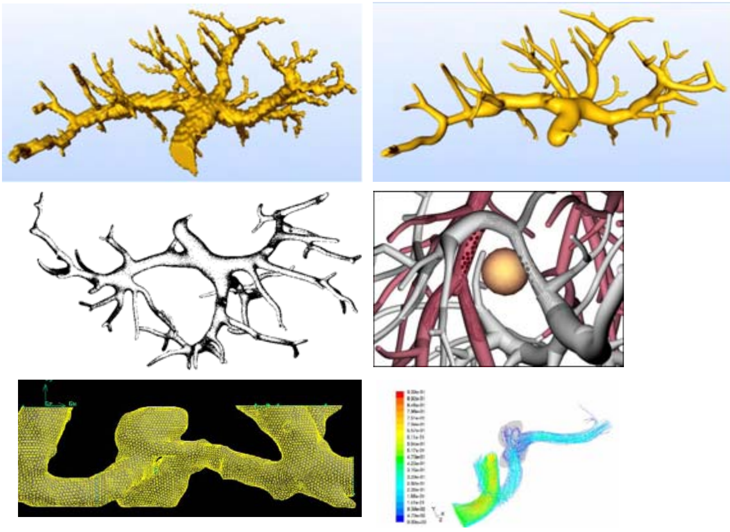
Visualization of Vascular Structures



Outline

- Methods for 3D Visualization of Vasculature
- Direct Volume Rendering
- Model-free Surface Visualization
- Model-based Surface Visualization
  - Explicit Construction of Vascular Geometries
  - Implicit and Parametric Methods
- From Vascular Surface Geometry to Simulation Models

"Traditional" Visualization Approaches

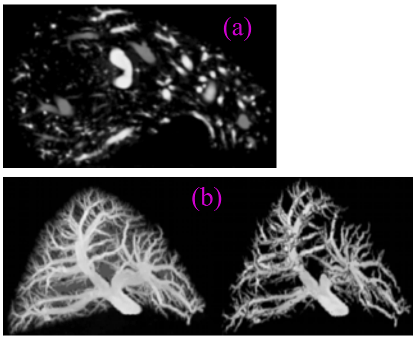
- Traditional approaches:

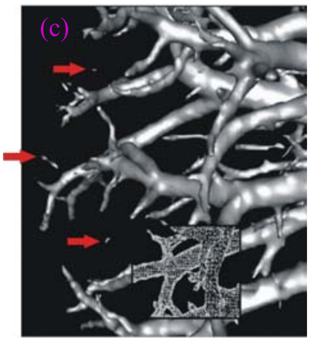
(a) slice-based examination

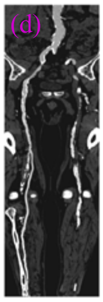
(b) Maximum Intensity Projection,
Closest Vessel Projection [Zuiderveld, 1995]

(c) Isosurface Rendering

(d) Curved Planar Reformation





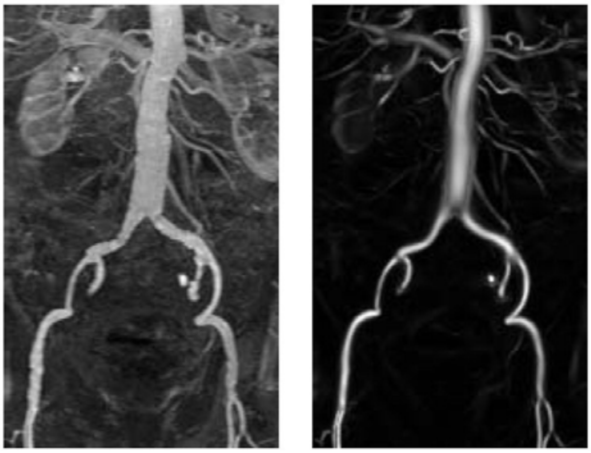


[Kanitsar, 2001]

Vascular Diagnosis vs. Surgery Planning

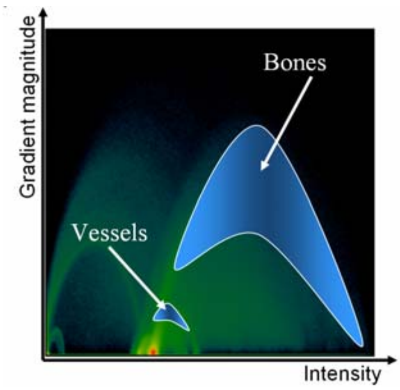
- Visualization in vascular diagnosis and vascular surgery:
  - Close adherence to the image data (vascular cross section)
  - Mostly slice-based examination, Curved Planar Reformations
  - 3D visualization must be accurate
  - Vascular surgery: bypass surgery, endoscopic treatment of aneurysms
- Visualization 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 due to image noise, partial volume effect and limited resolution of CT and MRT
  - Reconstruction of vascular structures based on a model

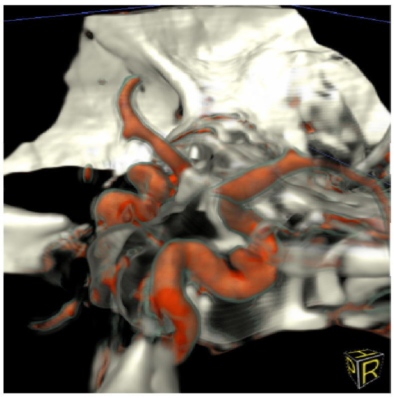
Direct Volume Rendering



MIP visualization. Right image: After applying a „vesselness“-filter. [Frangi, 1998]

Direct Volume Rendering

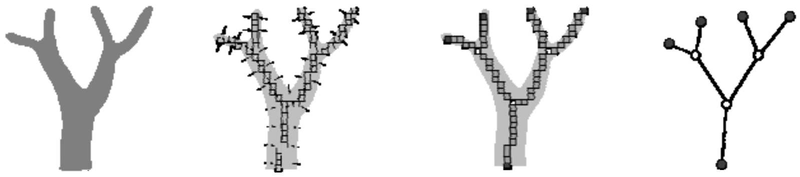




1D Transfer Functions do not allow to distinguish skeletal structures and contrast-enhanced vessels. [Vega, 2003]

Image Data and Vessel Analysis

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



[Selle, 2000]

Results of vessel analysis:

