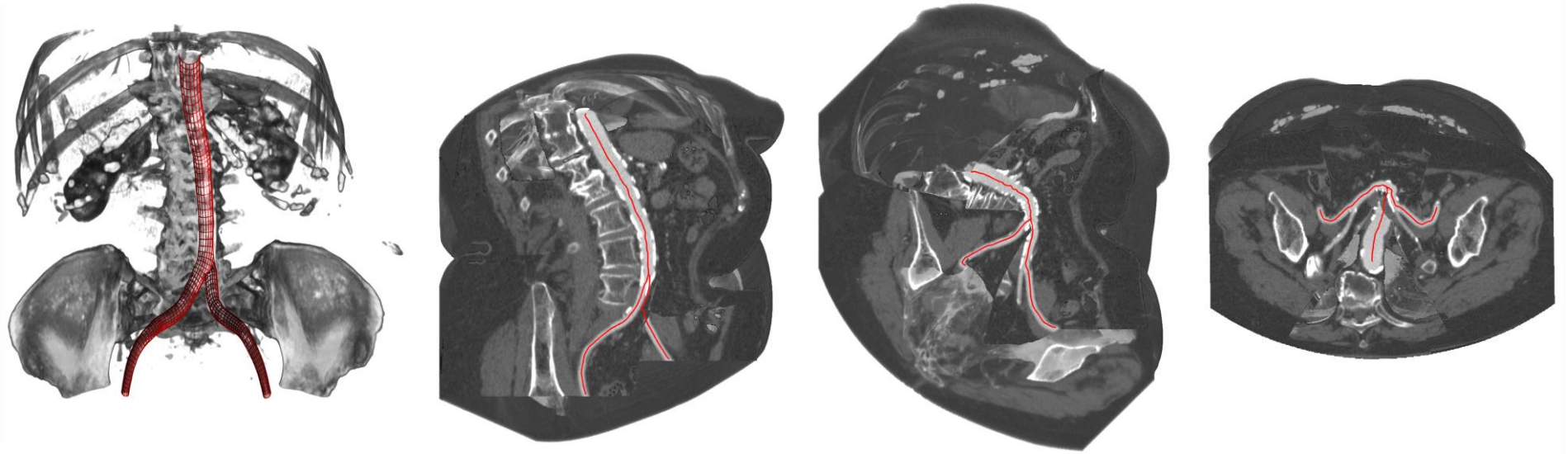
Curved Surface Reformation

- Belongs to projected CPRs
- A vessel is more relevant...
  - ...the closer it lies to viewer
  - ...the farther it is away from an occlusion
- Cost function penalizes distance along view direction and normal to it

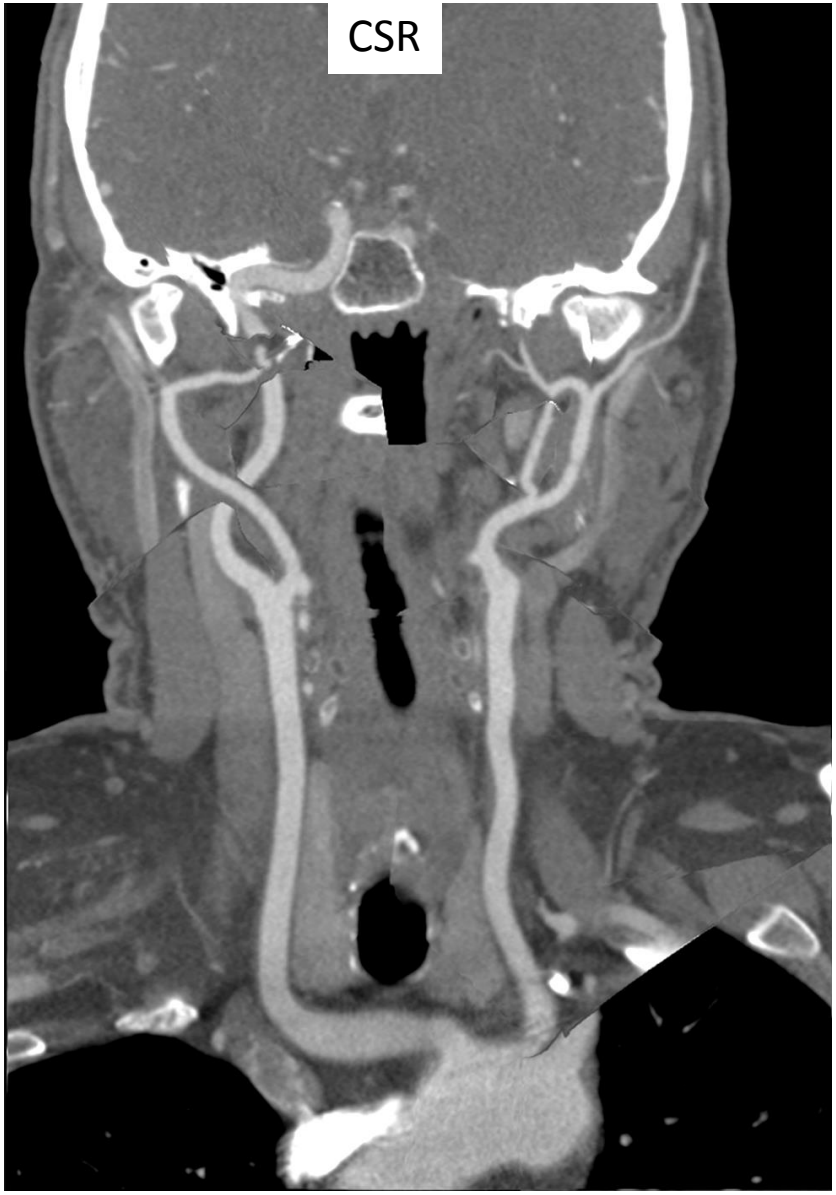


Curved Surface Reformation

- Improves CPR by allowing free navigation
- Preserves correct visibility of multiple vessels
- Fully 3D approach, not image-based
- Optionally render volume outside surface



