Visual Medicine: Part Two – Advanced Topics in Visual Medicine

Visualization of Vasculature

Steffen Oeltze

Visualization Research Group
University of Magdeburg, Germany

stoeltze@isg.cs.uni-magdeburg.de

Outline

Advanced Topics in Visual Medicine

- Visual Analysis of Perfusion Data
- Intraoperative Navigation and Medical Mixed Reality
- Diffusion Tensor Imaging
- **Visualization of Vasculature**
- Fast Tagged Multi-resolution Volume Rendering
- GPU-aided Computed Tomography
- Soft-Tissue-Simulation

Questions and Answers

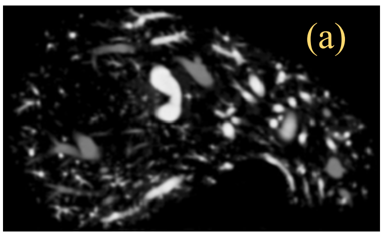
Structure

- Introduction
- Image Data and Vessel Analysis
- Model-Based Visualization of Vasculature
- Application Scenarios
- Validation
- Model-Free Visualization of Vasculature
- Conclusion and Future Work

Introduction – Traditional Visualization Approaches

Visualization of vasculature in vascular diagnosis, surgery planning and medical education

Traditional approaches: slice-based examination (a), *Maximum Intensity Projection, Closest Vessel Projection* [Zuiderveld, 1995] (b), *Isosurface Rendering* (c), *Curved Planar Reformation* (d)



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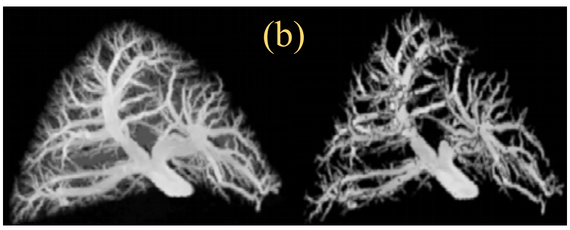

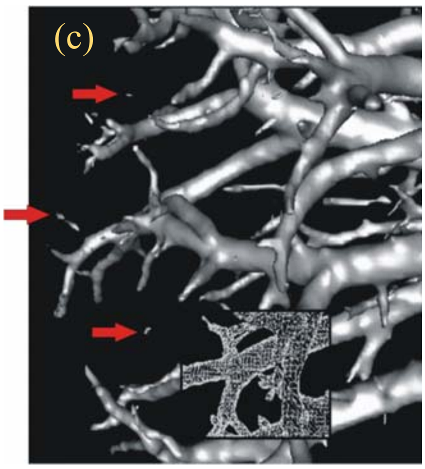

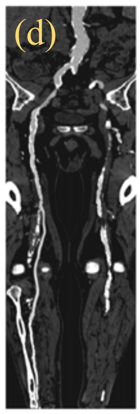

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Introduction – Vascular Diagnosis vs. Surgery Planning

Visualization in vascular diagnosis:

- Close adherence to the image data (vascular cross section)

➔ Mostly slice-based examination, Curved Planar Reformations

➔ 3D visualization must be accurate

Visualization in **surgery planning and medical education**:

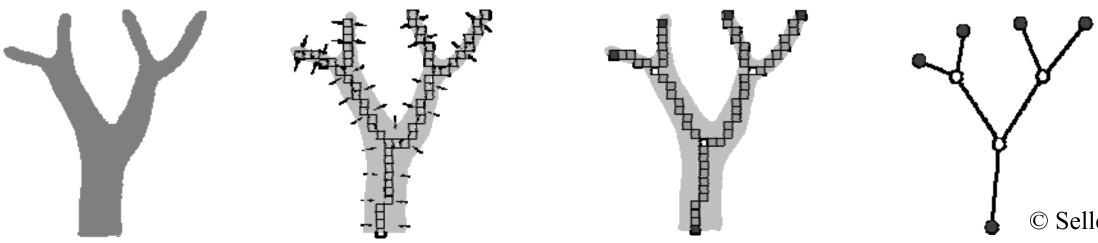
- Clear communication of topology and morphology
- Comprehension of spatial relations to other structures
- Correct depiction of curvature, depth relations and diminution of the diameter towards the periphery

➔ Traditional methods not well-suited here due to image noise, partial volume effect and limited resolution of CT and MRT

➔ **Reconstruction of vascular structures based on a model**

Image Data and Vessel Analysis

High resolution CT- or MR-data ➔ Segmentation ➔ Skeletonization ➔ Analysis of shape and branching pattern



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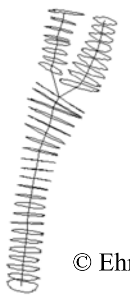
Results of vessel analysis:

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



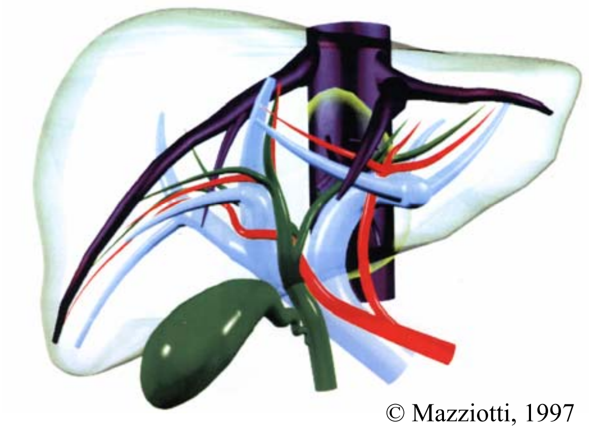
© Ehricke, 1994

Model-based Visualization – Model Assumption and Requirements

Simplifying model assumption:

- Circular cross-sections of non-pathological vessels

Keep in mind: methods are not intended for vessel diagnosis



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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

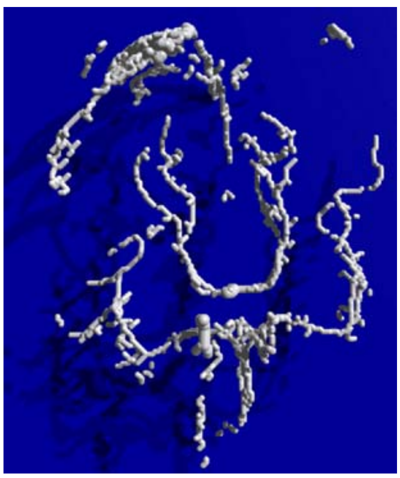
Model-based Visualization – Cylinder Fitting

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 subtrees

Representation of the local vessel diameter by means of fitting cylinders along the vessel skeleton

Ray-tracing of the scene



© Gerig, 1993

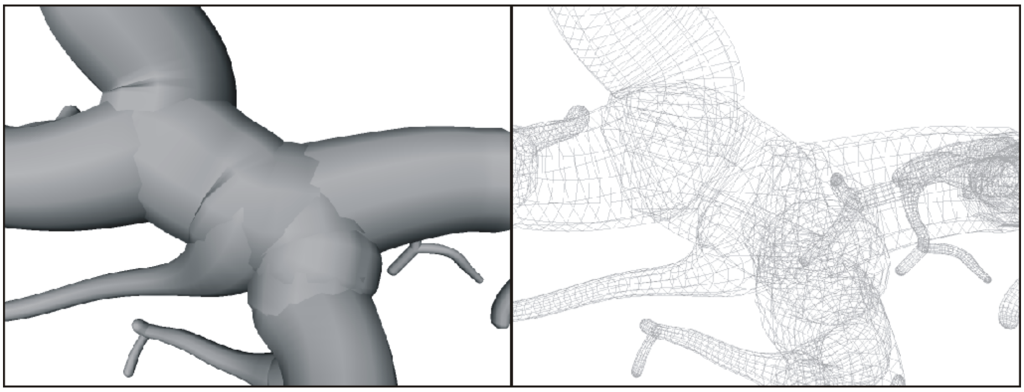
Model-based Visualization – Truncated Cone Fitting

Hahn et al., 2001: "*Visualization and Interaction Techniques for the Exploration of Vascular Structures*".

Directed, acyclic graph represents the vessel topology

Smoothing of the vessel skeleton and the associated radii

Representation of the vessel diameter by truncated cones



Model-based 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

© Ehricke, 1994

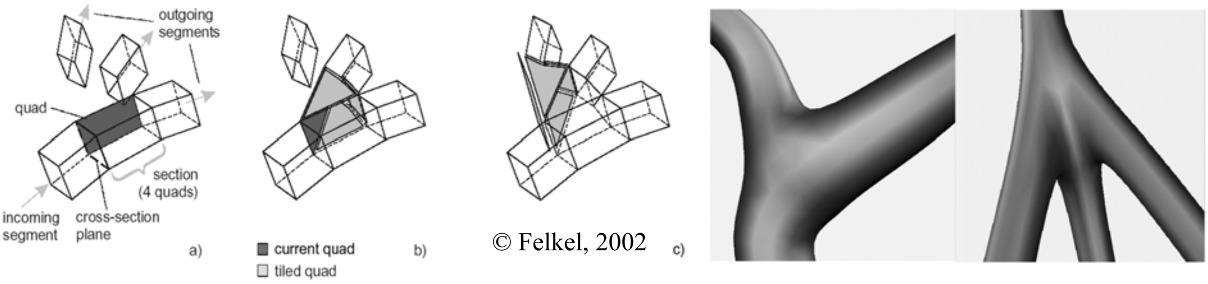
Model-based Visualization – Subdivision Surfaces

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



Model-based Visualization – Simplex Meshes

Bornik et al., 2005: *"Reconstruction and Representation of Tubular Structures using Simplex Meshes"*

Simplex Meshes: special kind of deformable models [Delingette99]

- Each vertex adjacent to 3 neighboring vertices

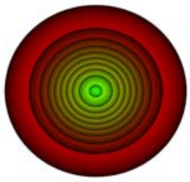
Visualization in two steps:

- Construction of an initial simplex mesh by connecting adjacent cross-section polygons in a sophisticated manner
- Iterative mesh deformation based on Newtonian law of motion
  - External forces directed to sampling points based on cross-sections and radii (affects mainly branchings)
  - External forces directed to boundary voxels of the segmentation result (affects regions with no circular cross-section shape)
  - Internal regularizing forces

Model-based Visualization – Convolution Surfaces (CS)

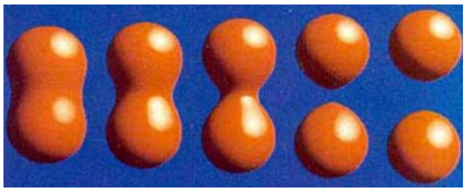
Oeltze and Preim, 2004: ”*Visualization of Anatomic Tree Structures with Convolution Surfaces*“.