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

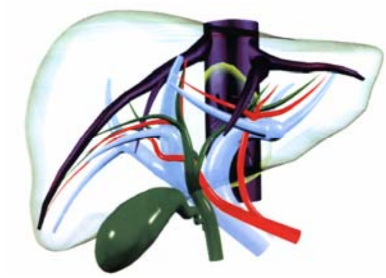
[Ehricke, 1994]

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



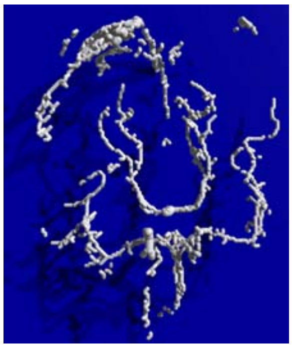
[Mazziotti, 1997]

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

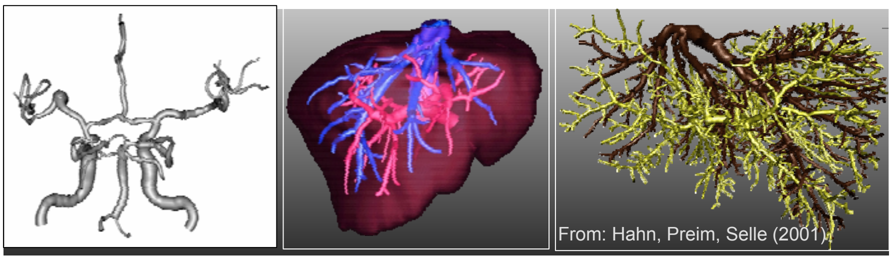
- Gerig et al., 1993: “Symbolic Description of 3d structures applied to cerebral vessel tree obtained from MR angiography volume data”.
- Graph representation (edges, nodes) of the vessel tree for structural analysis, e.g. identification of subtrees
- Representation of the local vessel diameter by means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



[Gerig, 1993]

Model-based Visualization – Truncated Cones Fitting

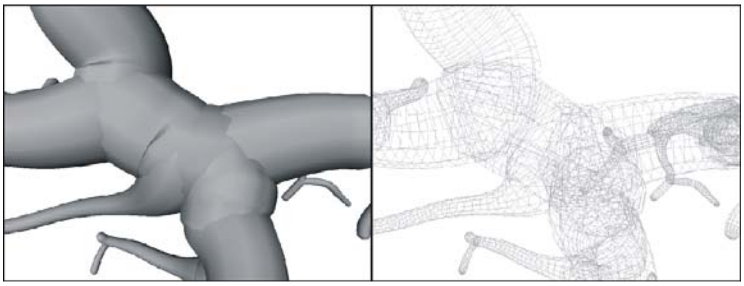
- Filtering: Smoothing of the skeleton and radius (Binominal filter)
- Mapping: 1. Concatenation of truncated cones along the skeleton
  2. Mapping of truncated cones to polygons



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)

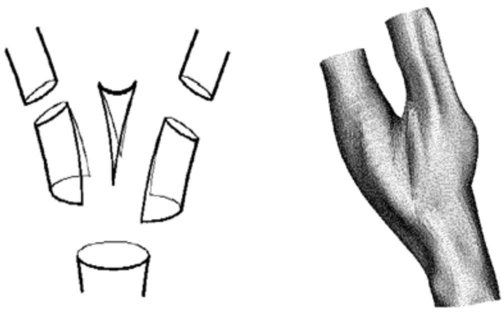
Model-based Visualization – Truncated Cones Fitting

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



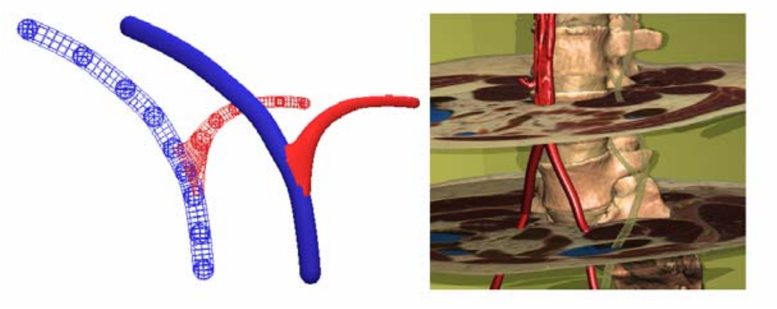
Model-based Visualization – Freeform Surfaces

- Spline-curves represent the vessel skeleton
- Voxel ring describes local cross section



[Ehricke, 1994]

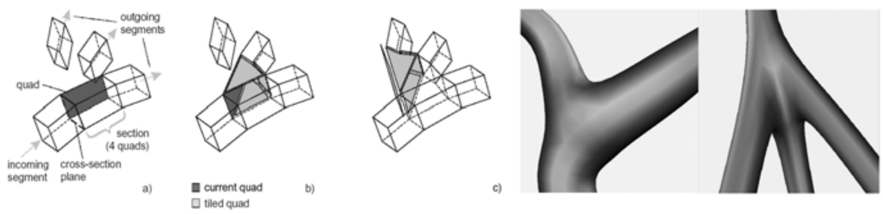
Model-based Visualization – Freeform Surfaces



Modelling incompletely segmented nerves and vascular structures with B-splines. Application within the VoxelMan
[Pommert, 2001]

Model-based Visualization – Subdivision Surfaces

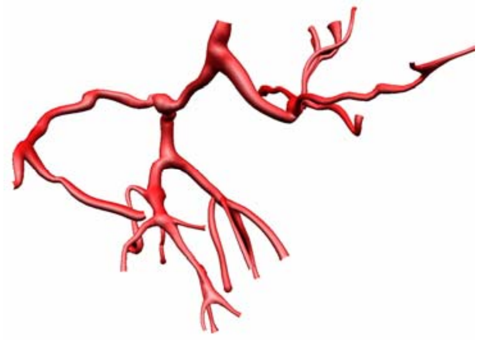
- Computation of reference frame for each skeleton voxel to avoid twisting of the reconstructed vessel
- Visualization in two steps:
  - Construction of a coarse initial mesh by means of quads
  - Iterative refinement of the initial mesh applying Catmull-Clark subdivision surfaces



[Felkel, 2002]

Model-based Visualization – Subdivision Methods

- Enables trade-offs between quality and speed
- High quality at branchings possible



[Felkel, 2004]

Model-based Visualization – Simplex Meshes

Simplex Meshes: special kind of deformable models [Delingette, 1999]