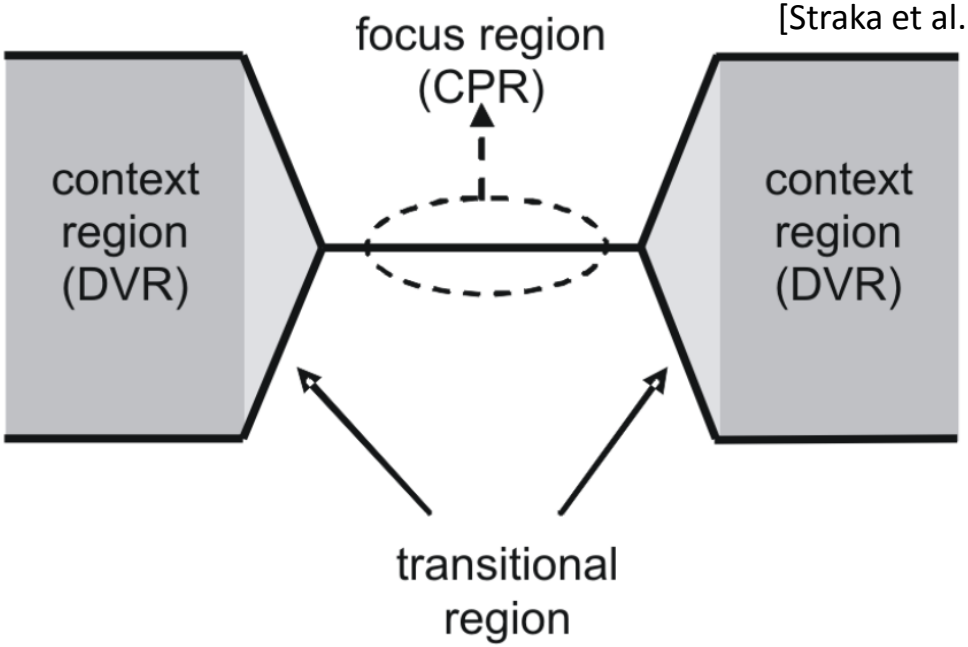
Curved Surface Reformation



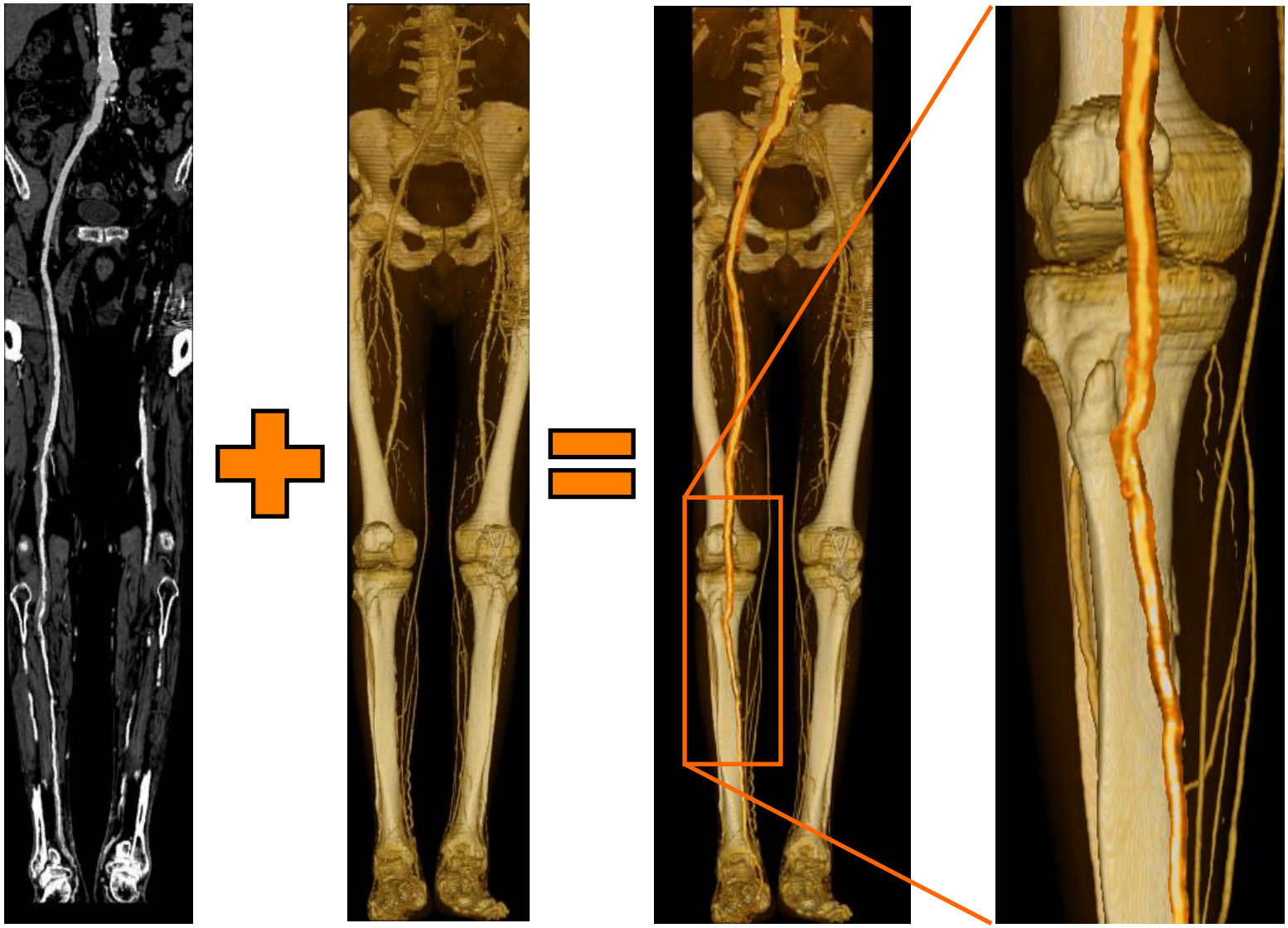
VesselGlyph

- Combine DVR (context) and CPR (focus)
- Generalization of various visualization techniques (VR, CPR, MIP, …)
- Displays un-occluded objects in a correct anatomic context

[Straka et al. 2004]



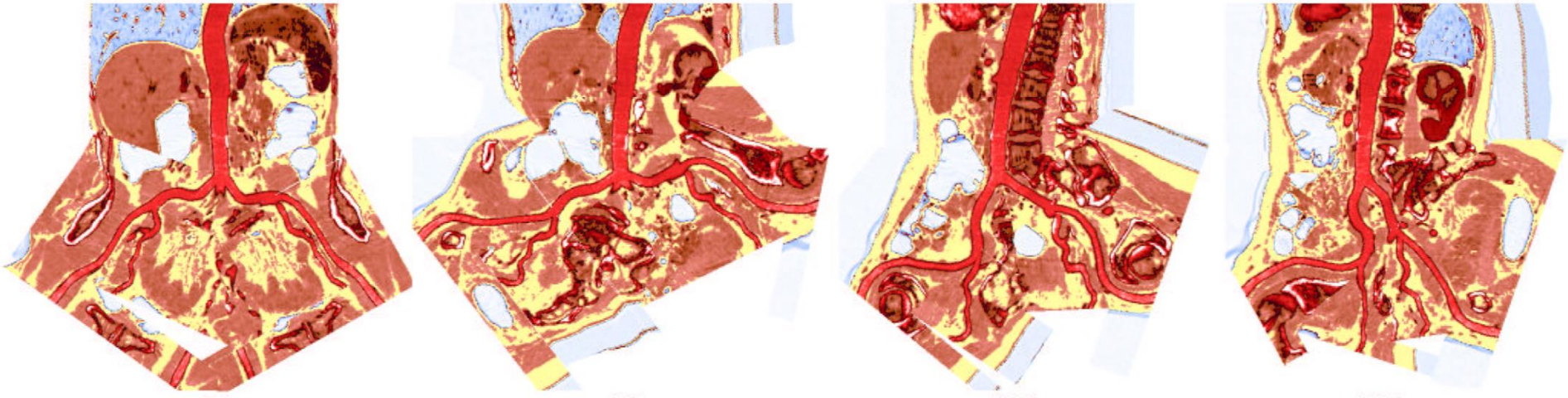
