Visualization and Virtual Reality in Medicine

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Tutorial Syllabus

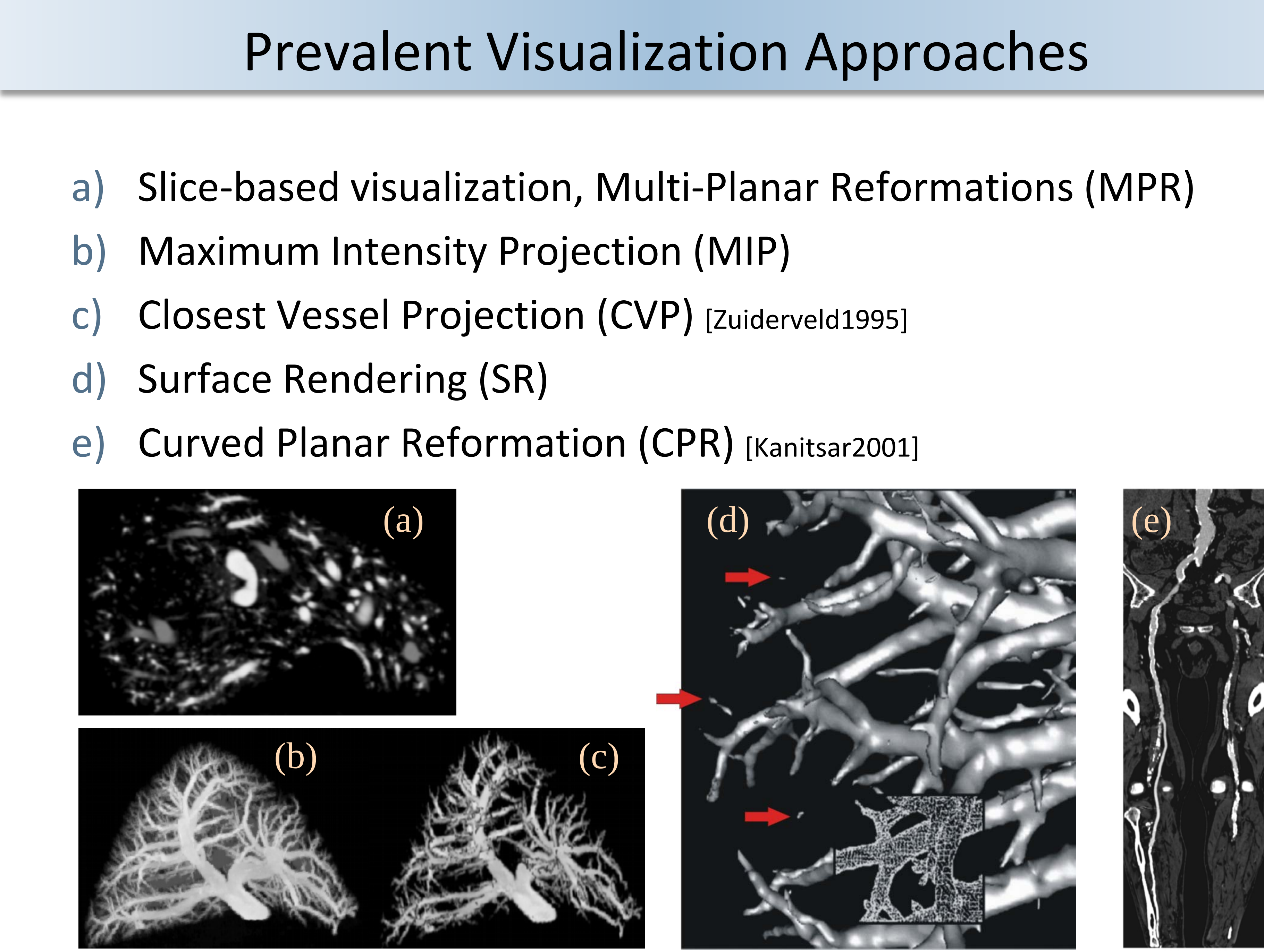
Surface Visualization - Marching Cubes and its improvements - Smoothing of surface visualizations	(40 min.)
3D Vessel Visualization	(30 min.)
Labeling Medical Visualizations	(20 min.)
Break	(15 min.)
Direct Volume Visualization - Ray casting and texture-based approaches - Projection methods	(40 min.)
Multifield Medical Visualization	(30 min.)
Virtual Endoscopy	(20 min.)

Vessel Visualization - Structure

- Basic Visualization Approaches
- Model-based Surface Visualization
- Model-free Surface Visualization
- Direct Volume Rendering Approaches

Prevalent Visualization Approaches

a) Slice-based visualization, Multi-Planar Reformations (MPR)
b) Maximum Intensity Projection (MIP)
c) Closest Vessel Projection (CVP) [Zuiderveld1995]
d) Surface Rendering (SR)
e) Curved Planar Reformation (CPR) [Kanitsar2001]



Different Application Fields

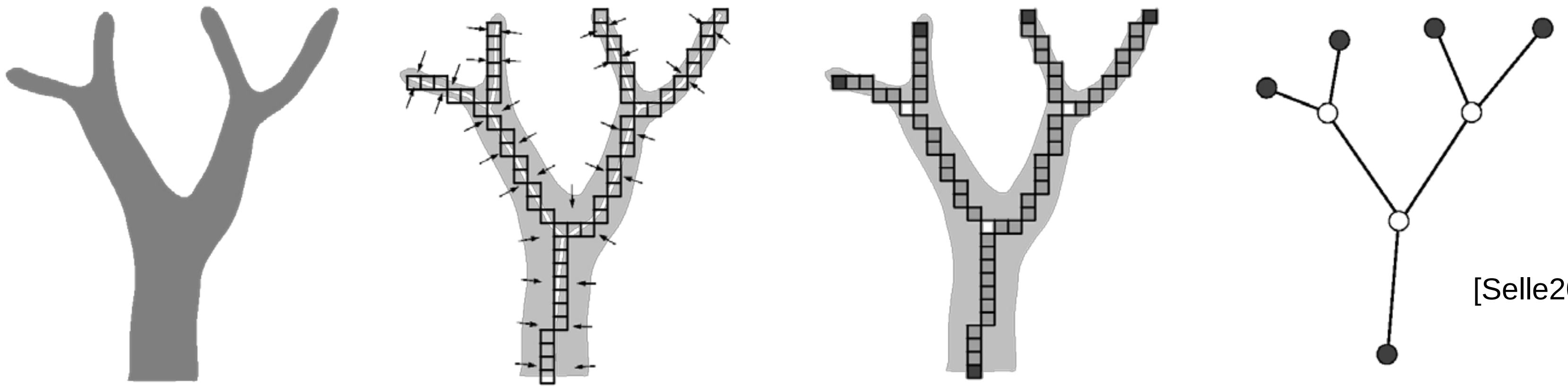
- Visualization in vascular diagnosis and vascular surgery:
  - Vascular surgery: bypass surgery, endoscopic treatment of aneurysms
  - Close adherence to the image data (vascular cross section)
  - Mostly slice-based examination, CPR
  - 3D visualization must be accurate

- Visualization in surgery planning and medical education:
  - 3D visualization must clearly communicate topology
  - Often, simplifying assumptions regarding morphology
  - Comprehension of spatial relations to other structures
  - Correct depiction of curvature, depth relations, and diminution of the diameter toward the periphery
  - MIP, CVP, and SR not well-suited due to image noise, partial volume effect ,and limited resolution of CT and MRT
  - Often, reconstruction of vascular structures based on a model

Model-based Surface Visualization

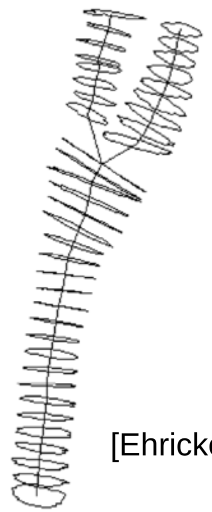
Model Generation

- High resolution CTA- or MRA-data ➔ Segmentation ➔ Skeletonization ➔ Analysis of shape and branching pattern



[Selle2000]

- Resulting model:
  - Graph represents vascular topology
  - Edges = branches, nodes = branchings
  - List of skeleton voxels per branch
  - Radii per skeleton voxel
  - Branching information



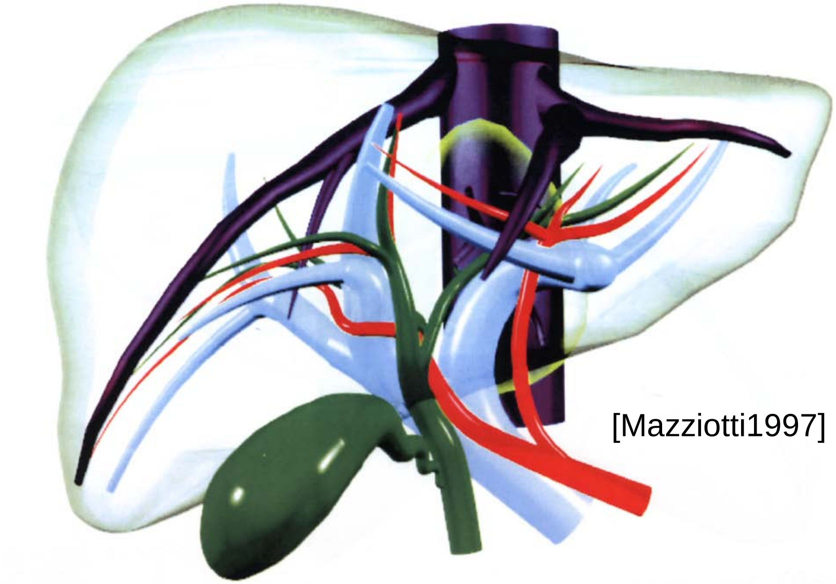
[Ehricke1994]

Model Assumption and Visualization Requirements

Simplifying model assumption:

- Circular cross-sections of non-pathological vessels

Keep in mind: methods are not intended for vessel diagnosis



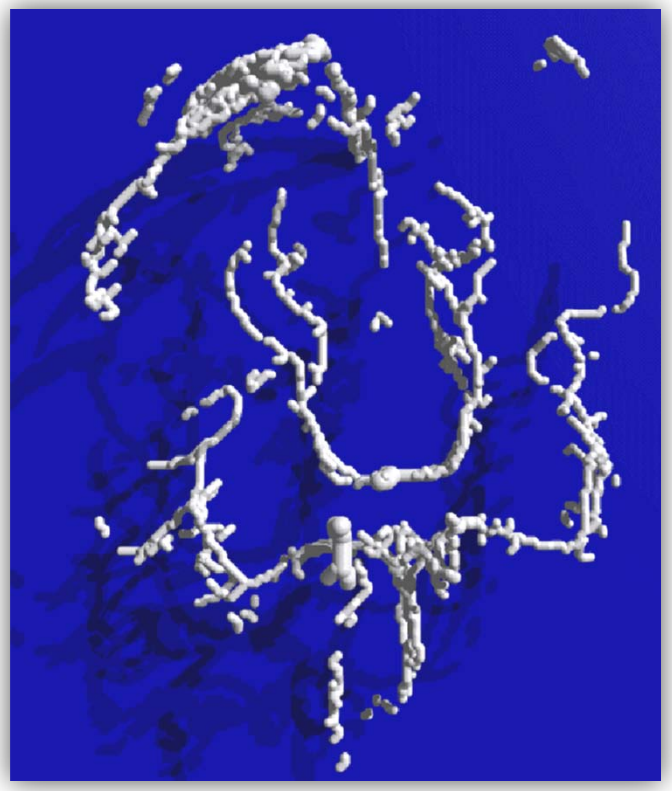
[Mazziotti1997]

Requirements:

- Correct representation of the vessel diameter
- Smooth, organic looking vessel shape
- Uniform treatment of all branching types
- Closed vessel ends
- Avoidance of structures inside the vessels

Cylinder Fitting

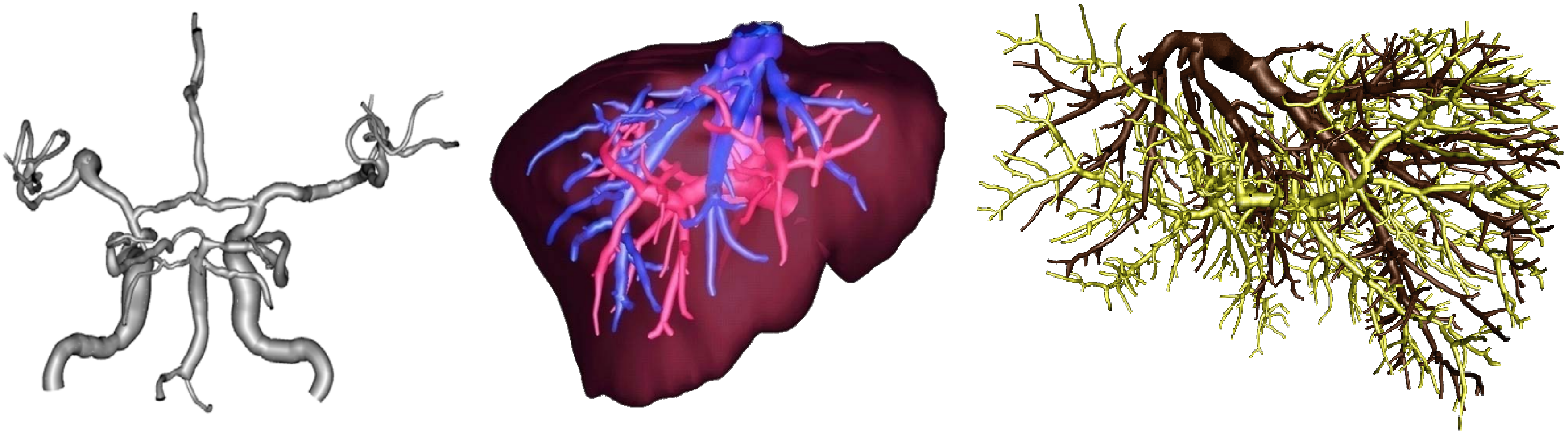
- *Gerig et al., 1993: "Symbolic Description of 3d structures applied to cerebral vessel tree obtained from MR angiography volume data"*
- Graph representation (edges, nodes) of the vessel tree for structural analysis, e.g. identification of sub trees
- Representation of the local vessel diameter by means of fitting cylinders along the vessel skeleton
- Ray-tracing of the scene



[Gerig1993]

Truncated Cone Fitting

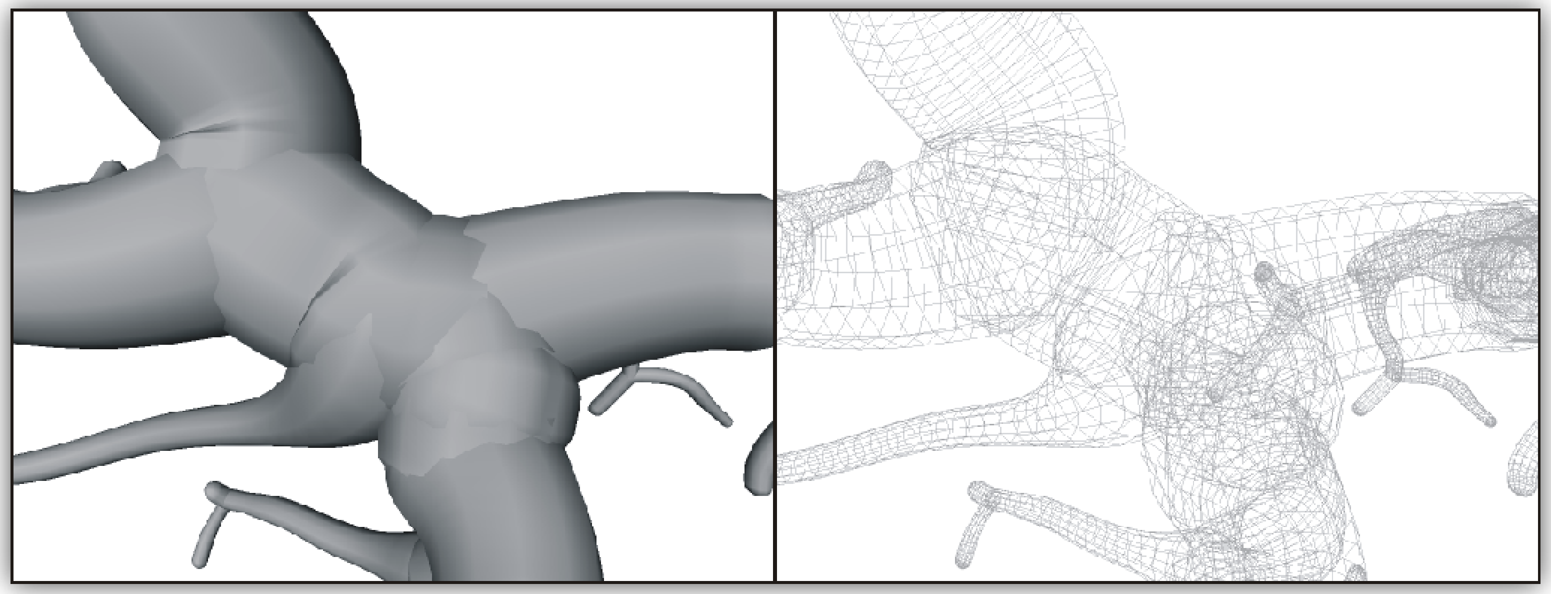
- *Hahn et al., 2001: “Visualization and Interaction Techniques for the Exploration of Vascular Structures”*
- Filtering: Smoothing of the skeleton and radius (Binominal filter)
- Rendering: Mapping of the model to geometric primitives
  1. Concatenation of truncated cones along the skeleton
  2. Mapping of truncated cones to polygons



- Left: Cerebral blood vessels (MR-Data: Prof. Terwey, Bremen)
- Middle: Hepatic vein and portal vein of clinical dataset (CT-Data: Prof. Galanski, MH Hannover)
- Right: Corrosion cast of the human liver (Data: Prof. Fasel, Uni Genf)

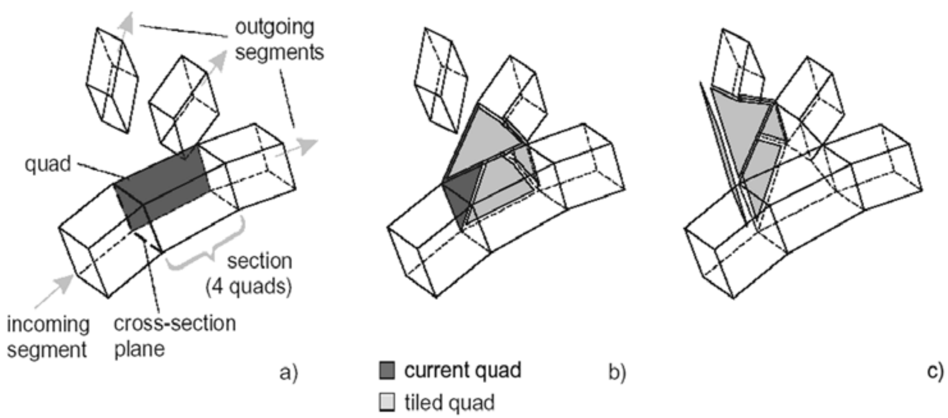
Truncated Cone Fitting

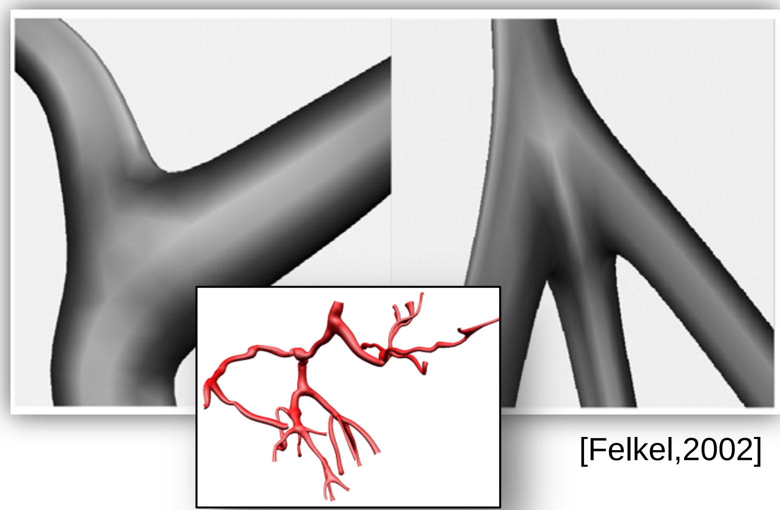
- Discontinuities at branchings become obvious at close-up views
- Inner polygons are constructed and therefore not suitable for virtual angioscopy
- **But**: A very fast method which has been applied in routine since 2004 (used for planning ~ 3000 interventions)



Subdivision Surfaces

- *Felkel et al., 2002: "Surface Reconstruction of the Branching Vessels for Augmented Reality Aided Surgery"*
- Computation of reference frame for each skeleton voxel to avoid twisting of the reconstructed vessel
- Visualization in two steps:
  - Construction of a coarse initial mesh by means of quads
  - Iterative refinement of the initial mesh applying Catmull-Clark subdivision surfaces