- Each vertex adjacent to 3 neighboring vertices

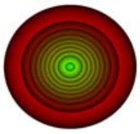
Visualization in two steps [Bornik, 2005] :

- Construction of an initial simplex mesh by connecting adjacent cross-section polygons
- Iterative mesh deformation based on Newtonian law of motion
  - External forces and internal regularizing forces

Visualization of Vascular Structures: Implicit Methods

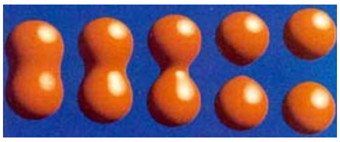
Idea (exploration of implicit surfaces):

- Implicit functions (F(x,y,z) – Iso = 0)
- Original application in computer graphics
  - Blobby Molecules for the display of electric fields, Blinn [82]



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

$$\omega = width\ coefficient$$



[Blinn, 1982]

Implicit surfaces for the visualization of tree structures

- Energy distribution: skelett points as energy sources
- Skelett points define isospheres
- Problem: Smooth surfaces at line segments
  → Solution: Convolution Surfaces (Jules Bloomenthal)

Visualization of Vascular Structures: Convolution Surfaces

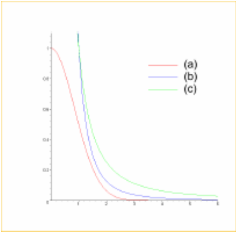
Convolution Surfaces (Bloomenthal and Shoemake [1991])

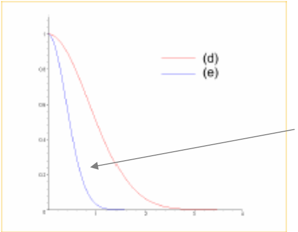
- Convolution of a signal with a filter
- Here: Convolution of line segments with a 3d-lowpass filter

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

- Polygonization with an isovalue depending on the filter

Visualization of Vascular Structures: Convolution Surfaces





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

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

$$Iso = 1/32 = 0.03125.$$

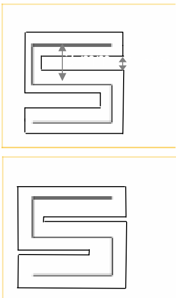
Exploration of filter functions.
Selection guided by the following criteria:

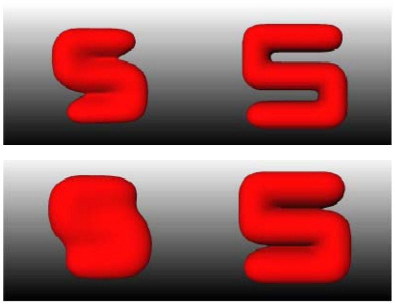
- Correct display of the radius,
- Unwanted-Effects,
- Fast computation

Result:

- A narrow Gaussian filter is a good choice.
- For even narrower filter kernels the implicit surface converges against the truncated cone visualization.

Visualization of Vascular Structures: Convolution Surfaces





Above: dist.: 3 mm, radius: 1 mm

Below: radius: 1.37 mm (3-1.37x2 = 0.26 mm)

Unwanted Blending

Left: Convolution with „normal“ Gaussian filter

Right: Convolution with narrow Gaussian filter

Visualization of Vascular Structures: Convolution Surfaces

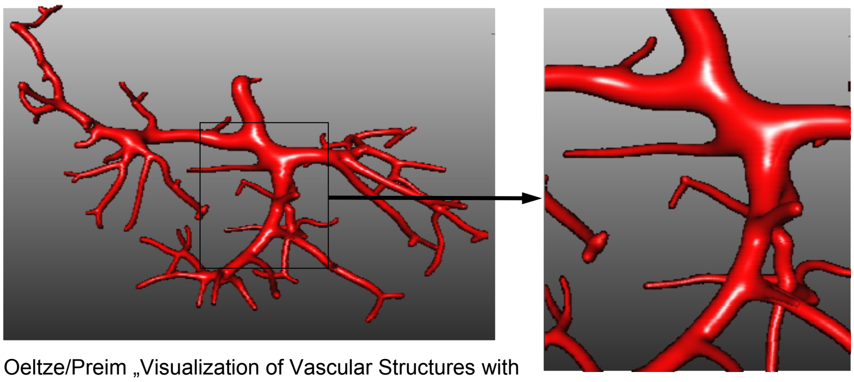
Studying blending effects by means of a trifurcation

- Blending Strength

- Bulging

Visualization of Vascular Structures: Applications of Convolution Surfaces

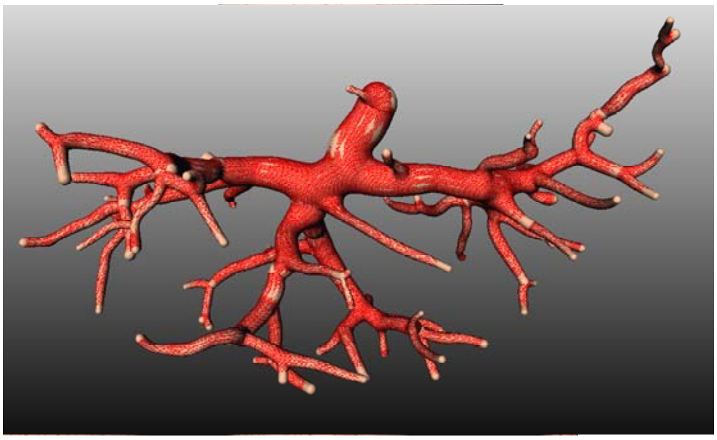
Portal vein of a human liver



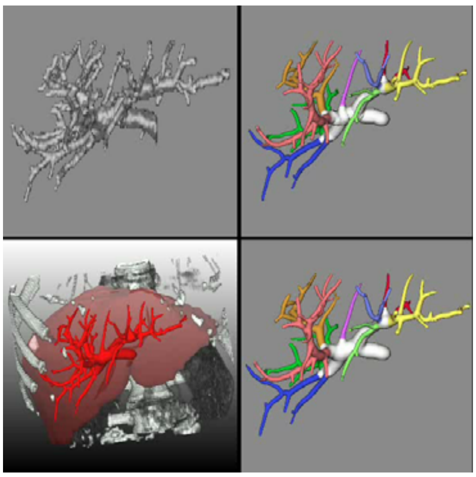
Oeltze/Preim „Visualization of Vascular Structures with Convolution Surfaces“, IEEE Transactions on Medical Imaging

Visualization of Vascular Structures: Validation of Convolution Surfaces

Comparison: Convolution surface as wireframe; truncated cones as shaded surface visualization.