VesselGlyph



[Straka et al. 2004]

Untangled Curved Planar Reformation

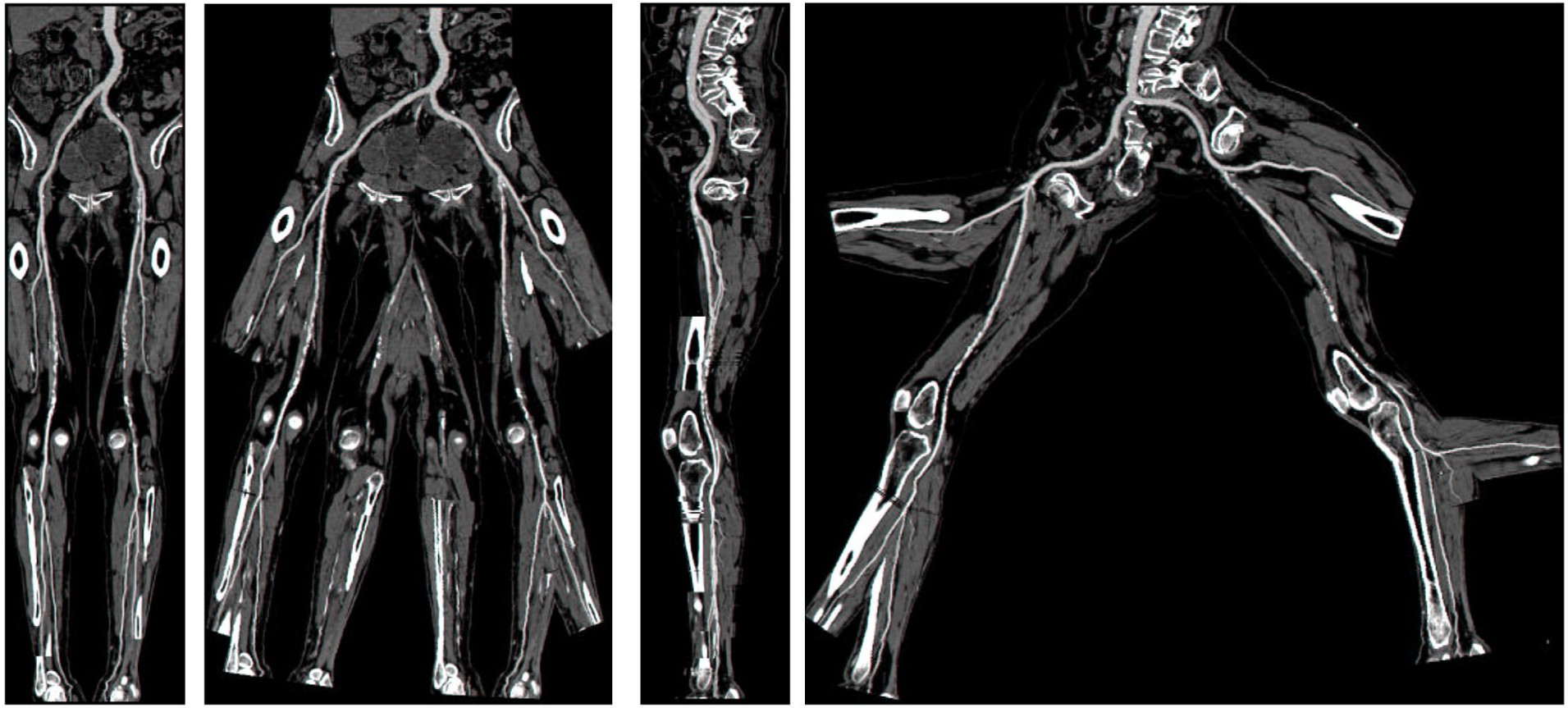
- **Goal:** Present CPRs of entire vascular tree without any occlusion
- Vessel segments projected into image-space
- Subsequently, stretched CPRs arranged such that the intersections of their convex hulls are minimized



