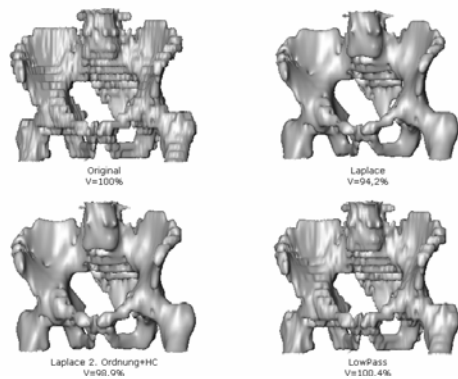
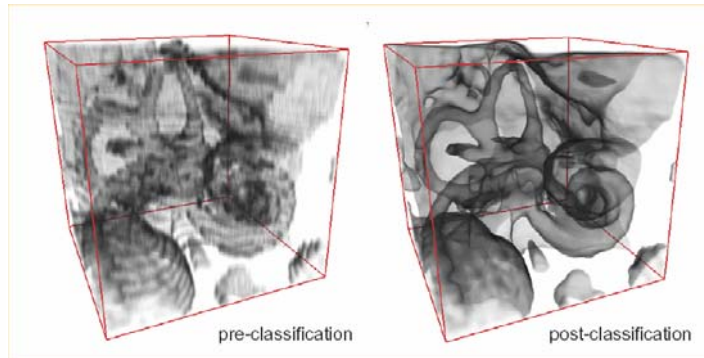


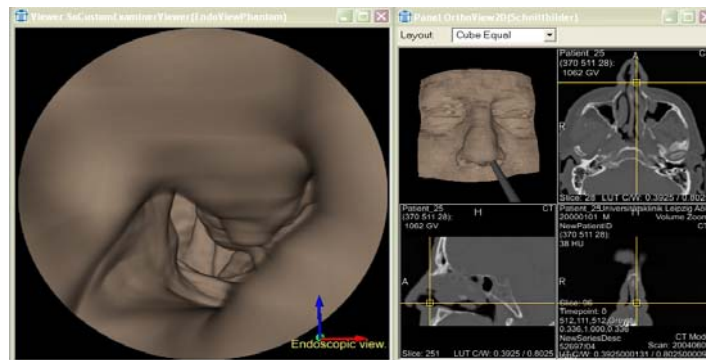
# Virtual Reality and Visualization



Surface  
visualization



Volume  
visualization



Virtual  
Endoscopy

## Content

2D and 3D Visualization for the Exploration of Medical Image Data	(15 min.)
Surface Visualization <ul style="list-style-type: none"> <li>- Marching Cubes and its improvements</li> <li>- Smoothing of surface visualizations</li> </ul>	(30 min.)
Direct Volume Visualization <ul style="list-style-type: none"> <li>- Ray casting and texture-based approaches</li> <li>- Projection methods</li> </ul>	(30 min.)
3D Vessel Visualization	(45 min.)
Virtual Endoscopy	(30 min.)
Virtual and Augmented Reality	(15 min.)

# Medical Image Data

Regular data in an orthogonal lattice

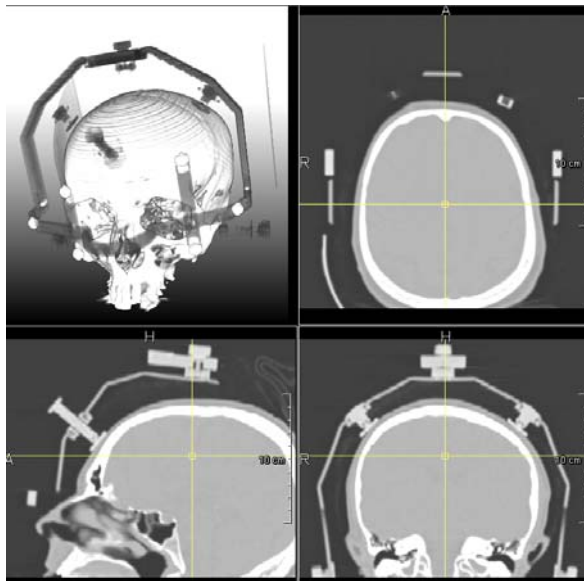
Resolution:

- Anisotropic datasets (slice distance > distance of pixels in the slice)
- Typical: CT or MRI data: 512x512 per slice,  
80-250 slices, resolution: 12 bit per slice,  
~ 20-50 MVoxel
- High-End: Multi-Slice CT: 1024x1024 per slice,  
up to 2000 slices (whole body scans), ~ 4000 MVoxel
- Less usual: PET, SPECT with a lower resolution