Application of implicit functions (Zero set F(p)-Iso=0)



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

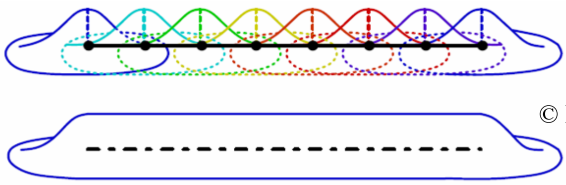
$$\omega = \textit{width coefficient}$$



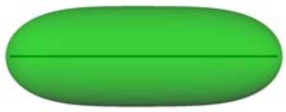
© Blinn, 1982

Convolution Surfaces [Bloomenthal 1991]:
(*Skeleton-based modeling*)

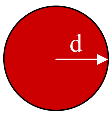
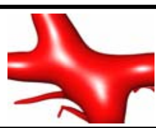
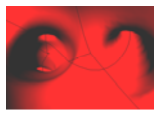
$$F(p) = \int_S h(s-p)ds = (h \otimes S)(p)$$



© Bloomenthal, 1995



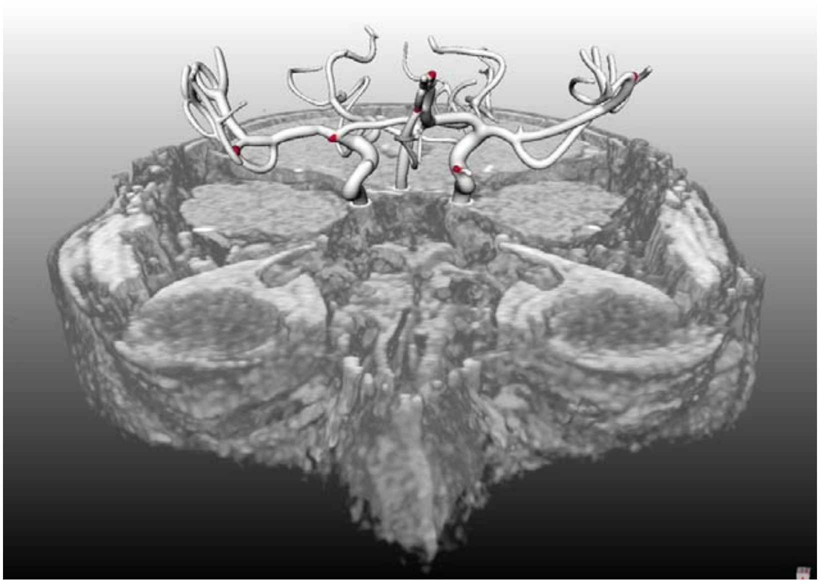
Model-based Visualization – Comparison of the Techniques

Method	Geometry					
Gerig, 1993	Cylinder	no local diminution	no	yes	no	no
Hahn, 2001	Truncated cone	yes	no	yes	yes	no
Ehricke, 1994	Freeform Surfaces	yes*	yes*	no*	no*	yes*
Felkel, 2002	Subdivision Surface	yes	yes	yes	no	yes
Bornik, 2005	Simplex Mesh	yes	yes	yes	yes	yes
Oeltze, 2004	Convolution Surface	yes	yes	yes	yes	yes

* guess

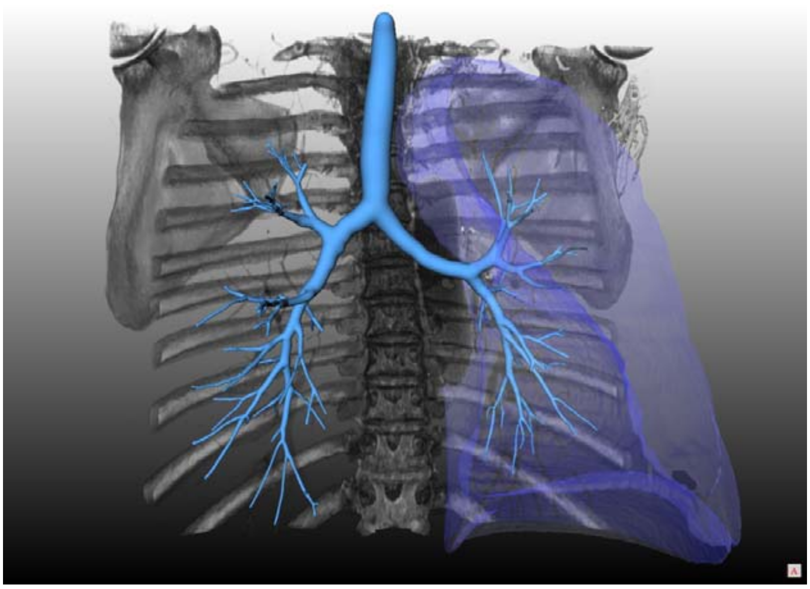
Application Scenarios –
Analysis of Cerebral Vasculature

Cerebral vasculature of a human brain. Colored accentuations mark suspicious locations indicating aneurysms. A volume rendering of the context supports the orientation.