[Kanitsar et al. 2003]

Untangled Curved Planar Reformation

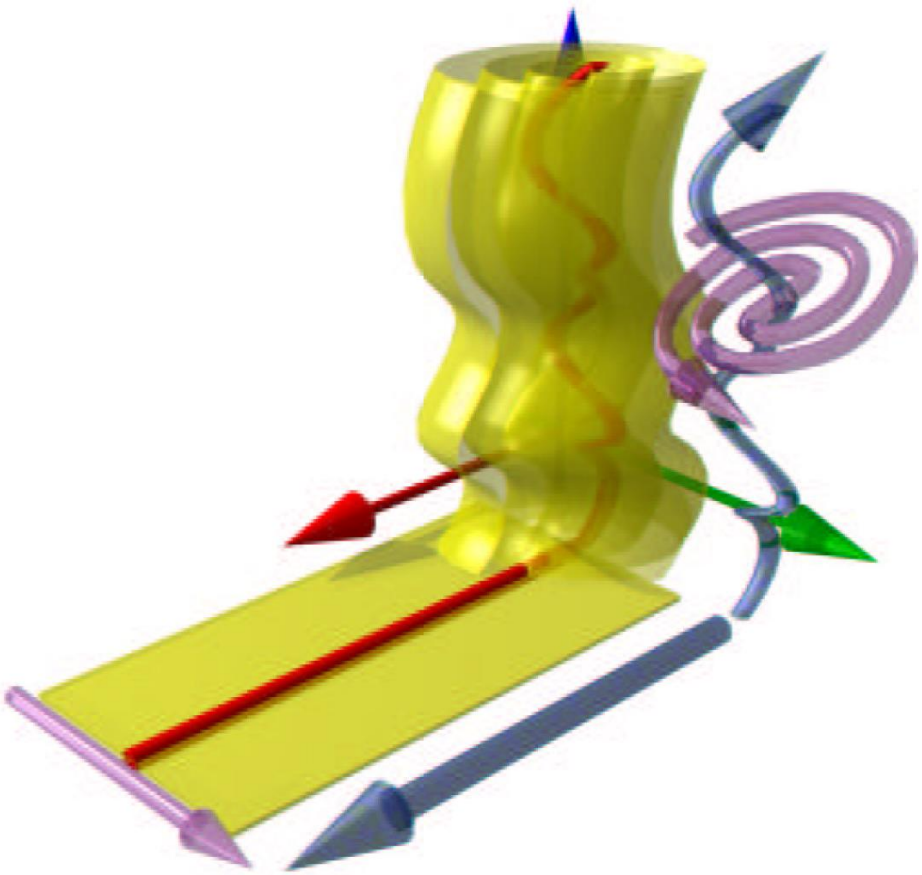
[Kanitsar et al. 2003]