Visualization of Vascular Structures: Validation of Convolution Surfaces



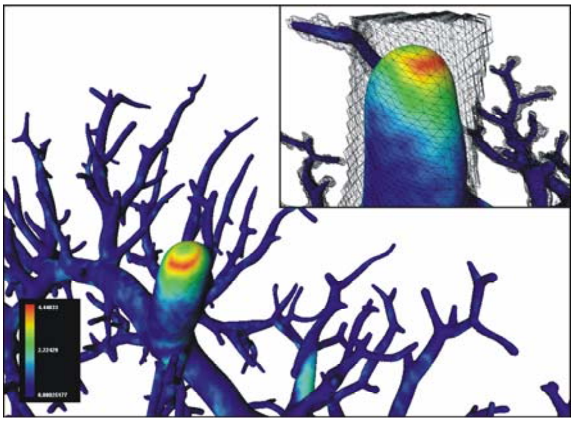
Visualization of Vascular Structures: Validation of Convolution Surfaces

- Quantitative validation (directional distances) between CS and Truncated Cones and CS to Isosurface of the segmentation result.
- Distances strongly depend on the width coefficient. Measurements with the following filter:

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

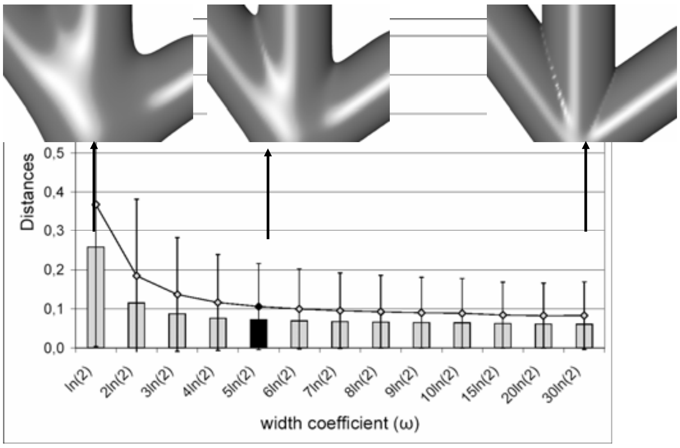
- Results:
  - Quantitative visualization (color coding)
  - Histogrammes of distances
  - Statistic Evaluation (mean, standard deviation, …)

Visualization of Vascular Structures: Validation of Convolution Surfaces



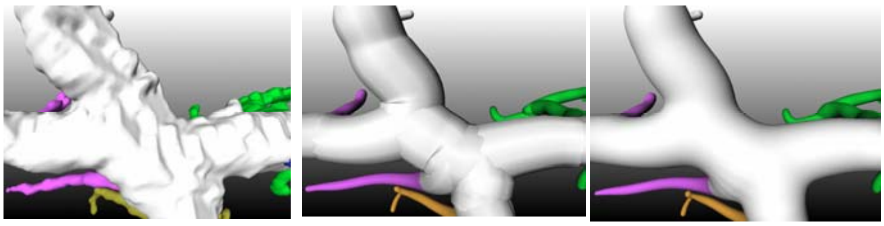
CS → Isosurface: Large distances only at the root of vascular trees

Visualization of Vascular Structures: Validation of Convolution Surfaces

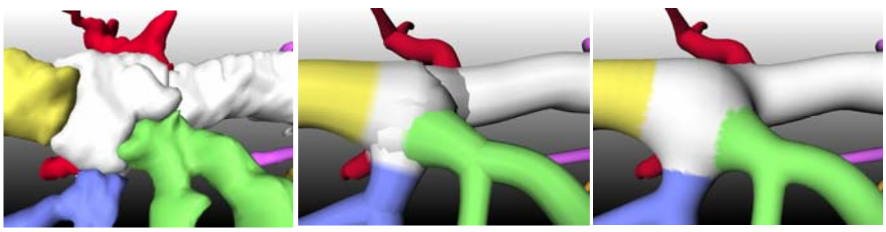


Width Coefficient versus accuracy (average and standard deviation of directional distances to isosurface)

Visualization of Vascular Structures: Evaluation of Convolution Surfaces



Isosurface of the segmentation result | Truncated Cones | Convolution Surfaces

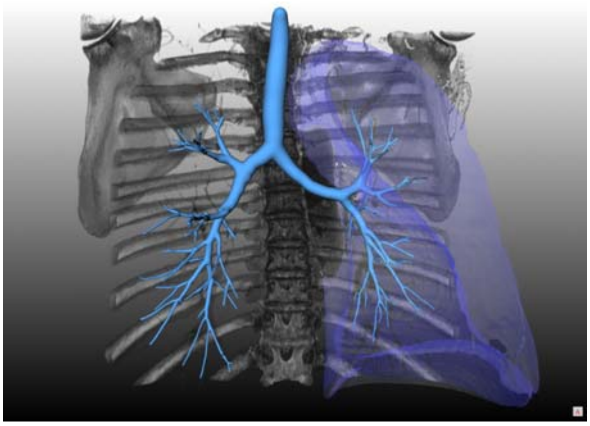


Visualization of Vascular Structures: Evaluation of Convolution Surfaces

Method	Clarity (n=11) Ø	σ	Comprehen-sibility (n=11) Ø	σ	Similarity to operative Views (n=8) Ø	σ	Visual Quality (n=11) Ø	σ
Iso	1.8	0.69	1.9	0.85	1.6	0.7	1.7	0.69
Cones	3.7	0.84	3.9	0.86	3.5	0.9	3.8	0.71
CS	4.1	0.87	4.1	0.89	4.0	0.89	4.2	0.76

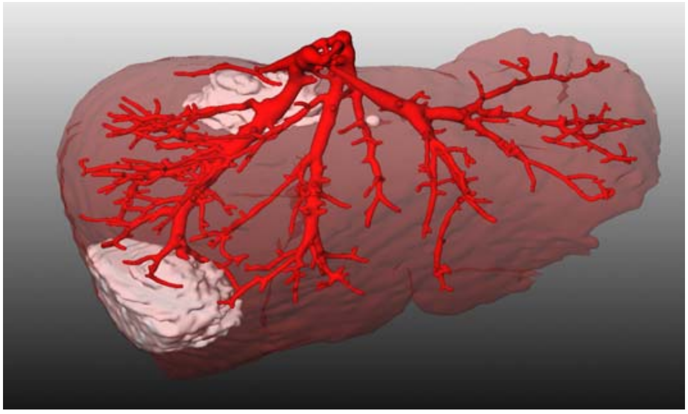
Application Scenarios – Analysis of the Bronchial Tree

Bronchial tree (> 3000 branchings, > 3 M triangles, 54 seconds) in a human lung (volume rendering).