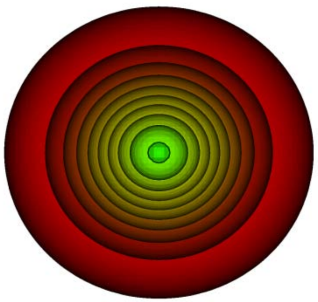




[Felkel,2002]

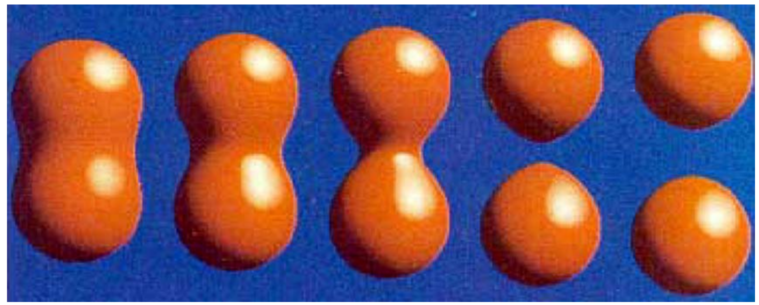
Convolution Surfaces

- *Oeltze and Preim, 2005: "Visualization of Vascular Structures: Method, Validation and Evaluation"*
- Application of implicit functions (Zero set F(p)-Iso=0)



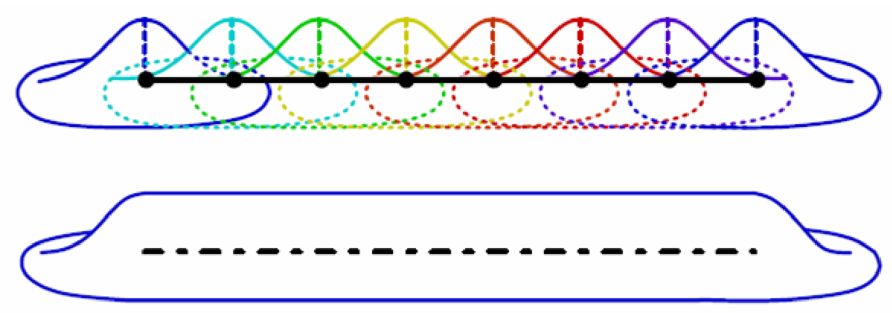
$$F(p) = e^{-\omega x^2}$$

$$\omega = width\ coefficient$$



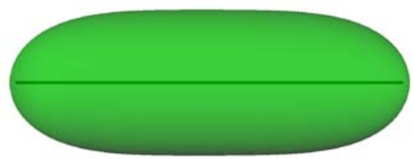
[Blinn1982]

- Convolution Surfaces [Bloomenthal1991]



[Bloomenthal1995]

Convolution of a line segment with a 3D low-pass filter



$$F(p) = \int_S h(s-p)ds = (h \otimes S)(p)$$

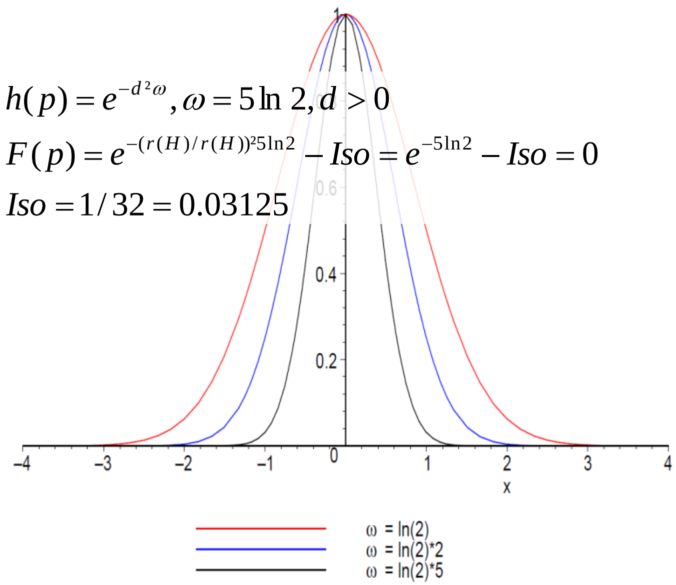
Convolution Surfaces

- Exploration of filter functions
- Selection guided by the following criteria:
  - Correct display of the diameter,
  - Avoid unwanted effects,
  - Fast computation

$$h(p) = e^{-d^2\omega}, \omega = 5\ln 2, d > 0$$

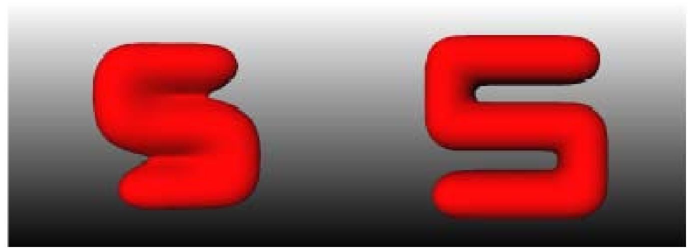
$$F(p) = e^{-(r(H)/r(H))^2 5\ln 2} - Iso = e^{-5\ln 2} - Iso = 0$$

$$Iso = 1/32 = 0.03125$$



Blending strength

Unwanted blending

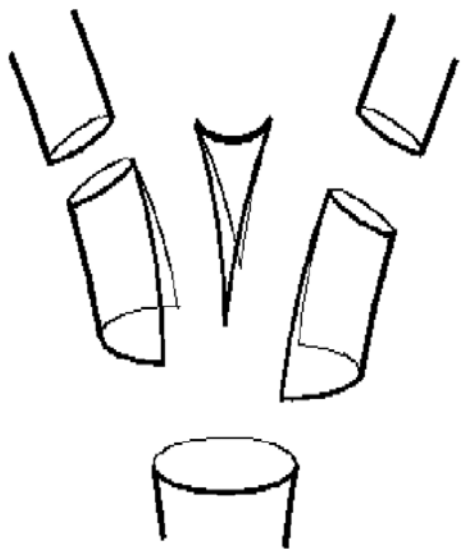


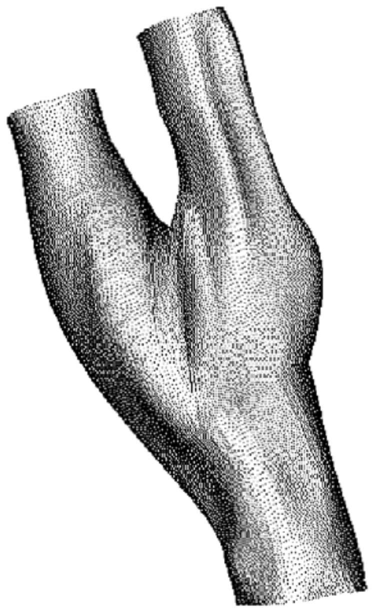
Bulging

- Results:
  - Narrow Gaussian is a good choice
  - For even narrower filter kernels, implicit surface converges against truncated cone visualization

Freeform Surfaces

- *Ehricke et al., 1994: “Visualization of vasculature from volume data”*
- Spline-curves represent the vessel skeleton
- Voxel ring describes local cross section
- Mean Square Approximation by means of freeform surfaces
- Arbitrary cross-sectional shapes may be reconstructed



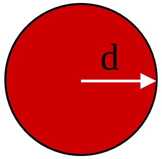
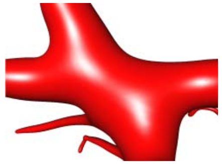
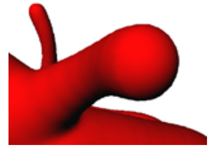


[Ehricke1994]

Simplex Meshes

- *Bornik et al., 2005: "Reconstruction and Representation of Tubular Structures using Simplex Meshes"*
- Simplex Meshes are simply-connected, i.e. each vertex is adjacent to 3 neighboring vertices [Delingette 1999]
- Visualization in two steps:
  1. Construction of an initial simplex mesh
     - Concatenation of adjacent approximating circular cross-sections
     - Special treatment of branchings necessary
  2. Use mesh as deformable model based on Newtonian law of motion
     - External forces either directed to
       - sampling points defined by original, polygonal cross-sections or
       - to boundary voxels of the segmentation result.
     - Internal regularizing forces
- Arbitrary cross-sectional shapes may be reconstructed

Comparison

Method	Geometry					
Gerig1993	Cylinder	no local diminution	no	yes	no	no
Hahn2001	Truncated cone	yes	no	yes	yes	no
Felkel2002	Subdivision Surface	yes	yes	yes	no	yes
Oeltze2004	Convolution Surface	yes	yes	yes	yes	yes
Reconstruction of arbitrary cross-sectional shapes						
Ehricke1994	Freeform Surfaces	yes*	yes*	no*	no*	yes*
Bornik2005	Simplex Mesh	yes	yes	yes	yes	yes