mpCPR untangled CPR mpCPR untangled CPR

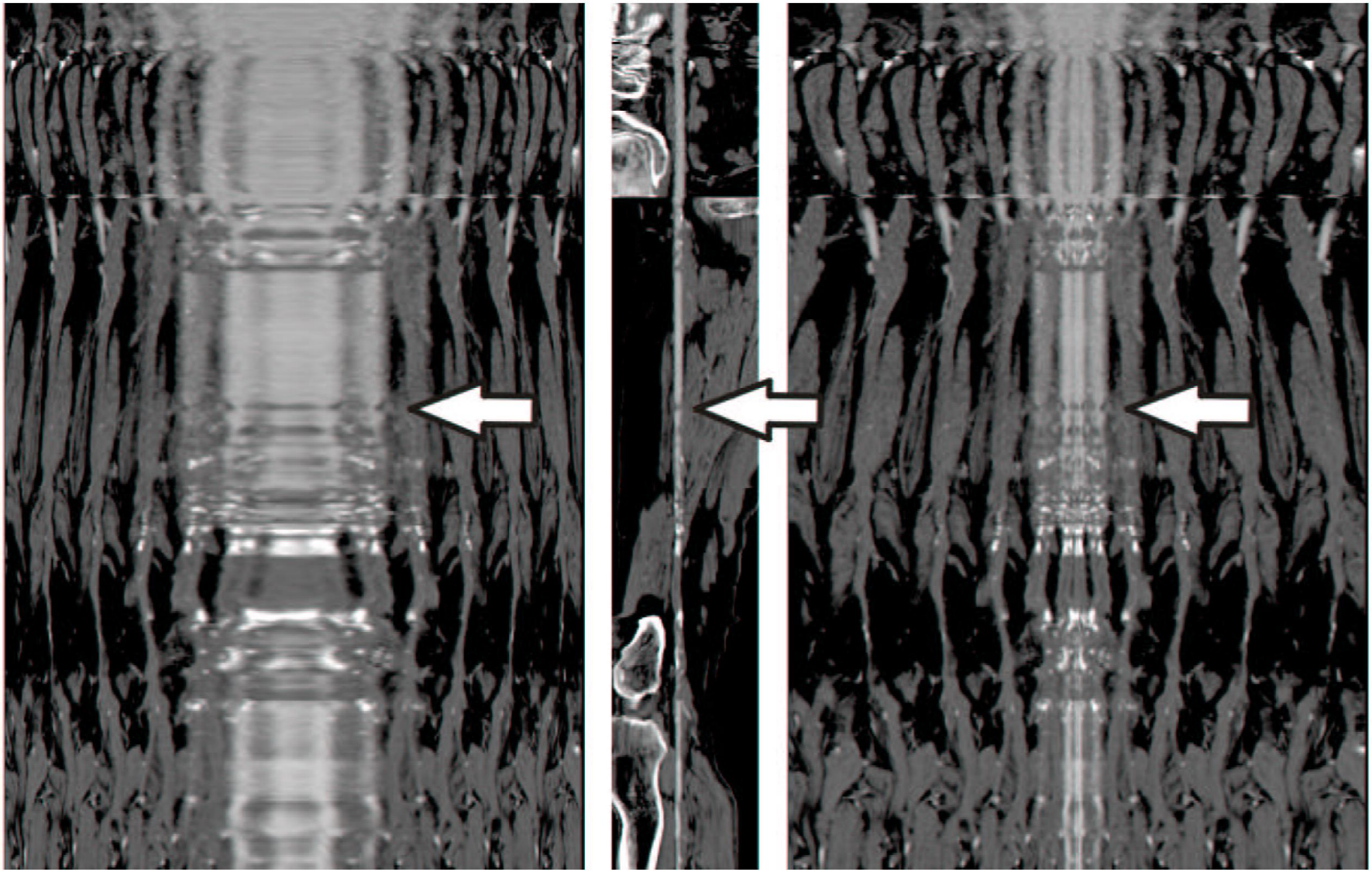
Helical Curved Planar Reformation

- Displays the interior of a vessel within a single image
- Surface flattened
- Rotation unnecessary



[Kanitsar et al. 2003]

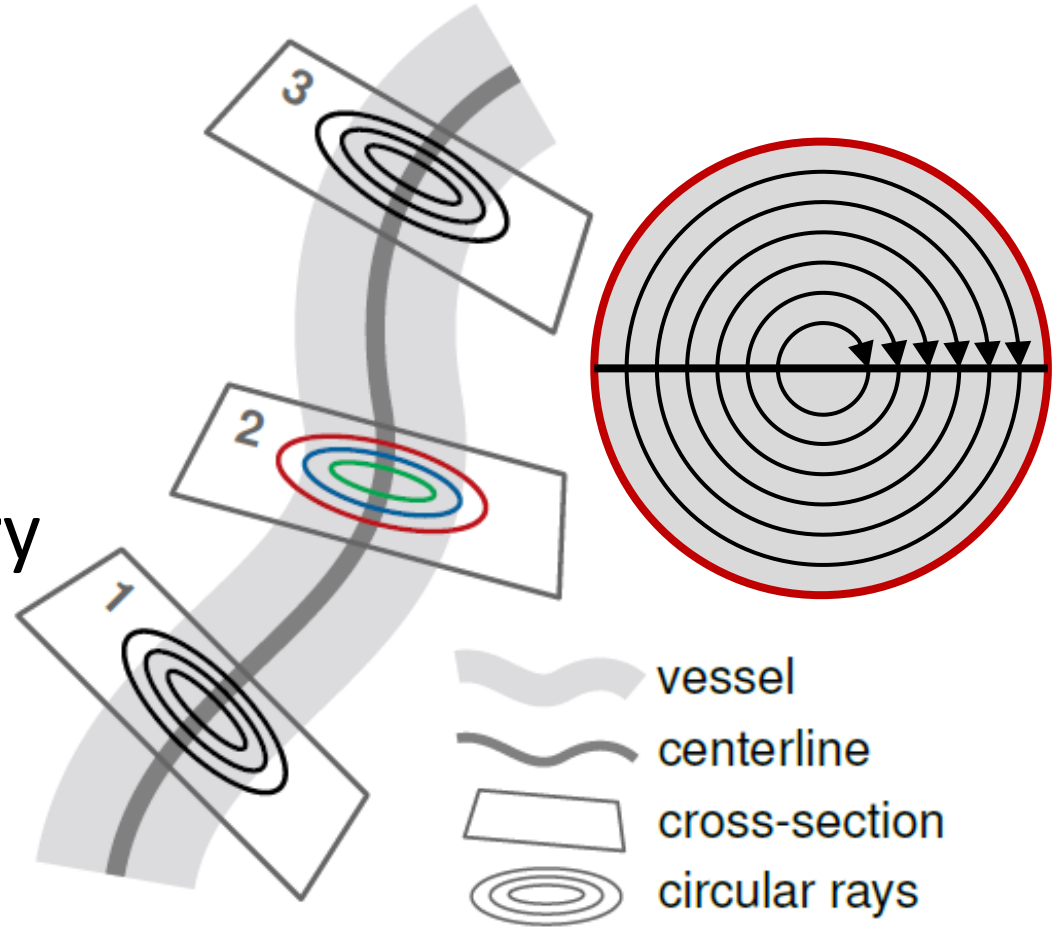
Helical Curved Planar Reformation



[Kanitsar et al. 2003]