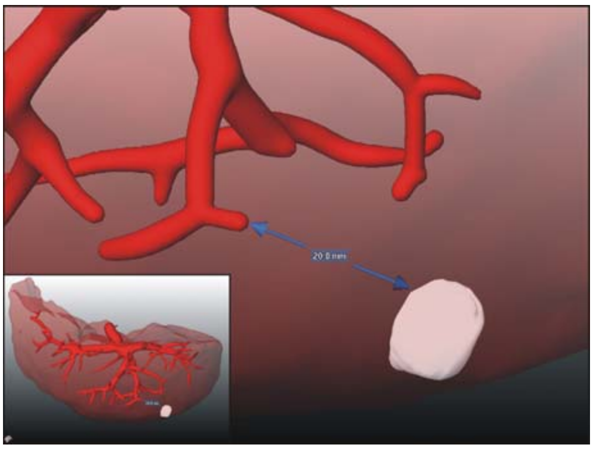
Application Scenarios - Tumor Resection (1)

Visualization of the portal vein inside a human liver (with three tumors).

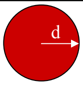
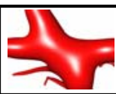
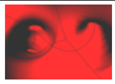


Application Scenarios – Tumor Resection (2)

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



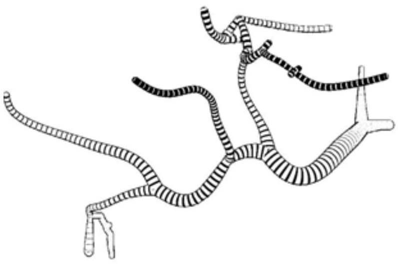
Model-based Visualization – Comparison

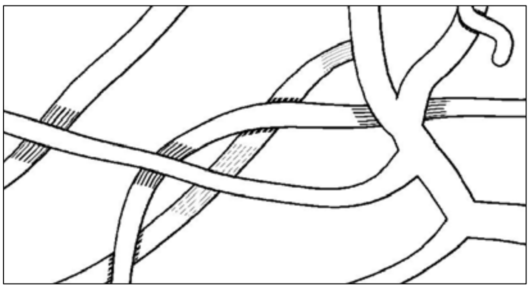
Method	Geometry					
Gerig, 1993	Cylinder	no local diminution	no	yes	no	no
Hahn, 2001	Truncated cone	Yes	no	yes	yes	no
Ehricke, 1994	Freeform Surfaces	yes*	yes*	no*	no*	yes*
Felkel, 2002	Subdivision Surface	Yes	yes	yes	no	yes
Bornik, 2005	Simplex Mesh	yes	yes	yes	yes	yes
Oeltze, 2004	Convolution Surface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

Illustrative Visualization of Vasculature

- Intraoperative projection of vasculature on liver surface
- Visualization of distance information by means of procedural textures
- Visualization method: truncated cones

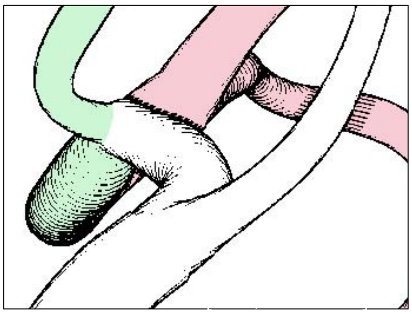
[Ritter et al. 2006]

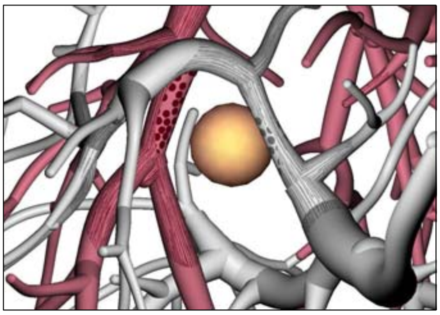




Illustrative Visualization of Vasculature

Visualization of surface orientation by means of hatching
Varying textures to code distances between structures





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Bernhard Preim, BVM Tutorial, März 2008

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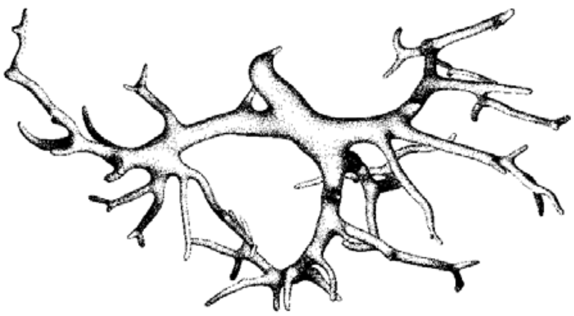
Illustrative Visualization of Vasculature



Stippling Convolution Surfaces with Textures. Minimal distortion of the stippling texture by using the PolyCubes-method. [Baer, 2007]

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Bernhard Preim, BVM Tutorial, März 2008

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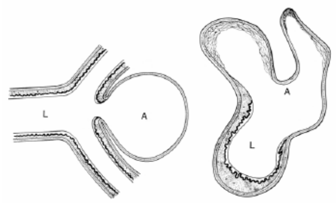
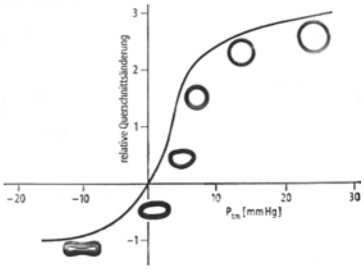
Model-Free Visualization

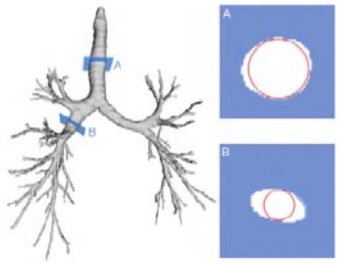
- Simplifying model-assumption of circular cross-sections is invalid for pathologic vessel parts, e.g. aneurysms
- Even Non-pathologic vessels may exhibit non-circular cross-sections



[Osborn, 1999]



[Schmidt, 2004]