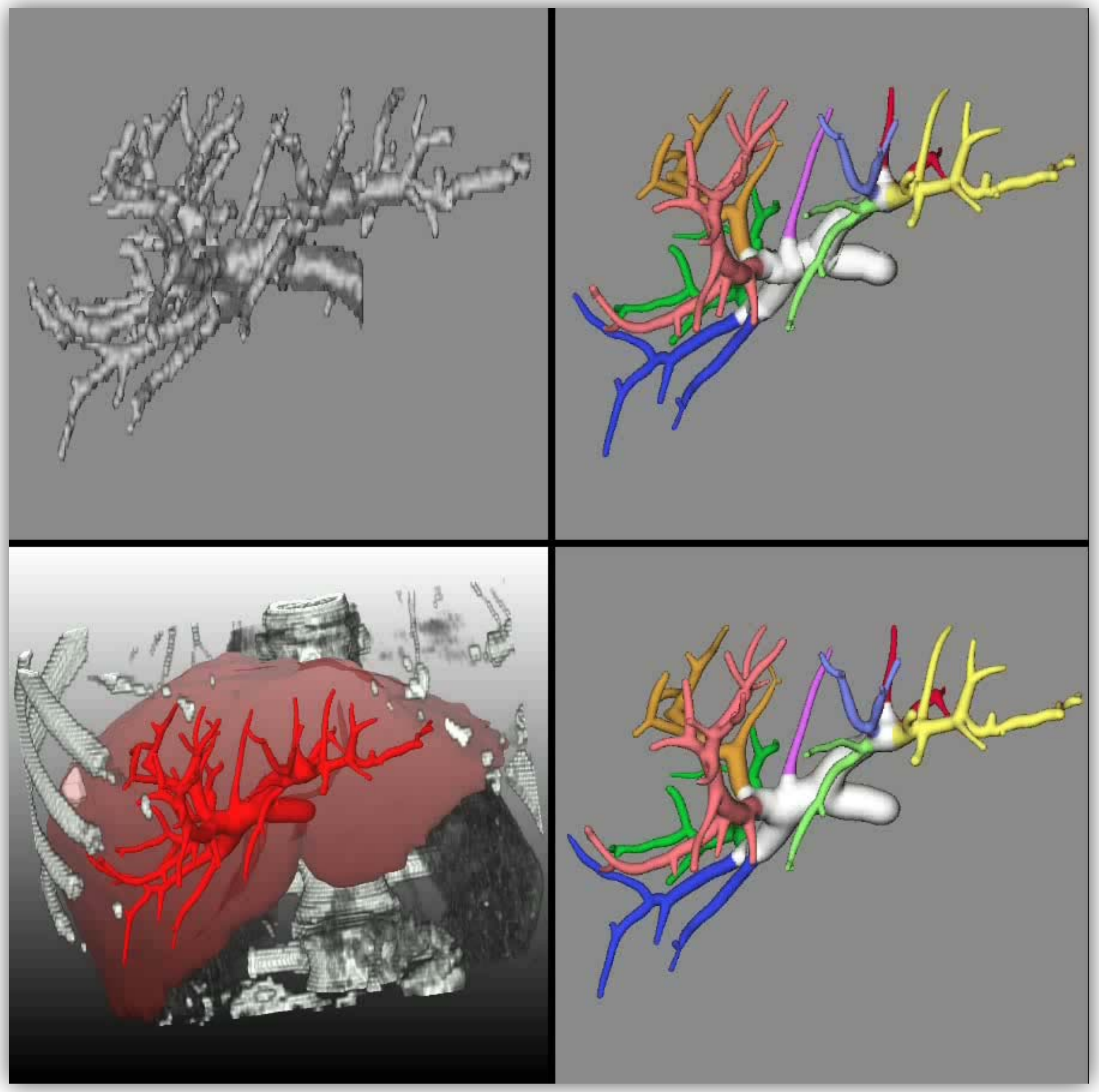
Comparison

Marching Cubes

Truncated Cones

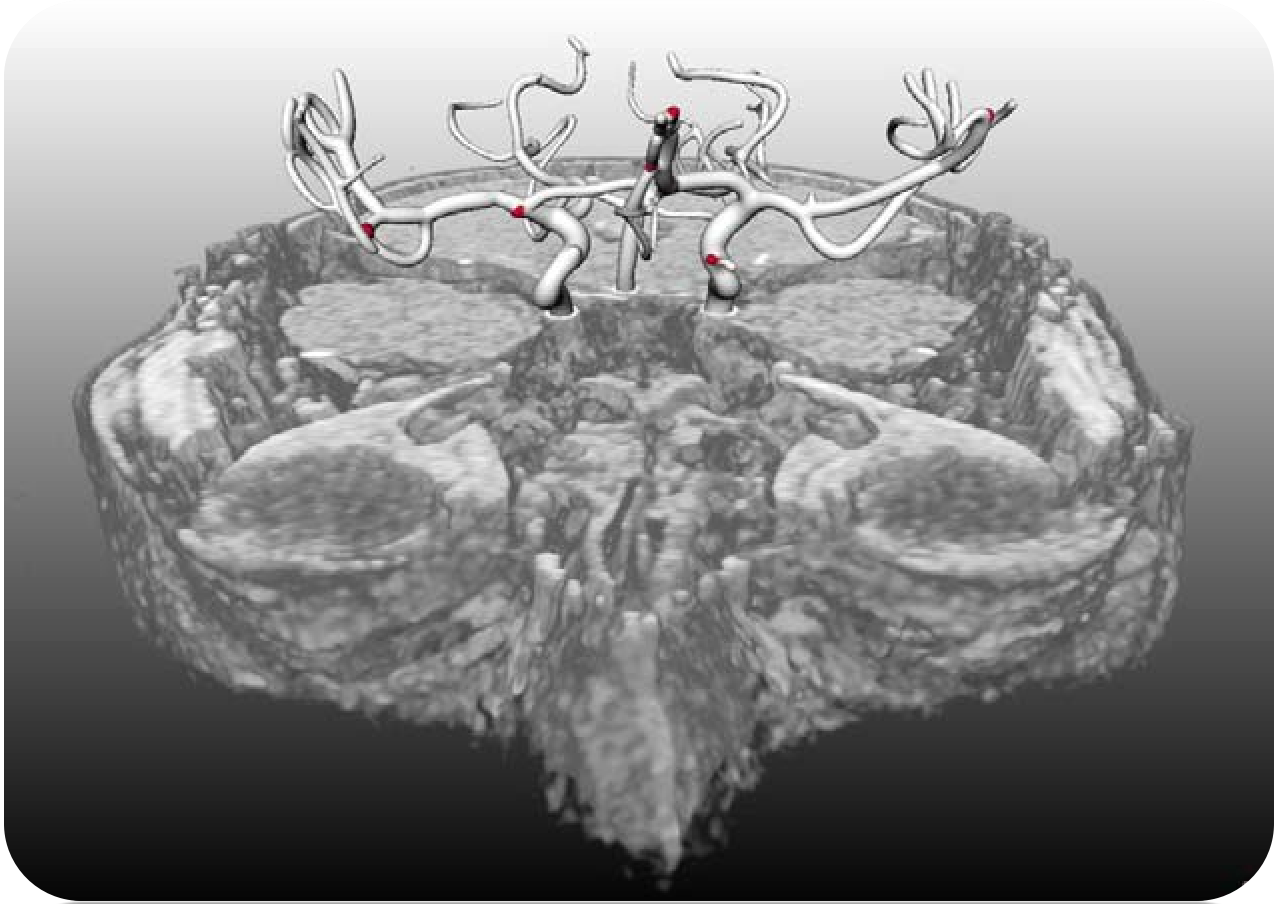
Context Information

Convolution Surfaces



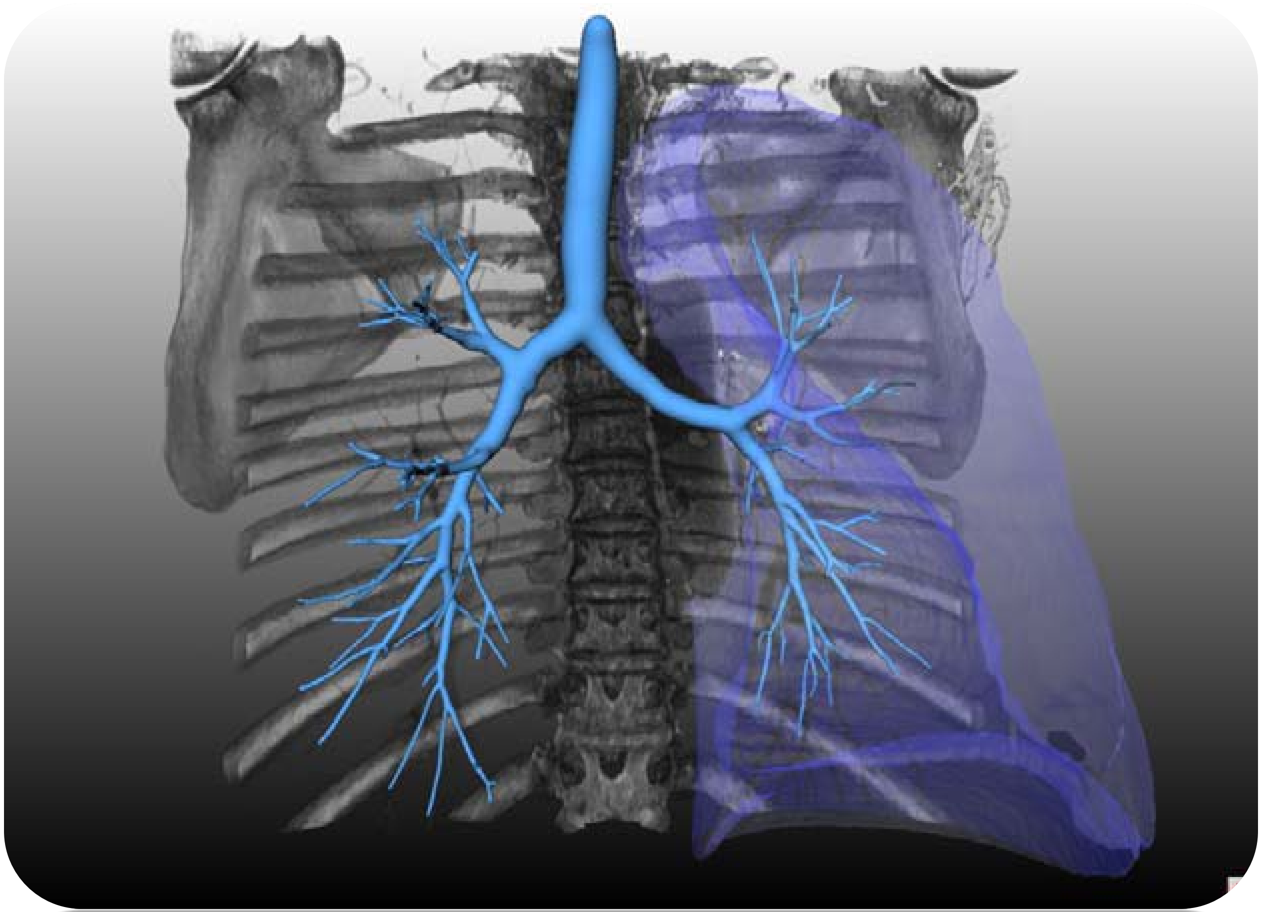
Application Scenarios

- Analysis of cerebral vasculature



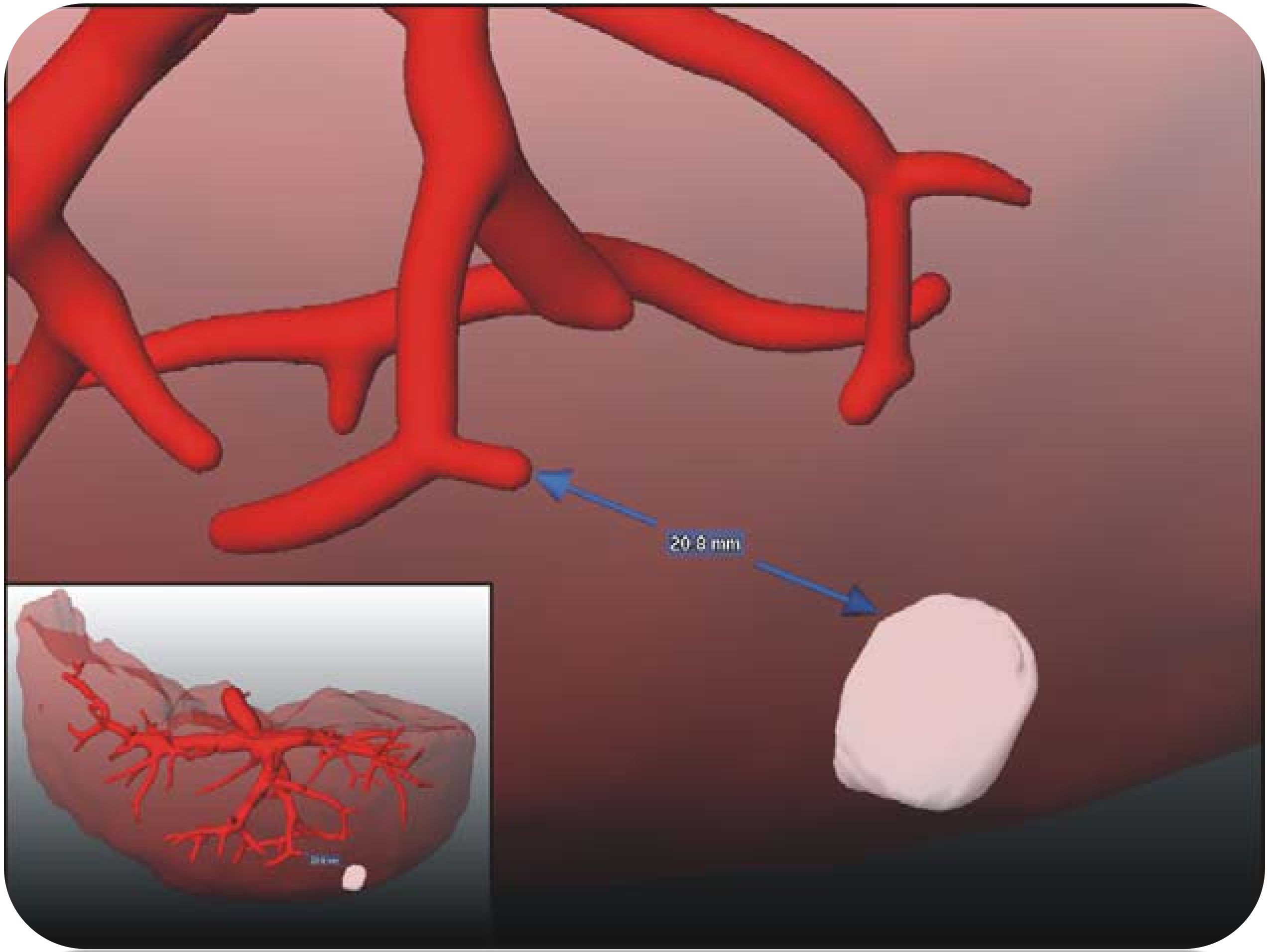
Application Scenarios

- Analysis of bronchial tree



Application Scenarios

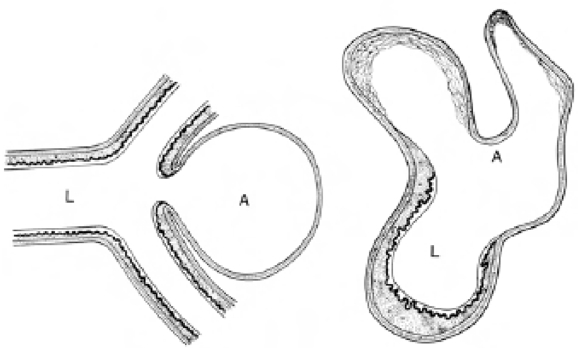
- Liver tumor resection



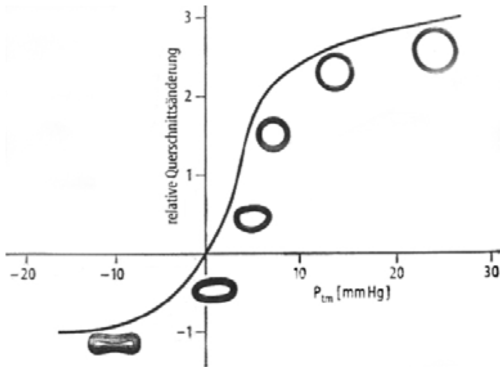
Model-free Surface Visualization

Characterization

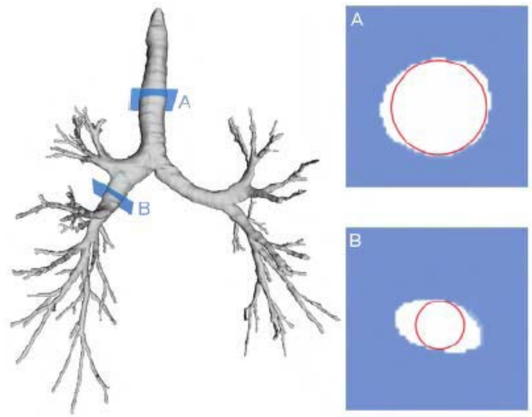
- Primary goal: correct representation of cross-sectional shape
- Simplifying model-assumption of circular cross-sections is invalid for pathologic vessel parts, e.g., aneurysms, and also for certain non-pathologic vessels, e.g., the trachea