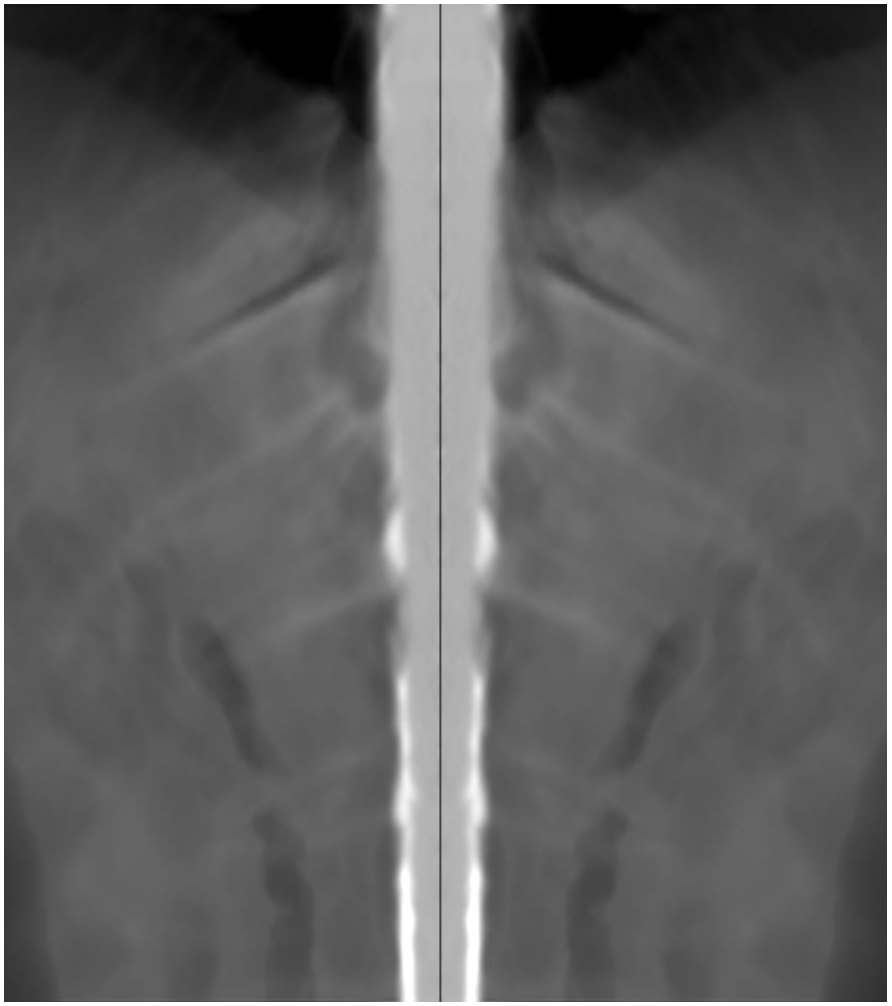
Curvicircular Feature Aggregation

- Nonlinear raycasting
- Circular rays
- Aggregates rotated CPRs into a single image
- Rotation unnecessary
- Vessels straightened