[Schumann, 2006]

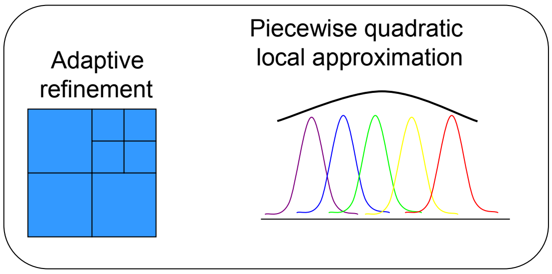
Model-Free Visualization – Multi-level Partition of Unity Implicits

Approximation of a point cloud by a surface [Ohtake et al. 2003]

- 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 surfaces
  – Blending of local approximations results in global approximation

Multi-level Partition of Unity Implicits

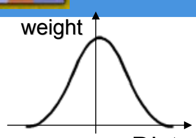


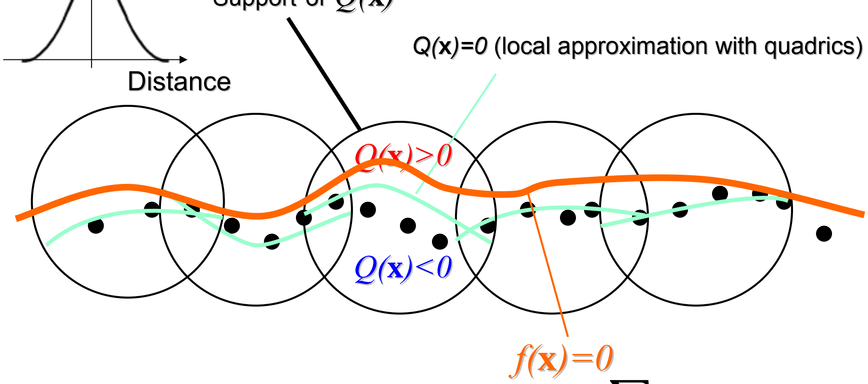
- Fast reconstruction of surfaces from scattered data
- Surface approximation with adaptive error control
- Search for points in spherical regions

Approximation with 14 million points

[Ohtake et al. 2003]

Model-Free Visualization Partition of Unity



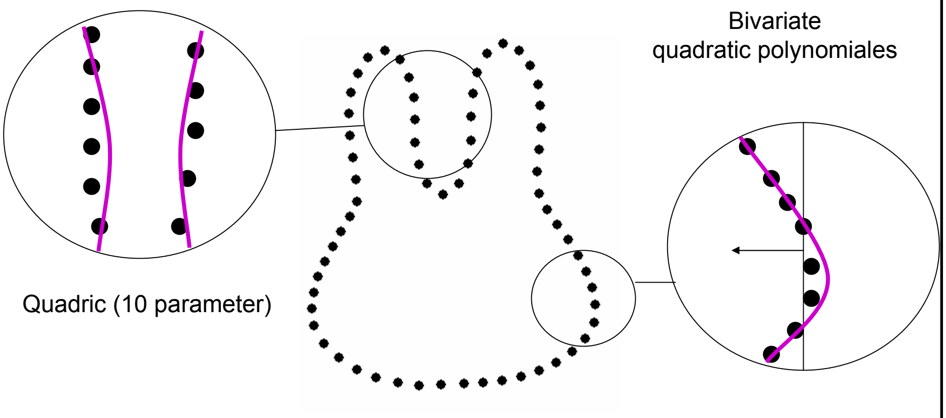


Weighted average of local approximations

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

Local Approximations

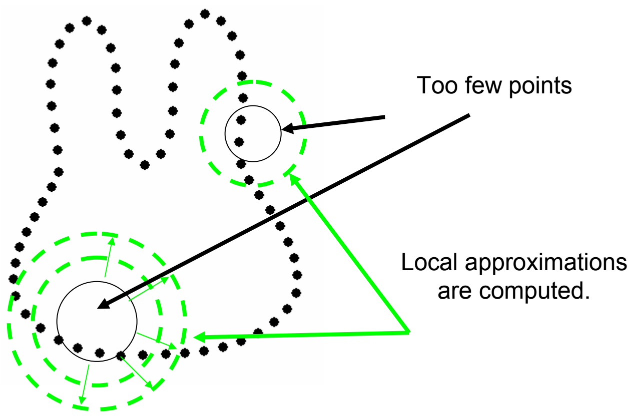
- Polynomial approximation (quadrics) with least square approach.



Adaptive subdivision guided by deviation of the normal

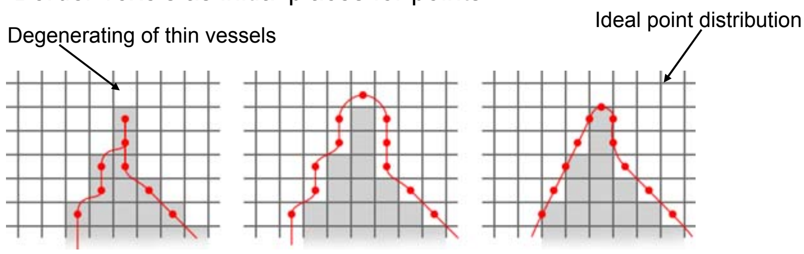
Local Approximations

- If not enough points are in the local region → expand it.
- Parameter: Maximum octtree depth, initial size of the region, growth factor