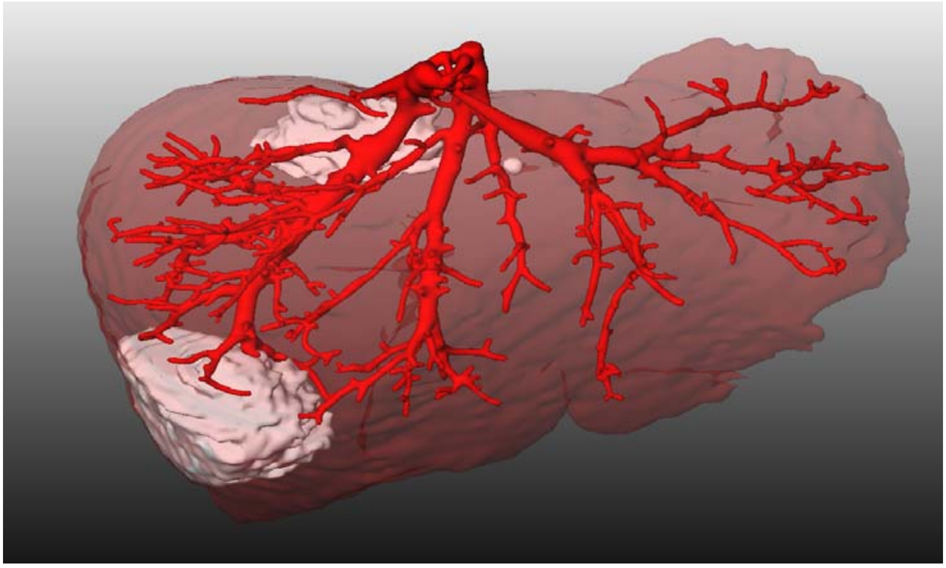
Application Scenarios –
Analysis of the Bronchial Tree

Bronchial tree in a human lung. The left pulmonary lobe is rendered transparent together with a volume rendering of additional vasculature and the surrounding bones.



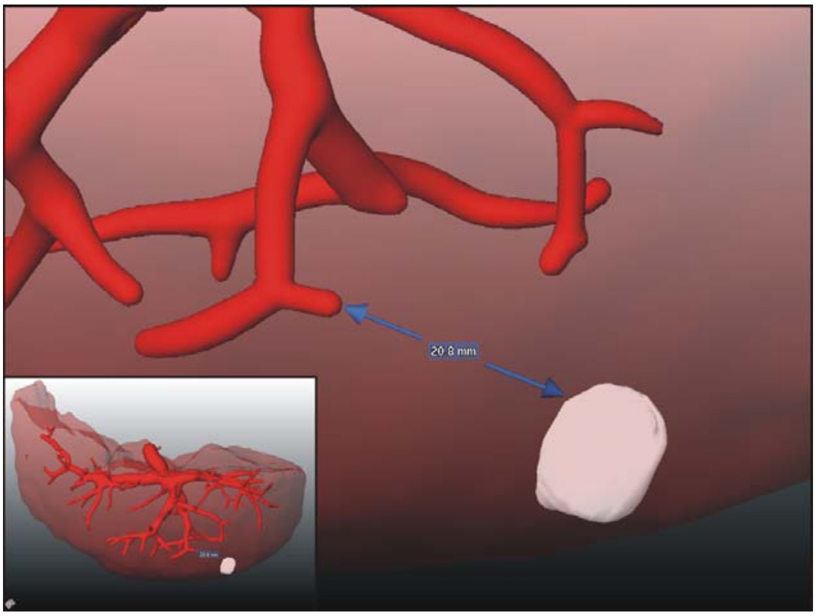
Application Scenarios – Tumor Resection (1)

Visualization of the portal vein inside a human liver. The liver is rendered transparent and three tumors are visualized as opaque surfaces.



Application Scenarios – Tumor Resection (2)

Measurement of the minimal distance between the portal vein and a tumor in preparation for a tumor resection.



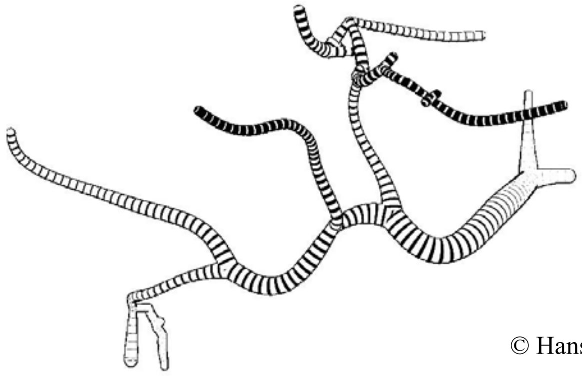
Application Scenarios – Augmented Reality (1)

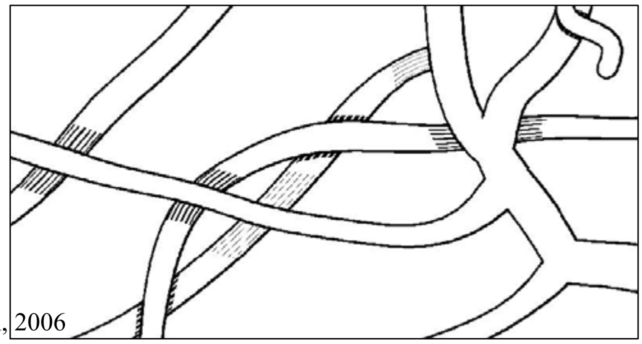
Ritter and Hansen, 2006: *"Real-time Illustration of Vascular Structures"*.
At this years IEEE Visualization, Session: xxx, Time: xxx