Curvicircular Feature Aggregation

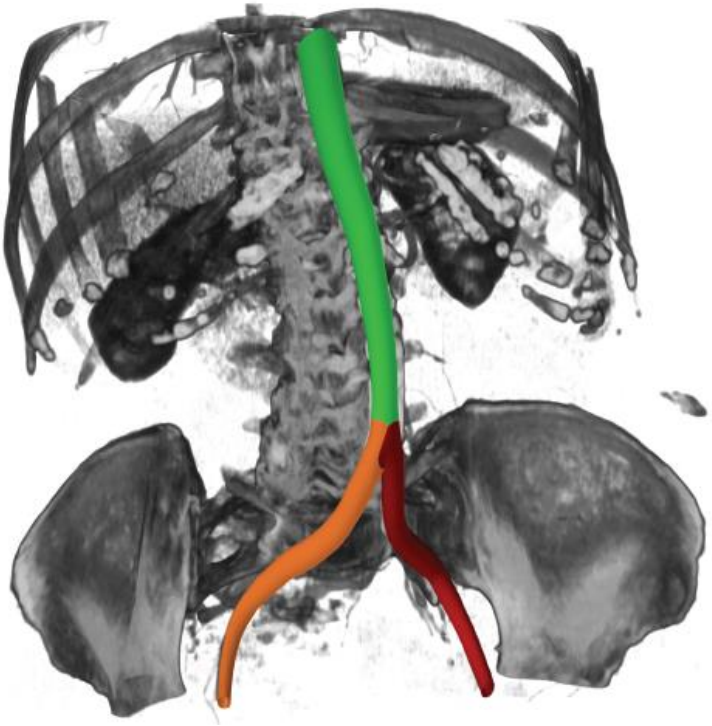
MIP MinIP

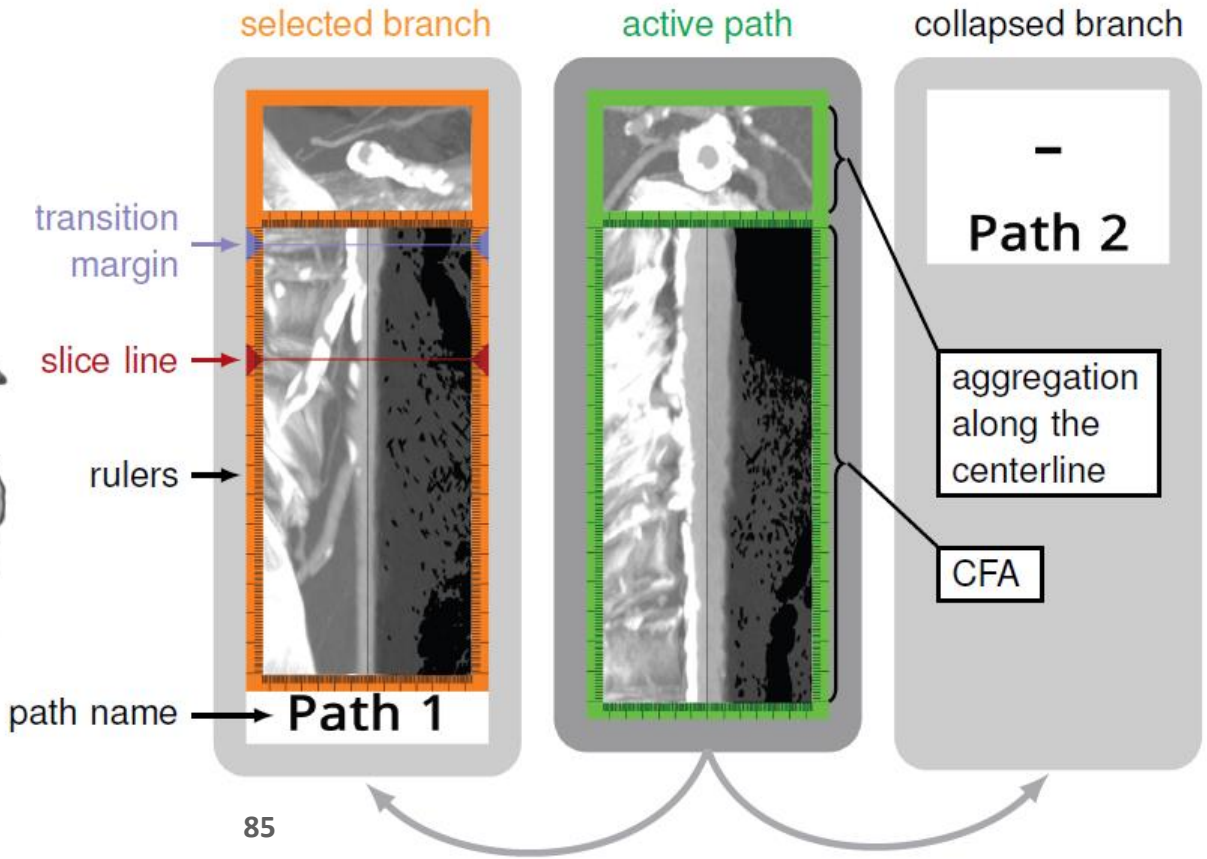


AVG AVG

Curvicircular Feature Aggregation

- Anatomical Layout
- Vessels grouped and presented according to their anatomical position