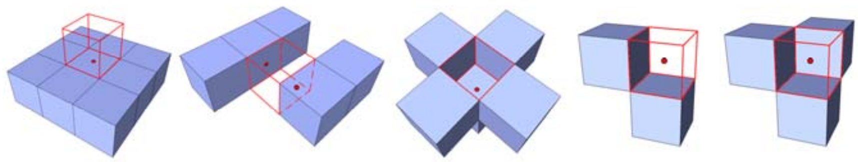


Model-Free Visualization

- Border voxels as initial places for points

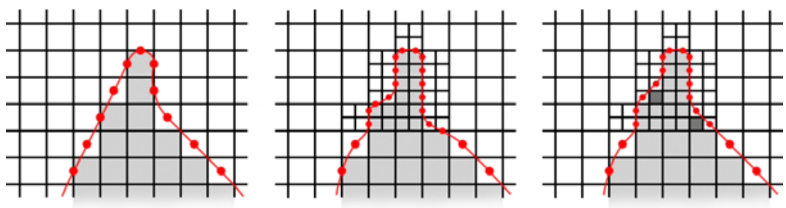


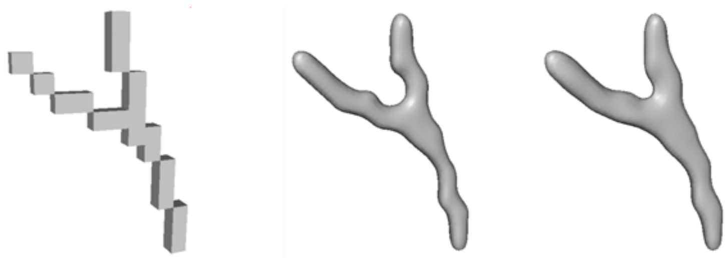
- Different cases for placing points



Model-Free Visualization

Adaptive subsampling of thin branches

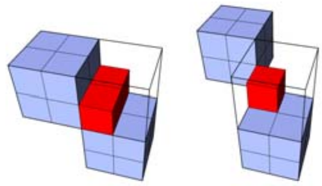




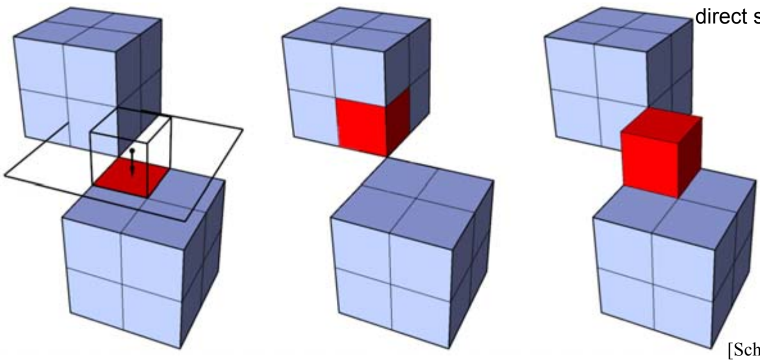
[Schumann, 2006 und 2007]

Model-Free Visualization

To reduce aliasing, subvoxel are included at certain features.

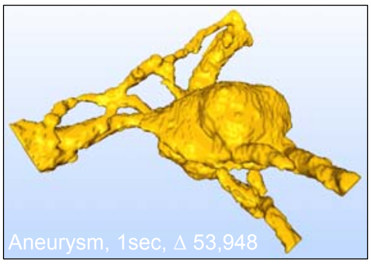


direct step / diagonal step

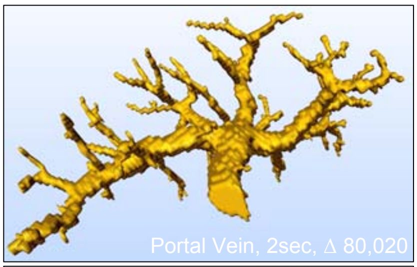


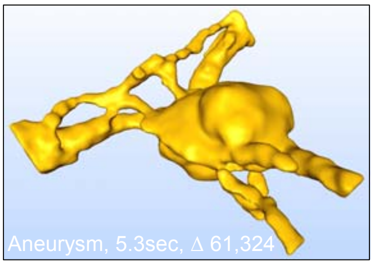
[Schumann, 2006 und 2007]

Model-Free Visualization – Results (1)

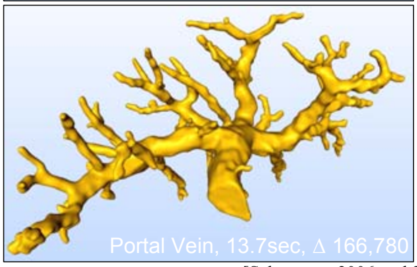


MC



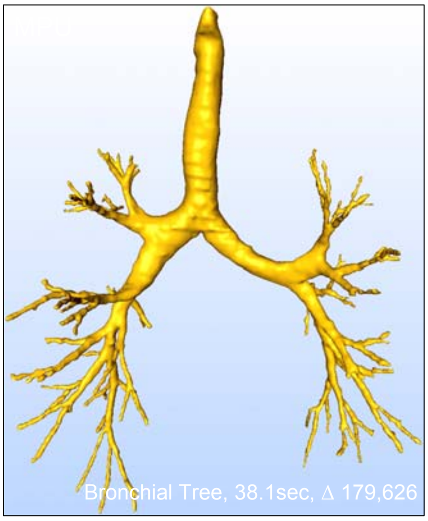


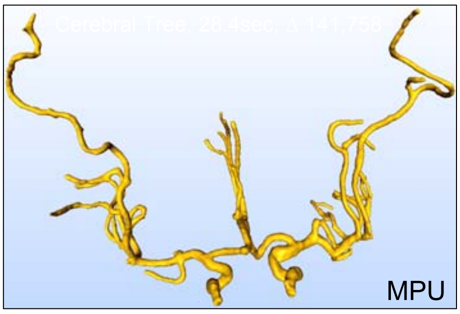
MPU



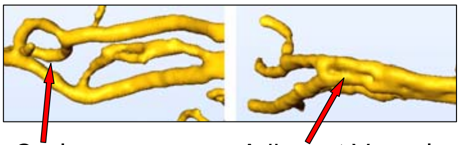
[Schumann, 2006 und 2007]

Model-Free Visualization – Results (2)



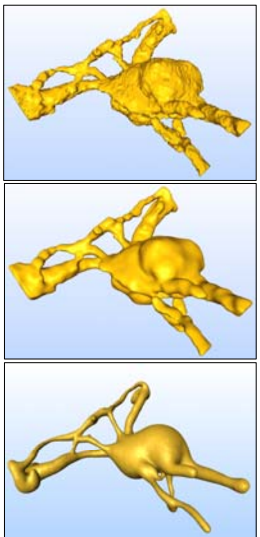


[Schumann, 2006]



Cycle Adjacent Vessels

Model-Free Visualization – Results (3)