Intraoperative projection of vasculature on liver surface

1Bit color-coded 2d-projection result

Visualization of distance info by means of procedural textures





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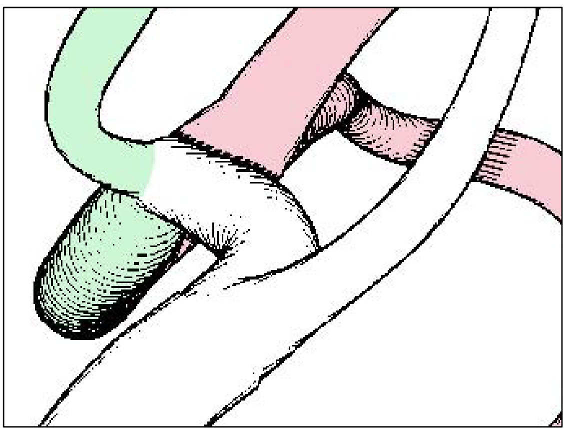
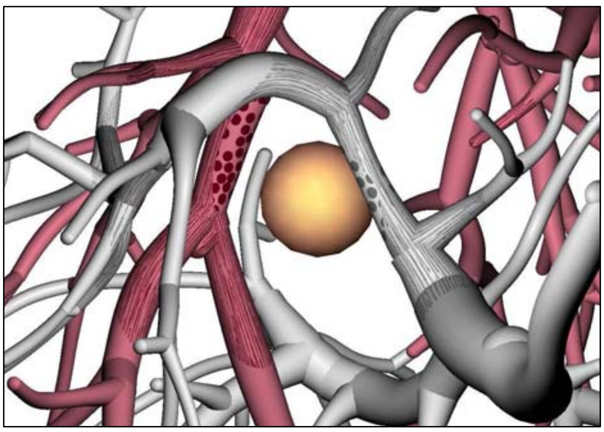
Application Scenarios – Augmented Reality (2)

Visualization of surface orientation by means of hatching

Varying textures to code distances between structures





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Validation – Preparation and Methods

Preparation:

- Selection of representative data sets
- Specification of meaningful validation parameters
- Definition of a reference (~Phantom)

Methods:

- Qualitative analysis by means of visually examining the reconstructed surface and a comparison with the reference
- Quantitative analysis by means of computing the local error between the reconstructed surface and the reference applying distance measurements
- Voxelization of the surface and a comparison with the result of the segmentation (from the vessel analysis step)

➔Volume preservation criterion (*global*)

➔Measurement of the deviation between corresponding vessel branches applying the Hausdorff-distance (*local*)

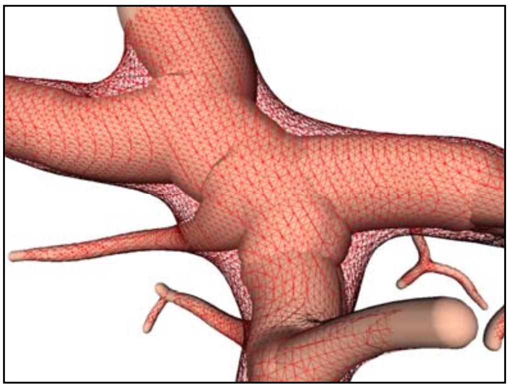
Validation – Exemplified for Convolution Surfaces

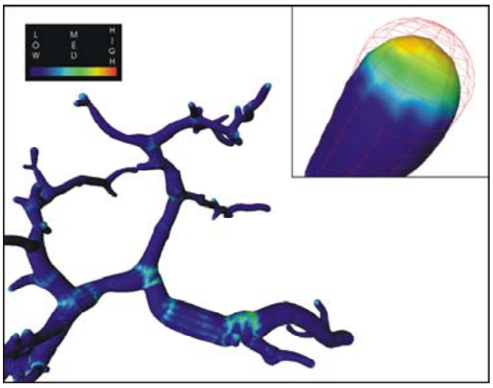
Oeltze and Preim, 2004: ” *Visualization of Vascular Structures: Method, Validation and Evaluation*“, *IEEE Transactions on Medical Imaging.*

Superimposition of CS and truncated cones

Distance measurements (computed using AMIRA™):

- Isosurface ➔ CS
- Truncated cones ➔ CS

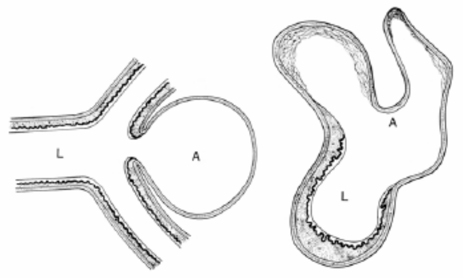




Model-Free Visualization

Simplifying model-assumption of circular cross-sections is invalid for pathologic vessel parts, e.g. aneurysms

Non-pathologic vessels may exhibit non-circular cross-sections as well, e.g. trachea and main bronchial tubes



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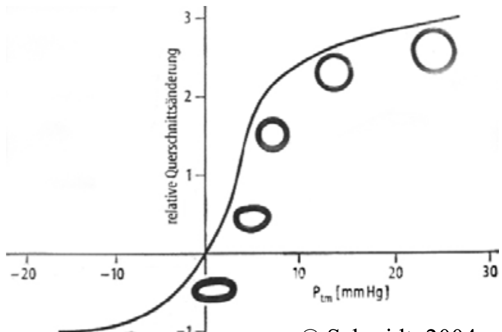