[Osborn1999]



[Schmidt2004]

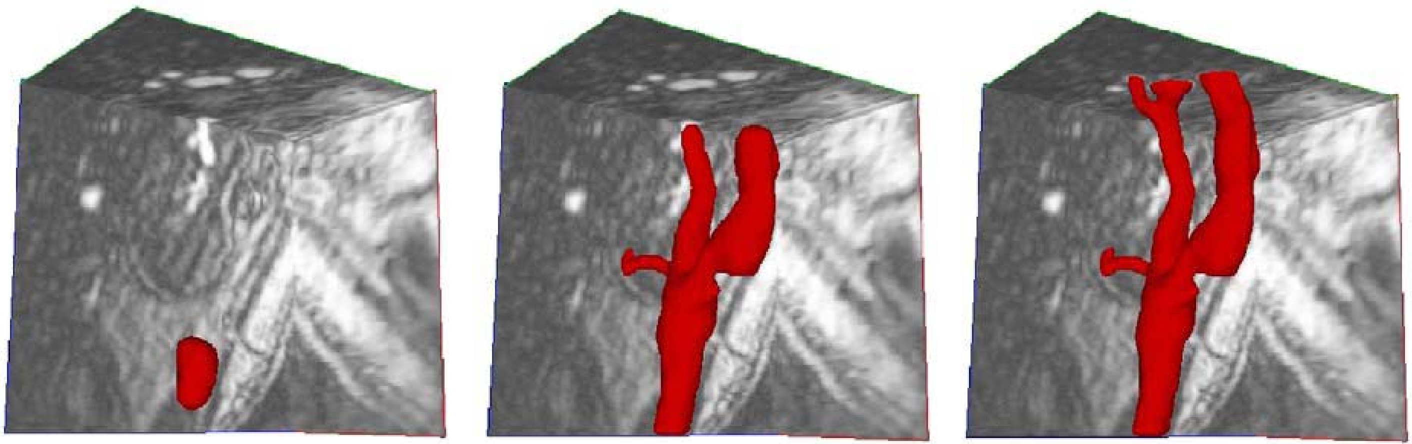


[Schumann2006]

- Model-free approaches are either based on
  - the original data, if segmentation and surface generation are intrinsically tied to each other, or
  - a segmentation mask including the vascular structures.

Level-Sets

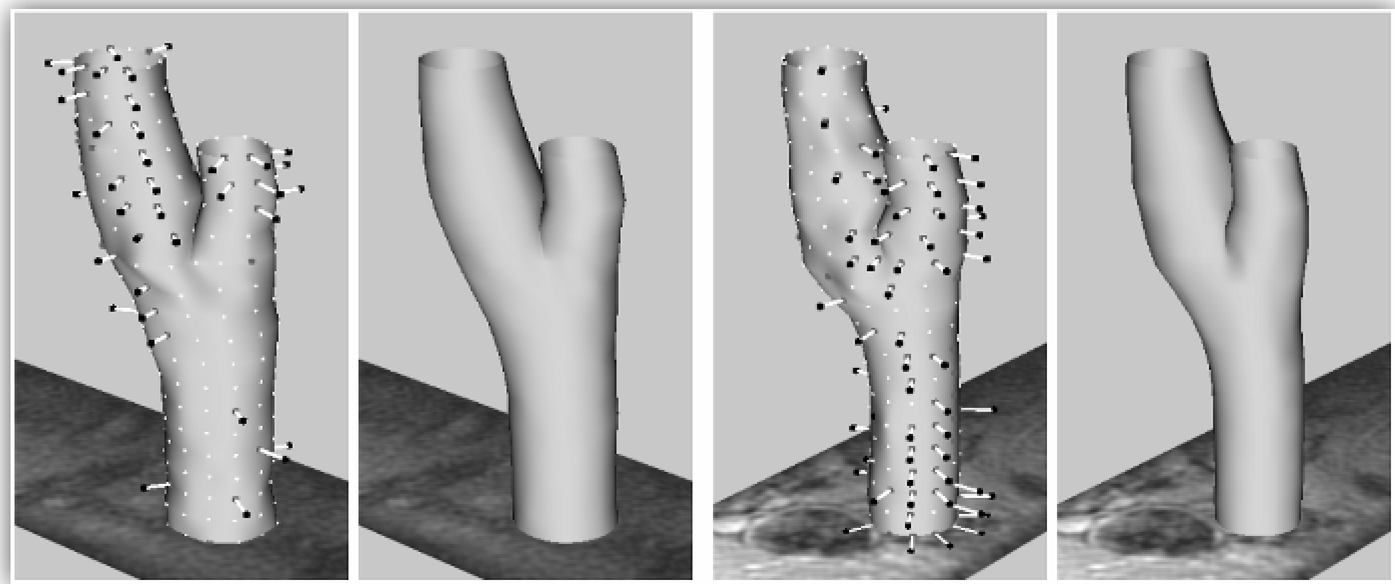
- *Deschamps et al., 2002: "Fast surface and tree structure extraction of vascular objects in 3d medical images"*
- Surface segmentation of thin, branching structures based on Fast-Marching and Level Set methods
- Algorithm:
  - Inflation of a "long balloon" from user-given starting point
  - Propagation of only one moving front and freezing of other points
  - Definition of a distance-based stopping criterion



[Deschamps2004]