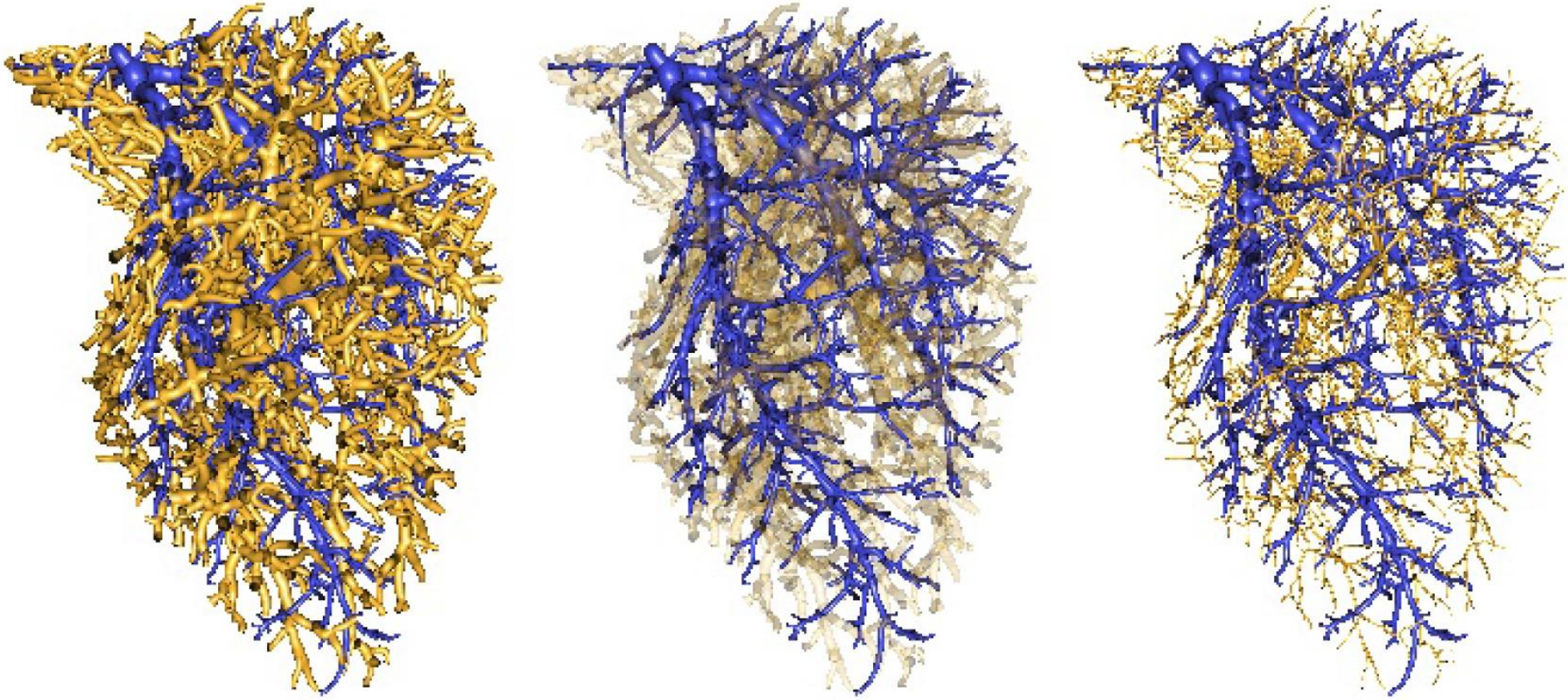




Exploration

Exploration of Vasculature

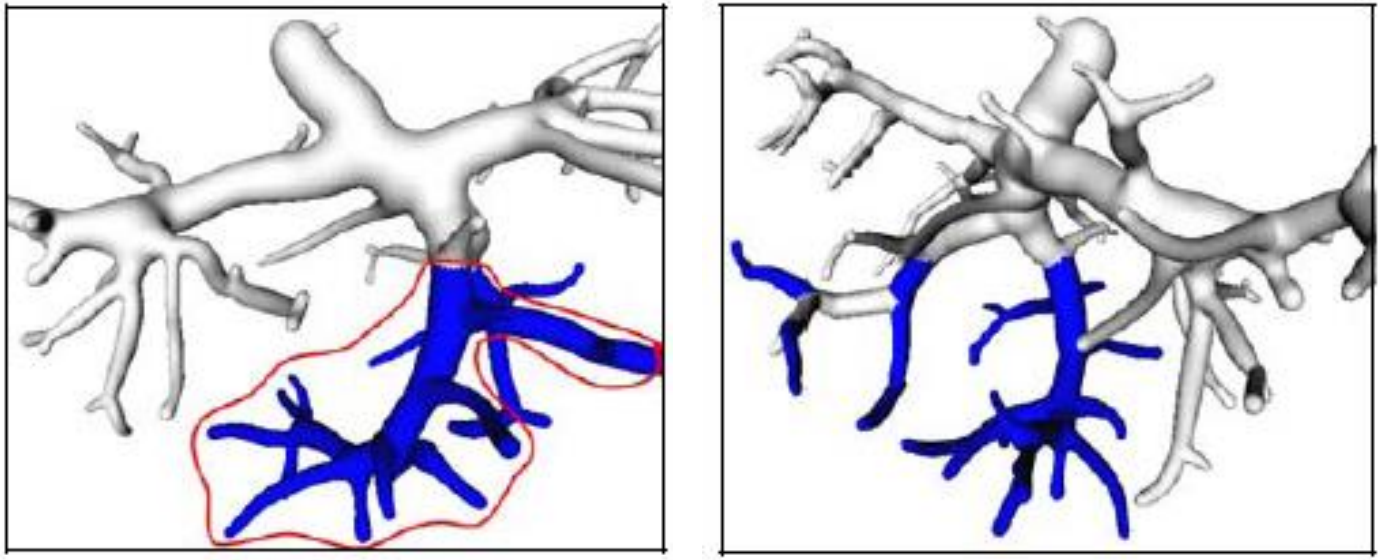
- Visualization of a complex vascular system
- Variation in transparency and radius progression



[Source: H. Hahn, B. Preim]

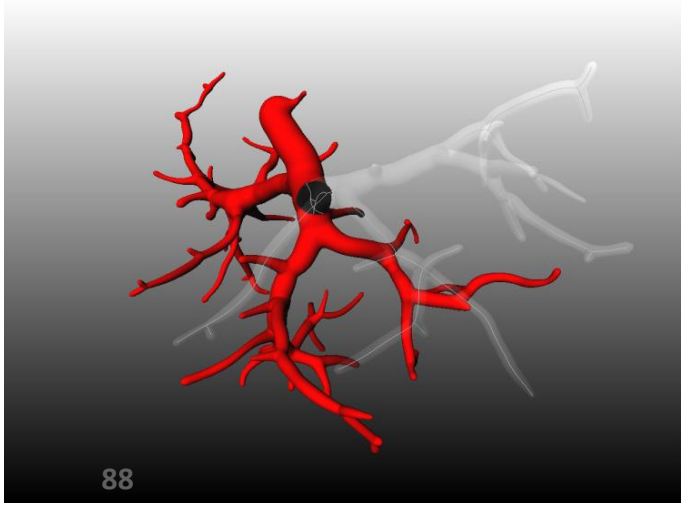
Exploration of Vasculature

- Ambuigities due to image-based selection



[von Hintzenstern 2006]

- Visualization of selected sub-trees



[Oeltze and Preim, 2004]

Summary

- Model-based (e.g., convolution surfaces)
- Model-free (e.g., MPU)
- Diagnostic methods (e.g., CPR)
- Exploration

Questions?

- Webpage: http://cg.tuwien.ac.at/courses/MedVis2/VU.html
- Abgabesystem: https://lva.cg.tuwien.ac.at/vismed2/

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