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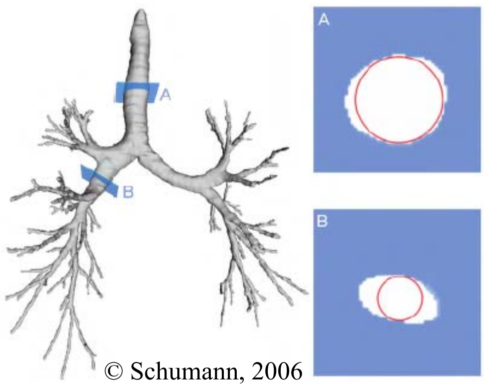

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Model-Free Visualization – Multi-level Partition of Unity Implicits

Ohtake, 2003: *"**M**ulti-level **P**artition of **U**nity **I**mplicits"*

Approximation of a point cloud by a surface

➔Visualization of vasculature based on post processed segmentation result (points placed within boundary voxels)

➔Arbitrary cross-sections may be reconstructed

➔Suitable for vessel diagnosis

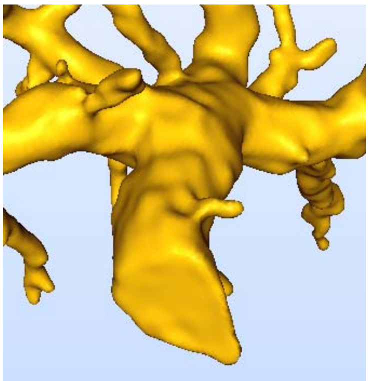
Algorithm:

- Spatial subdivision of the point cloud by an octree
- Local approximation by means of algebraic surfaces
- Blending of local approximations results in global approximation

Model-Free Visualization – Comparison with Marching Cubes

Why not using marching cubes and smoothing the result?

- No stair case artifacts
- Maintenance of thin vessels
- Accuracy and smoothness are parameterized
- Noise removal and robustness in the presence of holes



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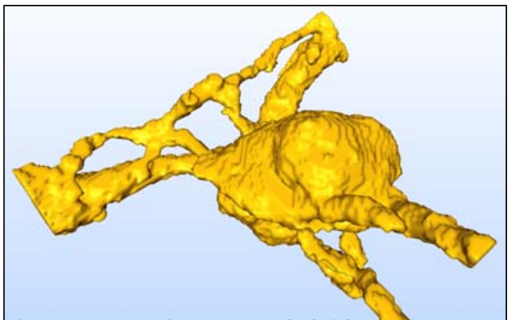
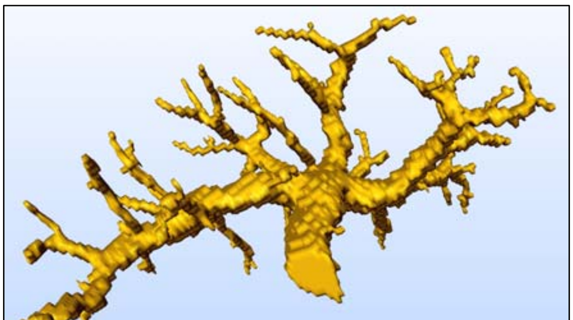
Model-Free Visualization – Results (1)