3D Active Shape Models

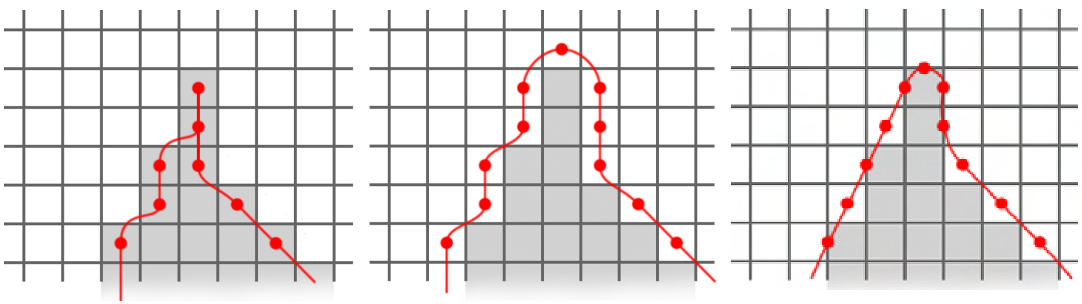
- *Lekadir and Yang, 2006: "Carotid Artery Segmentation Using an Outlier Immune 3D Active Shape Models Framework"*
- Construction of the ASM based on a training set
- Computation of tolerance intervals for outlier detection during training stage
- ASM fitting under consideration of the tolerance intervals



[Lekadir2006]

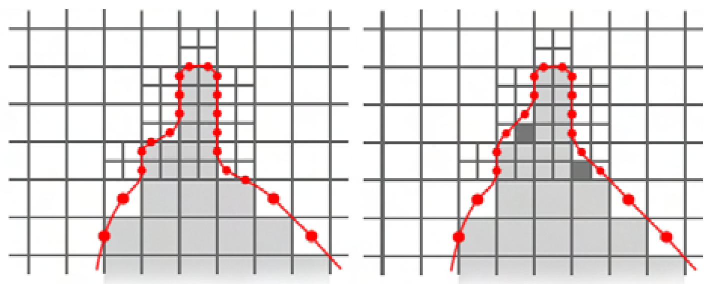
Multi-level Partition of Unity Implicits

- *Schumann et al., 2007: "Model-free Surface Visualization of Vascular Trees"*
- *Idea based on Ohtake et al., 2003: "Multi-level Partition of Unity Implicits"*
- Approximation of a point cloud by a surface
- Algorithm:
  1. Transforming segmentation mask into point cloud
  2. Refinement of point cloud at "stair cases" and very thin vessels
  3. Spatial subdivision of the point cloud by an octree
  4. Local approximation of the cloud by algebraic surfaces
  5. Blending of local approximations results in global approximation



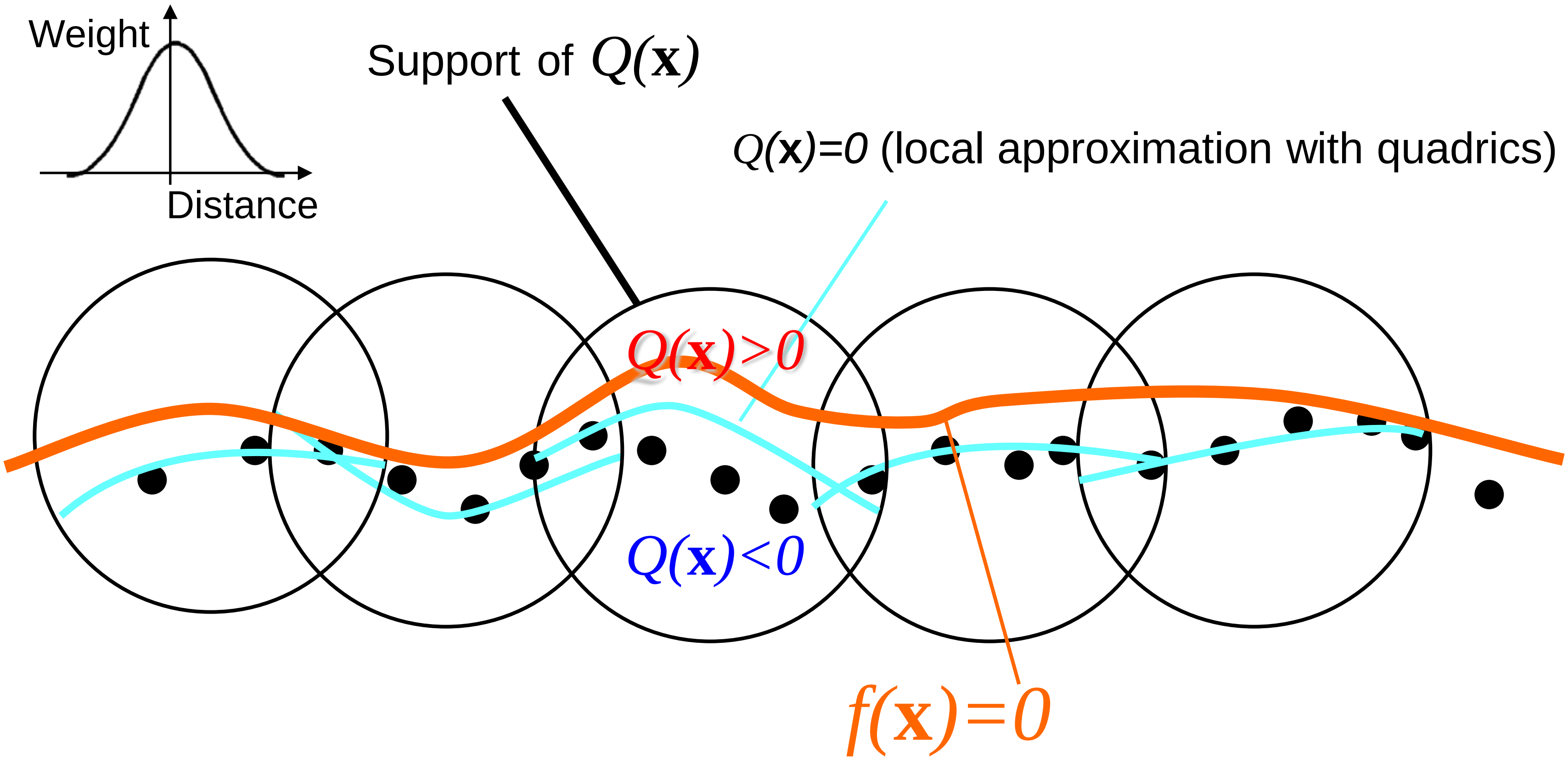
Transformation

Refinement



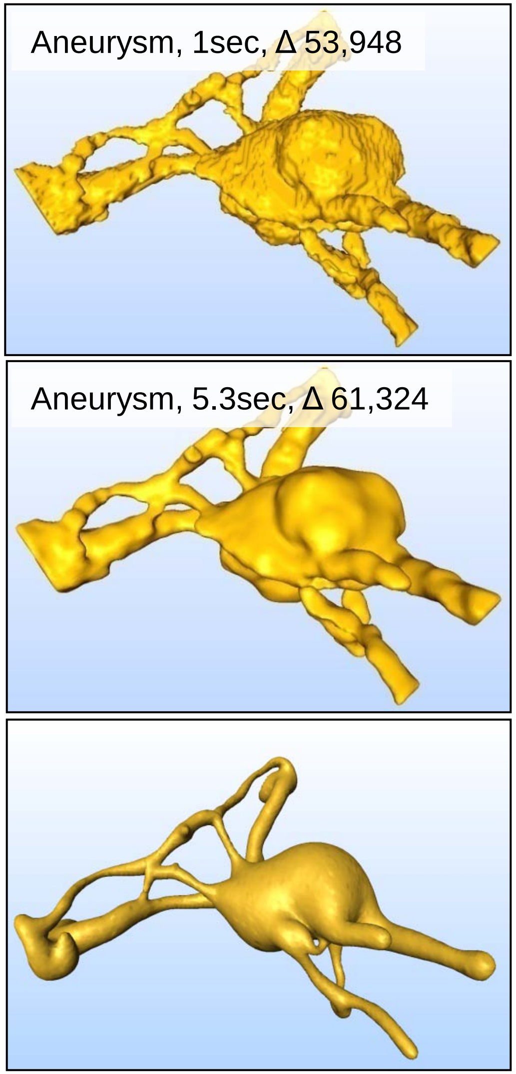
Multi-level Partition of Unity Implicits

- Local approximation and blending



Weighted average of local approximations: $f(\mathbf{x}) = \dfrac{\sum w_i(\mathbf{x})\, Q_i(\mathbf{x})}{\sum w_i(\mathbf{x})}$

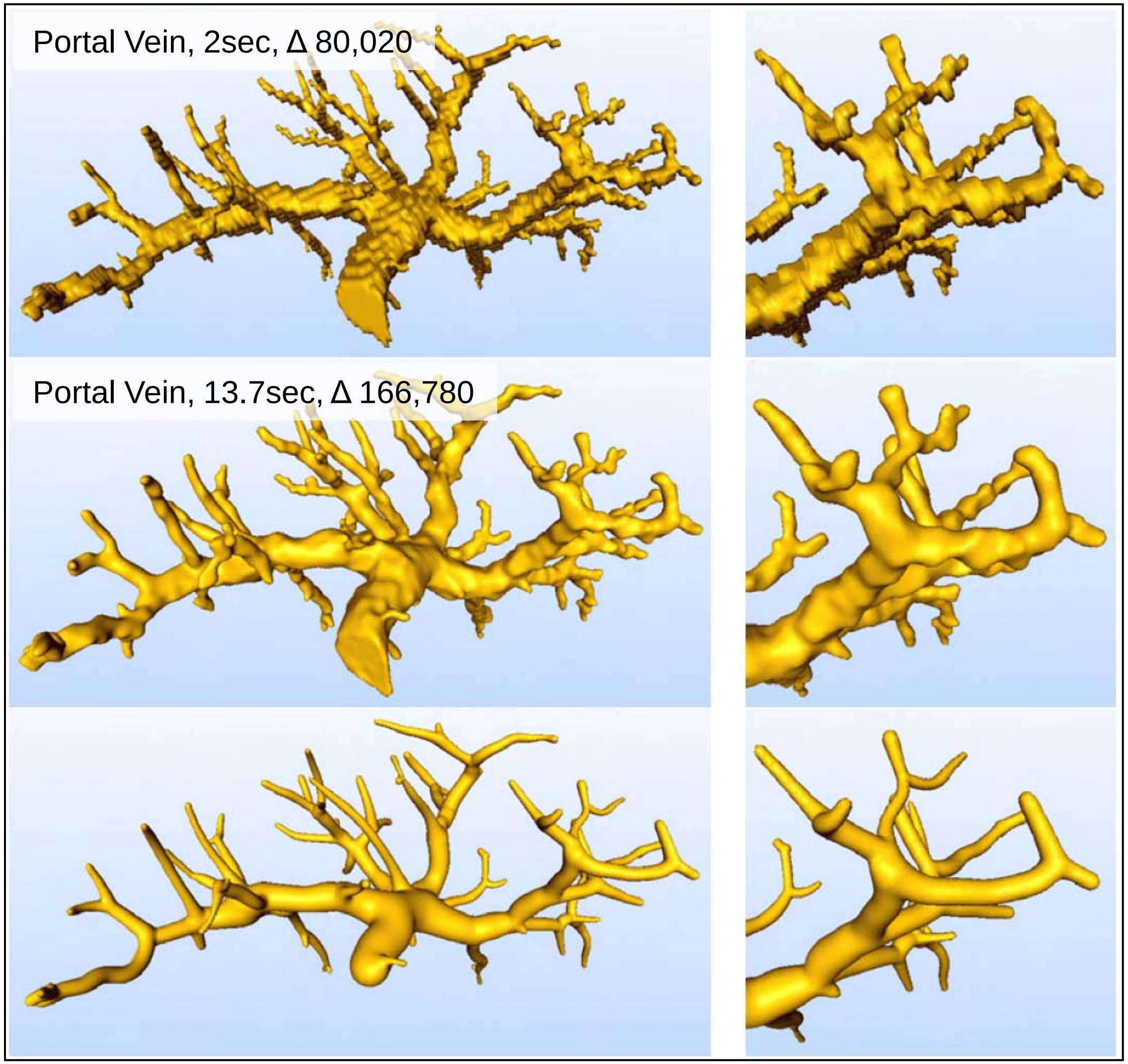
Multi-level Partition of Unity Implicits