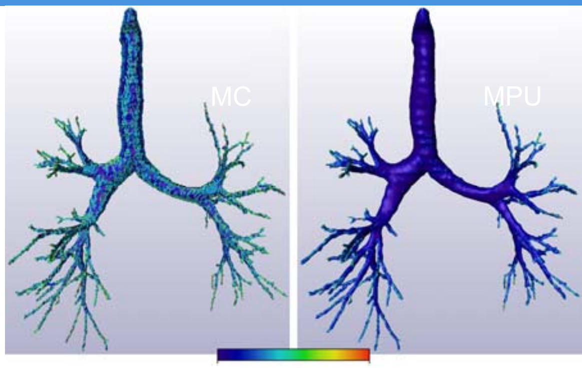
MC

MPU

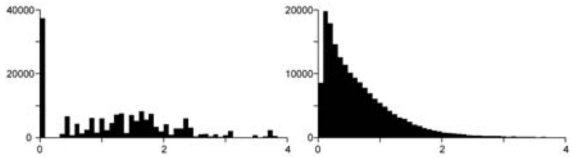
CS

Model-Free Visualization – Smoothness

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



- Histogram of the curvature values

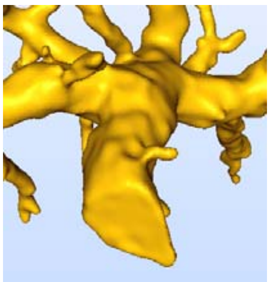


[Schumann, 2006 und 2007]

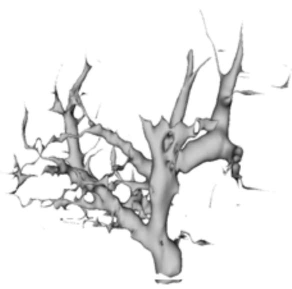
Model-Free Visualization – Comparison with Marching Cubes

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



[Schumann, 2006]



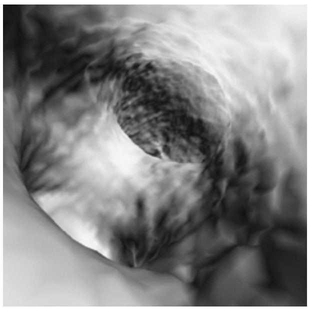
[Bade, 2006]

Model-Free Visualization – Surfaces Distances

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

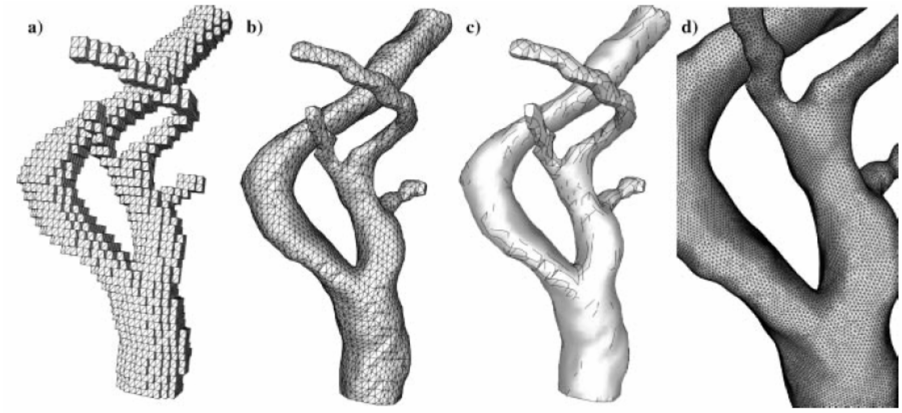
Dataset	Φ	σ	Rms	Median	Max	$>V_d/2$ [%]
Bronchial Tree	0.17	0.11	0.21	0.16	1.4	0.69
Portal Vein	0.17	0.11	0.2	0.15	0.84	0.82
Cerebral Tree	0.2	0.13	0.24	0.2	1.68	1.7
Aneurysm	0.21	0.16	0.27	0.19	1.9	4.1
Average	0.19	0.13	0.23	0.17	1.46	1.84

Virtual Angioscopy



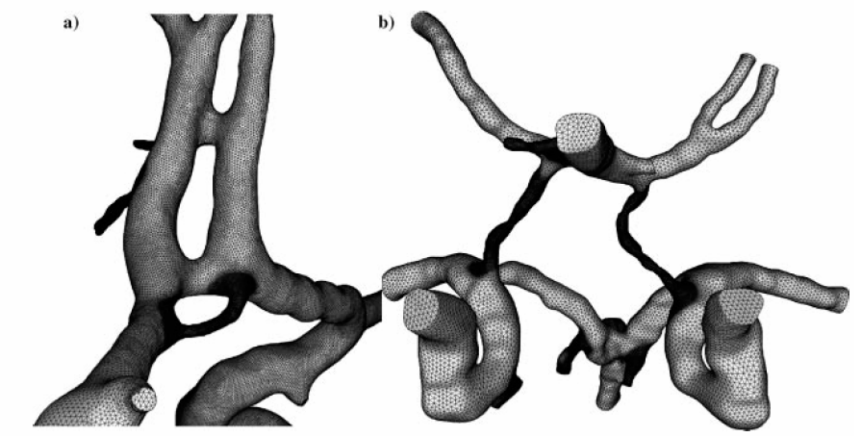
Visualization technique: Isosurface rendering based on smoothed segmentation result. Combination of overview and detail view. Specific application: Planning interventional treatment of cerebral aneurysms. [Bartz 99]

Simulation and Visualization of Blood Flow: Model Generation



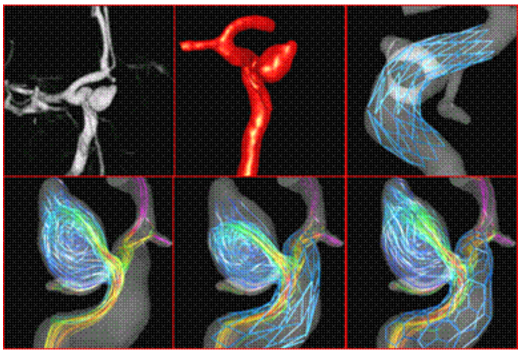
Voxel model – smoothed surface model – feature lines – adaptive refinement by considering Verfeinerung feature lines [Ceb01]

Model generation: Subdivision



- Adaptive refinement of grid resolution (element size) considering curvature
- Patient 1: 60 K Triangles → 800 K Tetraeder
- Patient 2: 175 K Triangle → 4 000 K Tetraeder, [Ceb01]

Visualization of Vasculature and Simulated Flow



- Inserting virtual stents for evaluating resulting hemodynamic situation. Clinical goal: Reconstruction of normal hemodynamic relations by optimal choic and placement of a stent
- Source: Webpage Juan Cebral

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 representation 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
- 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
- Mapping of additional information to the vascular surface, e.g. existence of plaque or blood flow quantities
- Adapting general methods to specific needs, e.g., exploration of the cardiovascular system

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