MC

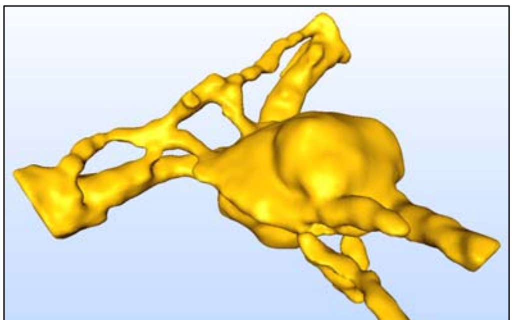


Aneurysm, 1sec, Δ 53,948

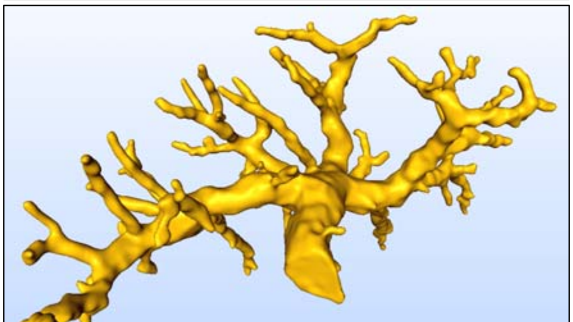


Portal Vein, 2sec, Δ 80,020

MPU



Aneurysm, 5.3sec, Δ 61,324



Portal Vein, 13.7sec, Δ 166,780

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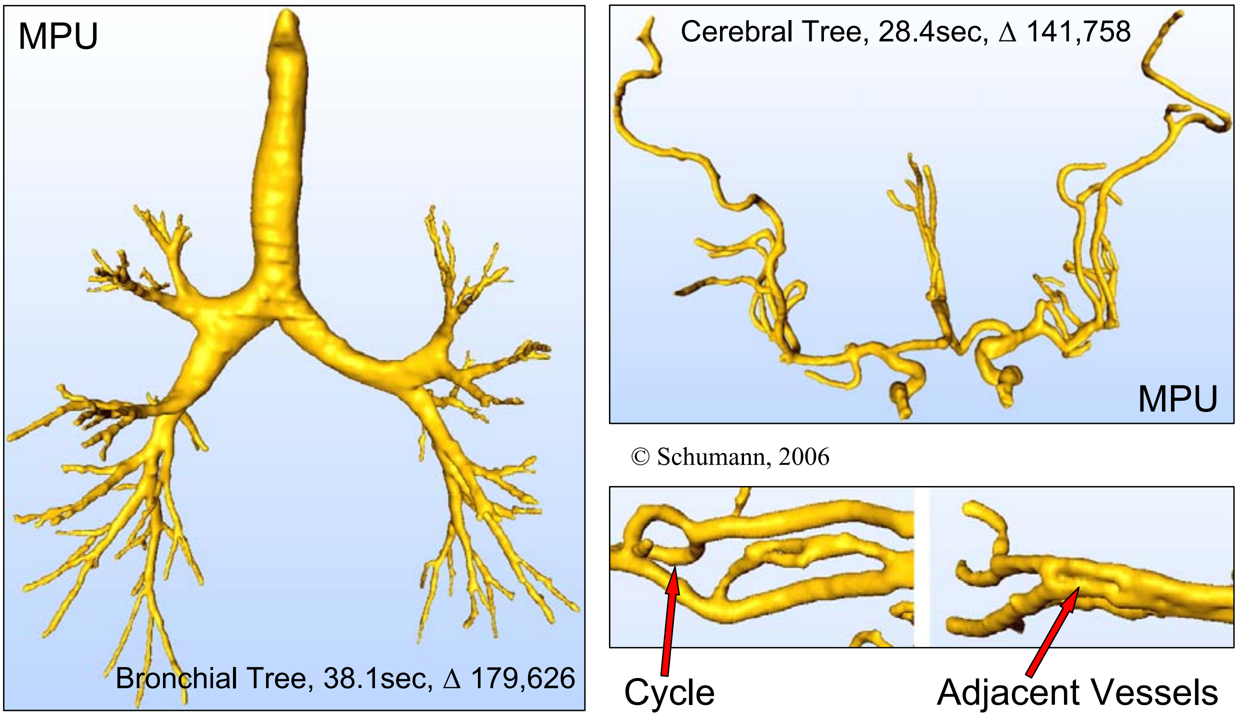
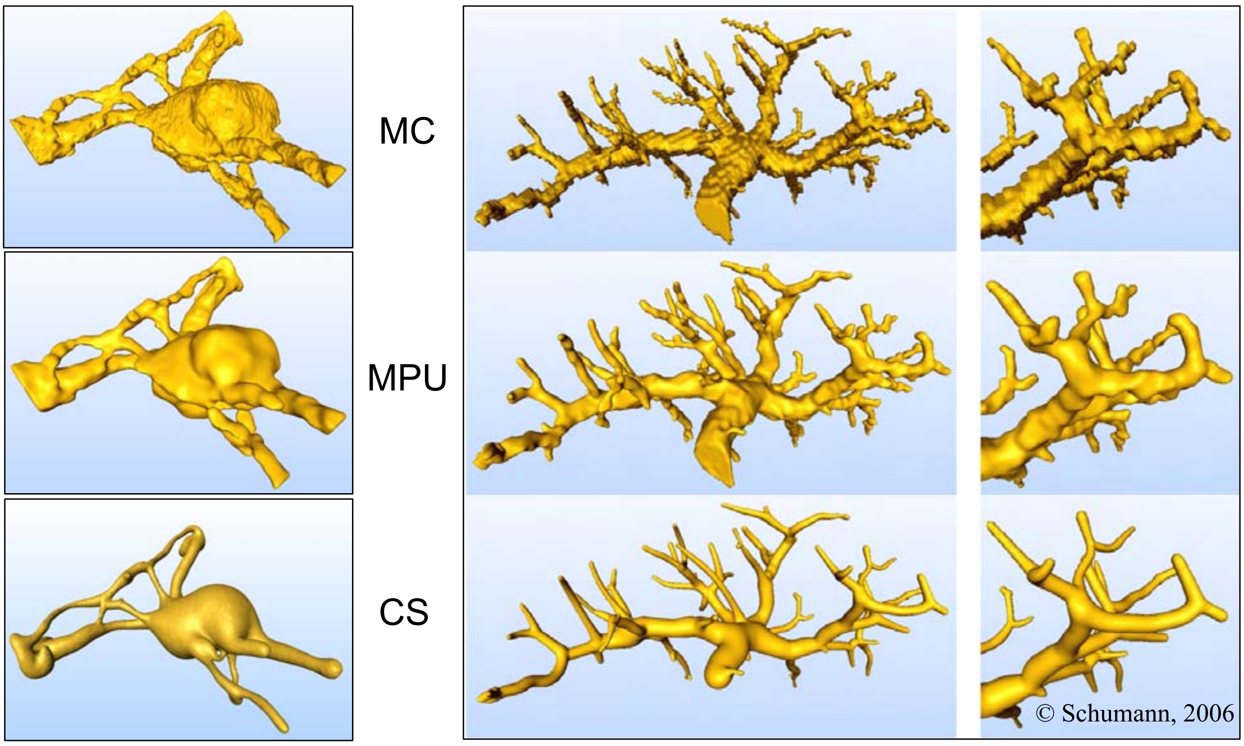
Model-Free Visualization – Results (2)