MC

MPU

CS



MC = Marching Cubes
CS = Convolution Surfaces

[Schumann2006]

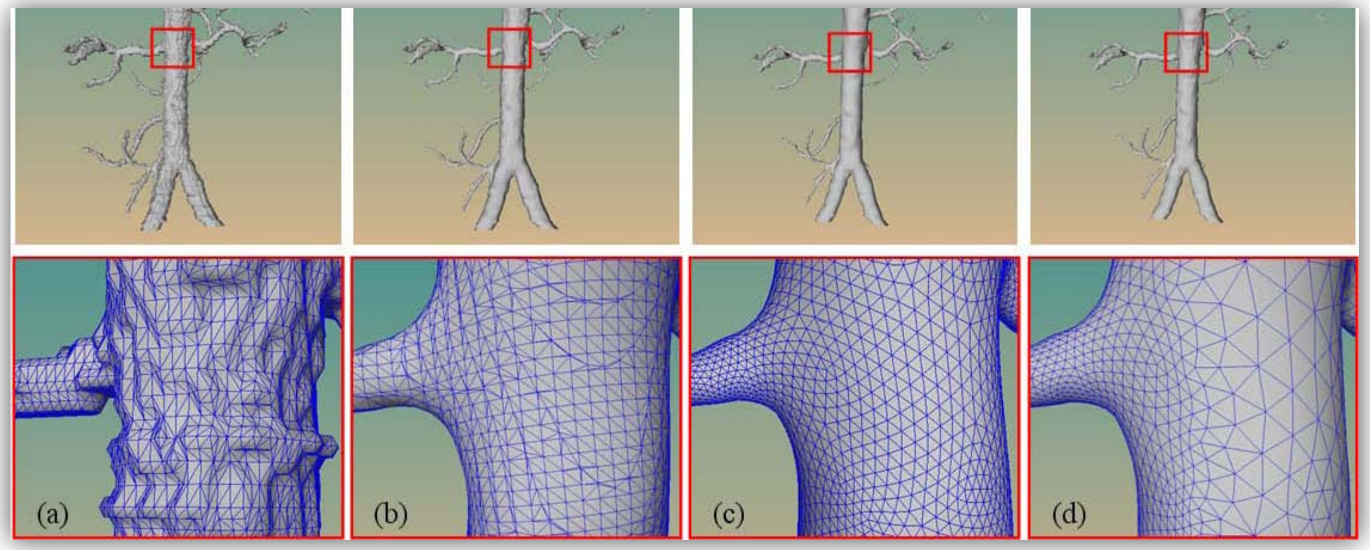
Multi-level Partition of Unity Implicits

Surface distances from MC- to MPU-result in voxel diagonals (V_d)

Dataset	Φ	σ	Rms	Median	Max	$>V_d/2$ [%]
Bronchial Tree	0.17	0.11	0.21	0.16	1.4	0.69
Portal Vein	0.17	0.11	0.2	0.15	0.84	0.82
Cerebral Tree	0.2	0.13	0.24	0.2	1.68	1.7
Aneurysm	0.21	0.16	0.27	0.19	1.9	4.1
Average	0.19	0.13	0.23	0.17	1.46	1.84

Improvement of Mesh Quality

- *Wu et al., 2010*: “Scale-Adaptive Surface Modeling of Vascular Structures”
- *Guo et al., 2013: “*Mesh Quality Oriented 3D Geometric Vascular Modeling Based on Parallel Transport Frame”
- Curvature-dependent generation of mesh yields less triangles and good triangle quality
- Important for, e.g., construction of volume mesh for CFD simulation and simulation-based surgical training and planning

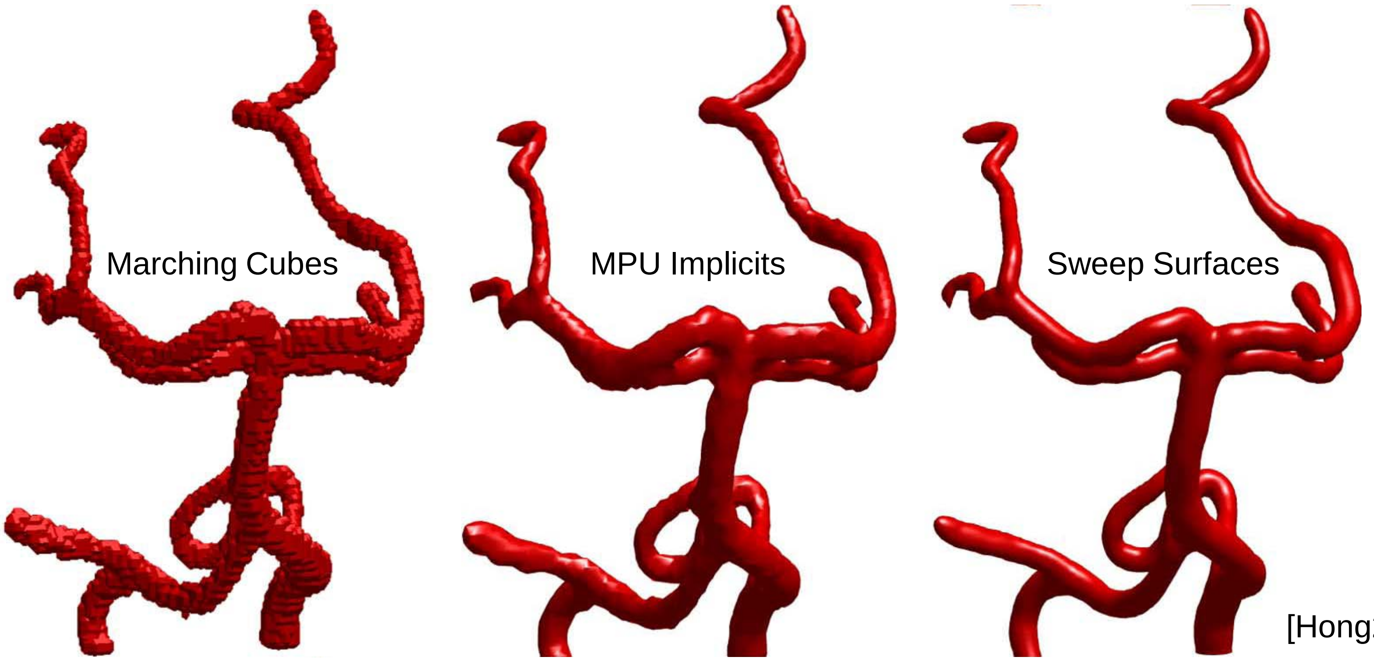


[Wu2010]

(a) Marching Cubes, (b) MPU Implicits, (c) Subdivision surface, (d) Wu’s variant of MPU Implicits

Improvement of Surface Smoothness

- *Hong et al., 2012*: “Implicit Reconstruction of Vasculatures Using Bivariate Piecewise Algebraic Splines”
- *Sweep surface* is created by
  - smoothly interpolating points representing vascular cross sections and
  - integrating these profiles, under consideration of their individual contributions, along the centerline with a *sweeping* technique.
- At branchings, weighting of branches and smooth blending

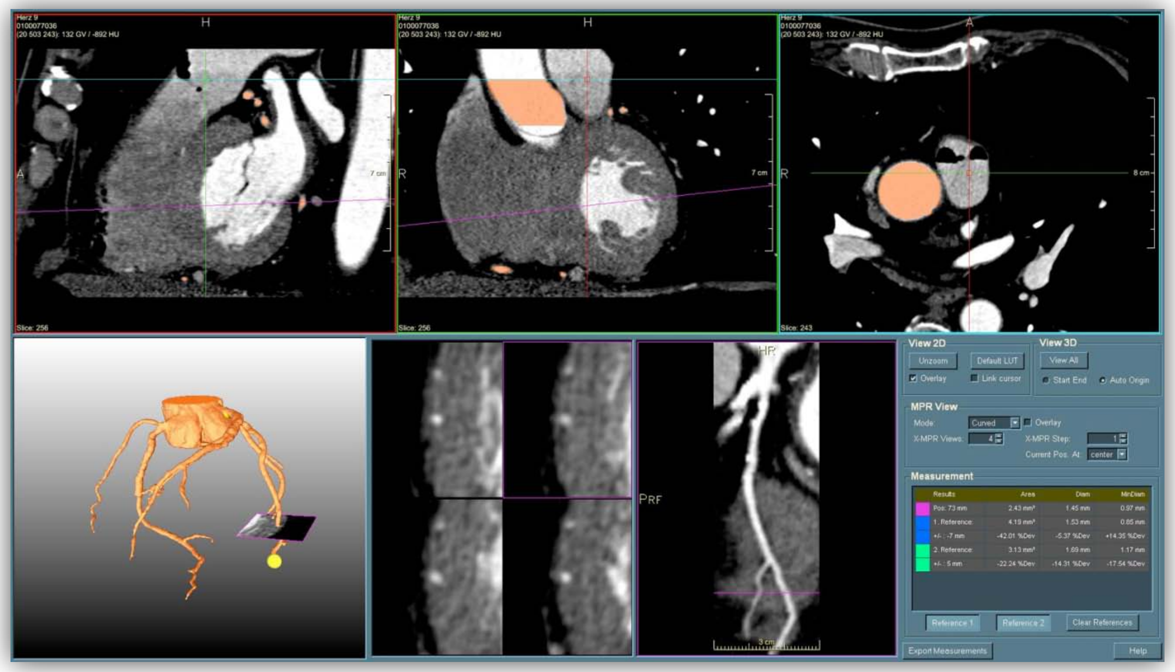


[Hong2012]