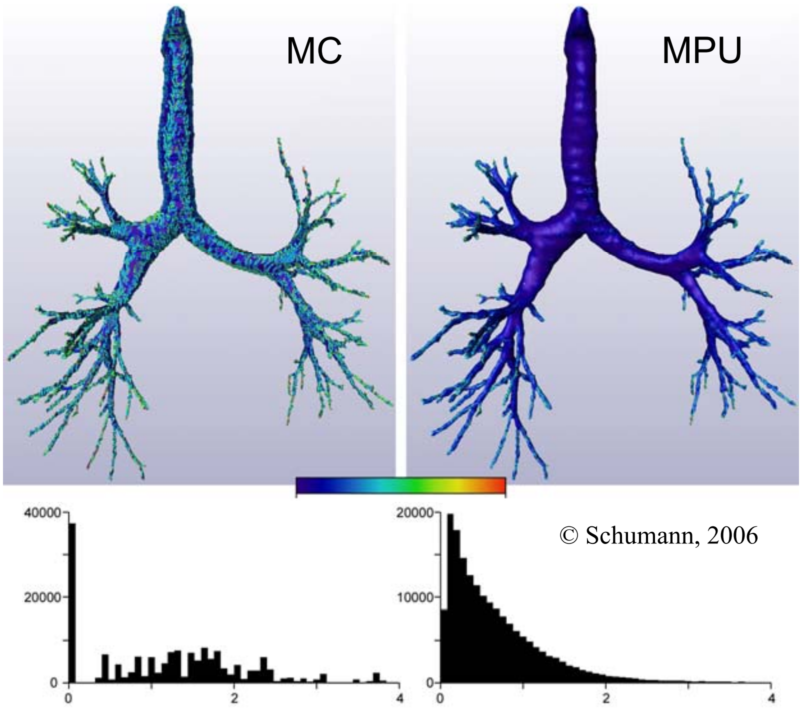


Model-Free Visualization – Results (3)



Model-Free Visualization – Smoothness

- Maximum curvature as a measure of smoothness
- Computed using AMIRA™
- Comparison of MC and MPU
- Histogram of the curvature values



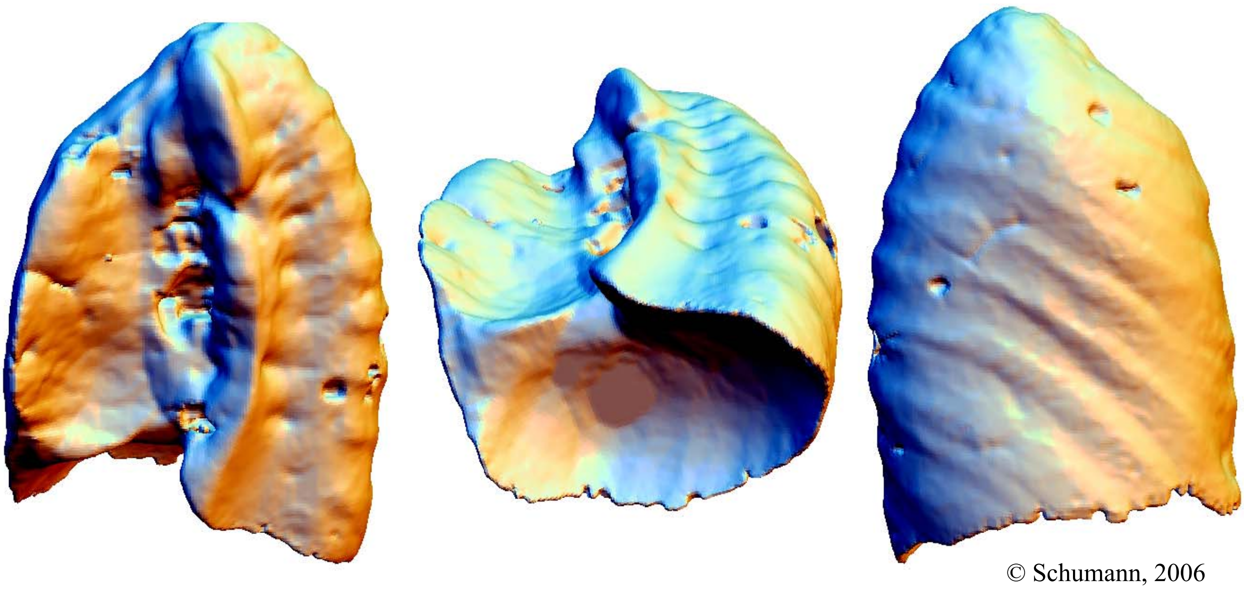
Model-Free Visualization – Surfaces Distances

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
Aneurysma	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

Model-Free Visualization – Application for Different Structures

Lung lobe, 1 minute, Δ 256,216



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Conclusion

Therapy planning and medical education require clear communication of topology and morphology

➔ Model-based reconstruction of the vascular surface

- *Subdivison* and *Convolution Surfaces* closely adhere to the data and generate smooth, organic looking surfaces

!!! Not suitable for vessel diagnosis due to simplifying model assumption of circular cross-sections

Vessel diagnosis requires accurate rep. of vascular cross-section

➔ Model-free reconstruction of the vascular surface directly from the segmentation result by means of MPUs

!!! Suitable for vessel diagnosis since no model assumption is made

Quantitative analysis of global/local deviations for validation

Future Work

Accelerating the visualization with Convolution Surfaces and MPUs to facilitate an application in clinical routine

Extension of the Convolution Surfaces approach to elliptical cross-sections

Hybrid visualization, integrating Convolution Surfaces and MPUs for vessel parts with nearly circular cross-sections and for vessel parts whose cross-sections strongly deviate from this model assumption, respectively

Integration of interaction facilities to explore vasculature, e.g. for selection, measurement and annotation

Mapping of additional information to the vascular surface, e.g. existence of plaque or blood flow quantities

Acknowledgements

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K.J. Klose, Institute of Radiation Diagnostics, Philipps-University Marburg

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