Direct Volume Rendering Approaches

Characterization

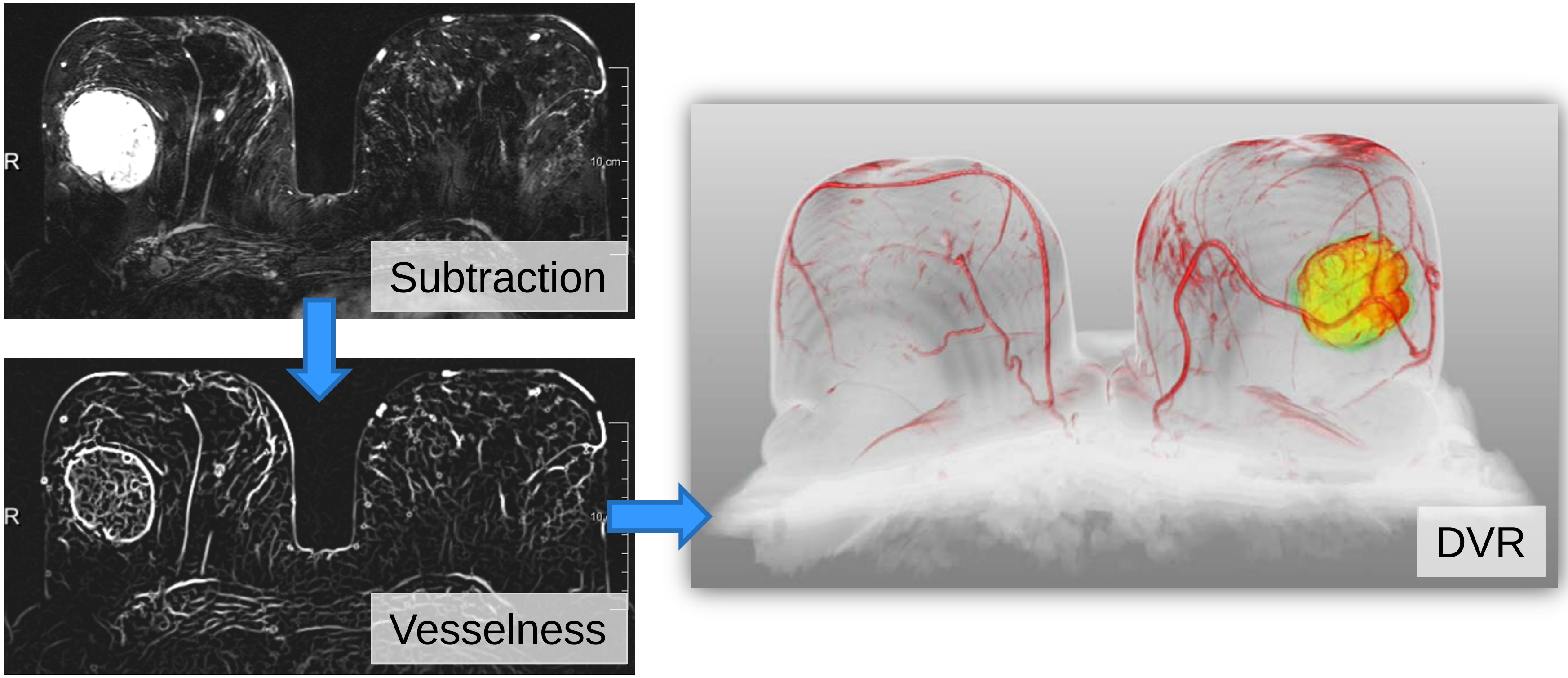
- Direct visualization of contrast-enhanced 3D/4D data
- Requires neither a segmentation nor an analysis of vasculature
- Often prefiltering of the data to further enhance vessels
- Good overview of the entire vasculature in 3D
- Often combined with methods for more detailed inspection of cross-sectional shape and vessel lumen, e.g., MPR and CPR



“MeVisCardio”
[Kuehnel2006]

Vessel Enhancement Filtering

- Popular vesselness filter by A. Frangi [Frangi1998]
- Computation of a vesselness measure based on the Eigenvalues of the Hessian (second order local structure of an image)



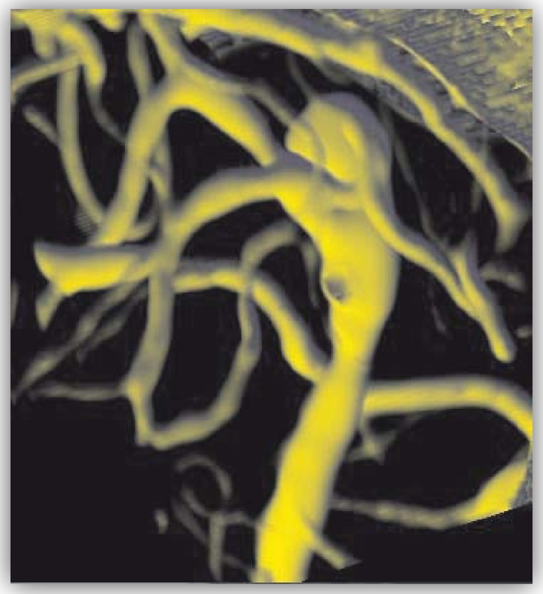
Data is courtesy of J. Wiener, Boca Raton Community Hospital, Florida, US

Non-Parametric Vessel Detection

- *Joshi et al., 2008: "Effective Visualization of Complex Vascular Structures Using a Non-Parametric Vessel Detection Method"*
- New vesselness measure that performs better at branches
- Based on an intensity profile around each voxel
- Combination of new measure with visualization techniques which improve shape as well as depth cues

DVR

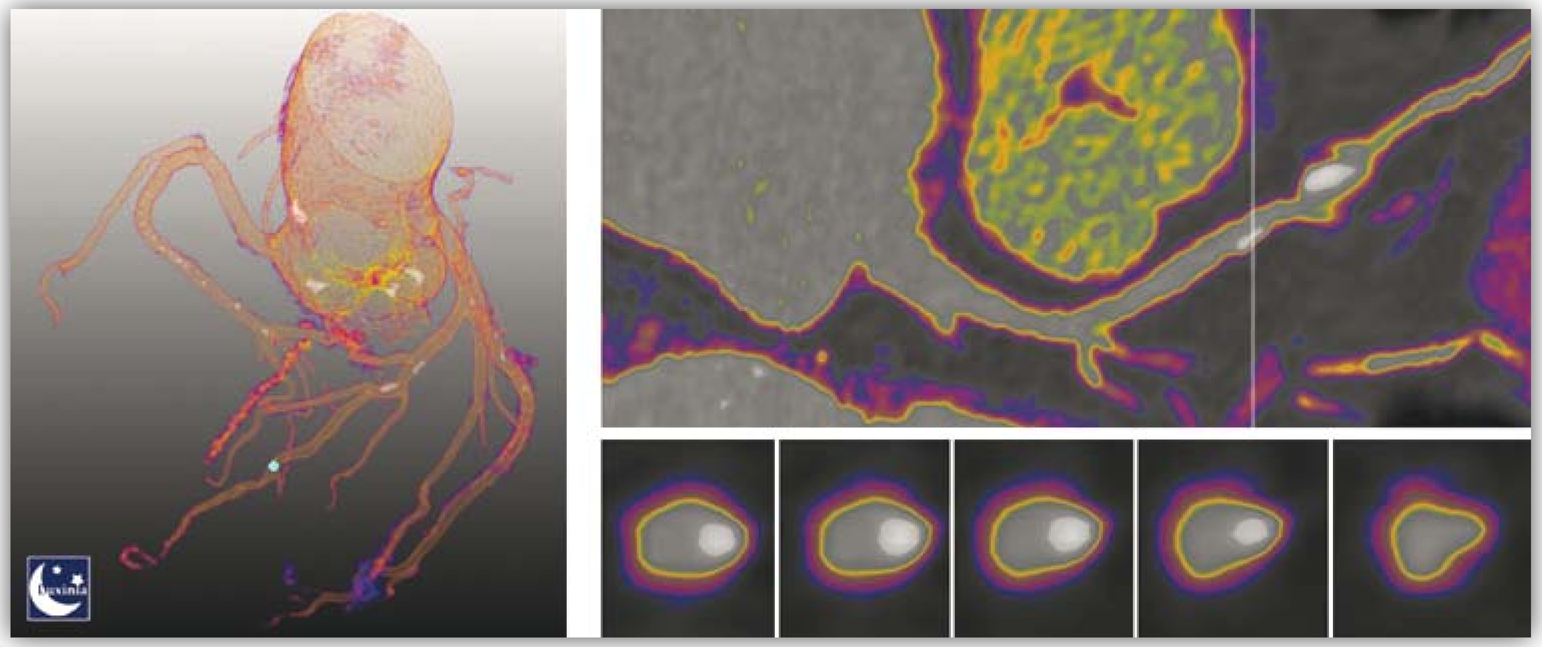
Vessel-enhancement and distance color blending



Tone shading

Automatic Transfer Function Specification

- *Glaßer et al., 2010: "Automatic Transfer Function Specification for Visual Emphasis of Coronary Artery Plaque"*
- Based on coarse segmentation of coronary tree
- Transfer function (TF) is automatically designed such that pathologic changes (plaque) are highlighted
- TF adaptation to each dataset by local histogram analysis



[Glasser2010]

Summary

- Prevalent Visualization Approaches
  - CPR and MPR well suited for inspecting vascular cross-sections
  - SR hampered by image noise and partial volume effect
  - MIP and CVP fail to always convey depth information correctly
- Model-based Surface Visualization
  - Communicates topology & morphology, unsuitable for vessel diagnosis
  - Approaches require segmentation and skeletonization of the vessels
- Model-free Surface Visualization
  - Suitable for vessel diagnosis, correct depiction of cross-sections
  - Vessel segmentation and visualization may compose a joint process
- Direct Volume Rendering Approaches
  - Appropriate as an overview visualization
  - Vessel enhancement as a pre-processing step
  - Coupling of a 3D representation with MPR and CPR views

Literature

To get an overview:

Preim and Botha [2014]: chapter “Visualization of Vascular Structures” in Visual Computing for Medicine – Theory, Algorithms, and Applications, 2nd ed., Morgan Kaufmann

Hong [2014]: “A Survey on the Visualization and Reconstruction of Vasculatures”, In: Proc. of SPIE

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Bühler [2004]: “Geometric Methods for Vessel Visualization and Quantification - A Survey”. Geometric Modeling for Scientific Visualization, Springer.

For more details:

Blinn [1982]: “A Generalization of Algebraic Surface Drawing”. ACM Trans. on Graphics, 1(3)

Bloomenthal [1991]: “Convolution Surfaces”. Computer Graphics (Proc. of ACM SIGGRAPH), Bd. 25.

Bloomenthal [1995]: Skeletal Design of Natural Forms. PhD thesis, University of Calgary.

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