## 2D and 3D Visualization for the Exploration of Medical Image Data

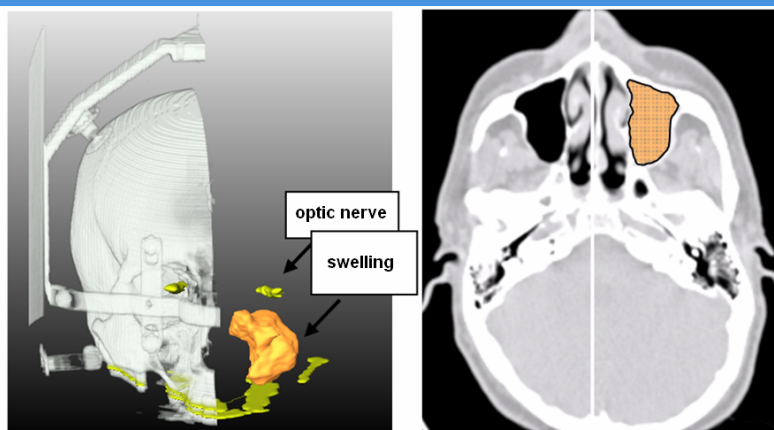
- 3D visualizations:
  - clearly arranged, descriptive, intuitive
  - give an overview on spatial relations
- 2D visualizations:
  - are common in radiological diagnostics
  - permit the precise evaluation of structures
  - permit exact selections (for measurements, ...)
- Combination of both representations with suitable synchronizations

# 2D and 3D Visualization for the Exploration of Medical Image Data



- Synchronized 2D and 3D views.
- The crosshairs in one of the orthogonal 2D views can be used to select the slice displayed in the other two 2D views.
- Brightness and contrast of one view can be transferred to other views.

# 2D and 3D Visualization for the Exploration of Medical Image Data

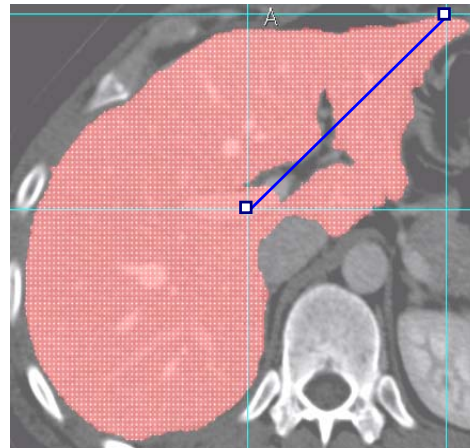
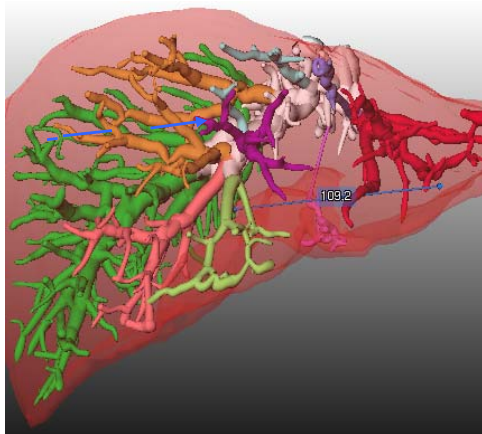


Images Dörte Apelt, MeVis Research

Planning of ENT interventions.

- 3D presentation of an ENT intervention. The relation between optic nerve and swelling is displayed, whereas a clip plane hides parts of the original data. Illustration of the swelling in the axial slice with a drawn-in clip plane.

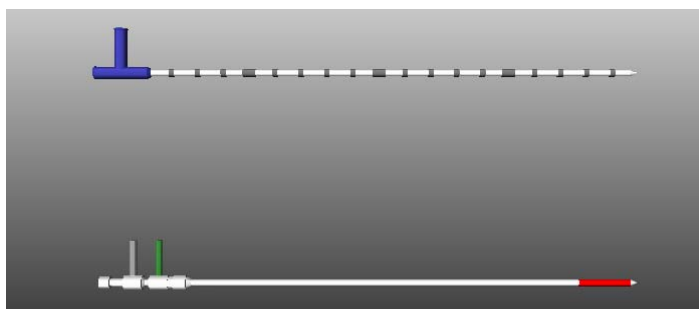
## 2D and 3D Visualization: Measurement



Distance measurement in 3D and 2D visualization. The endpoints of the lines can be moved in both views, whereas the respective view is adapted.

## 2D and 3D Visualization: Placement of Applicators

- Aims of exploration:
  - access planning of biopsies
  - planning of thermal ablations

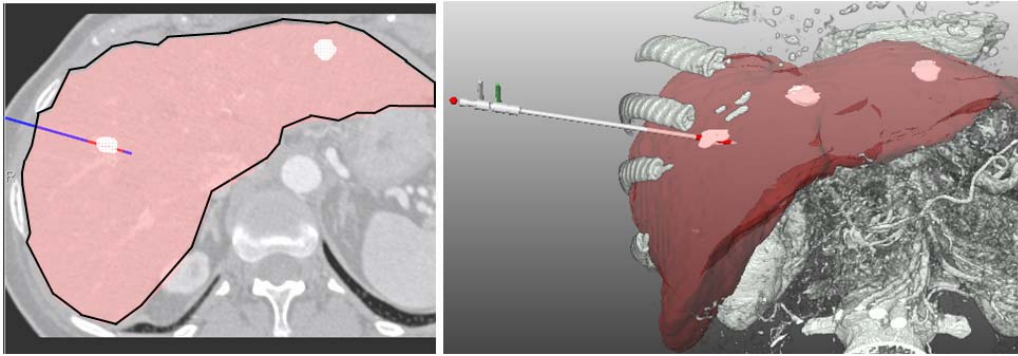


Images Courtesy  
Olaf Konrad, MeVis  
Research

Geometric models of high-frequency and laser applicators for the thermal treatment of liver tumors.



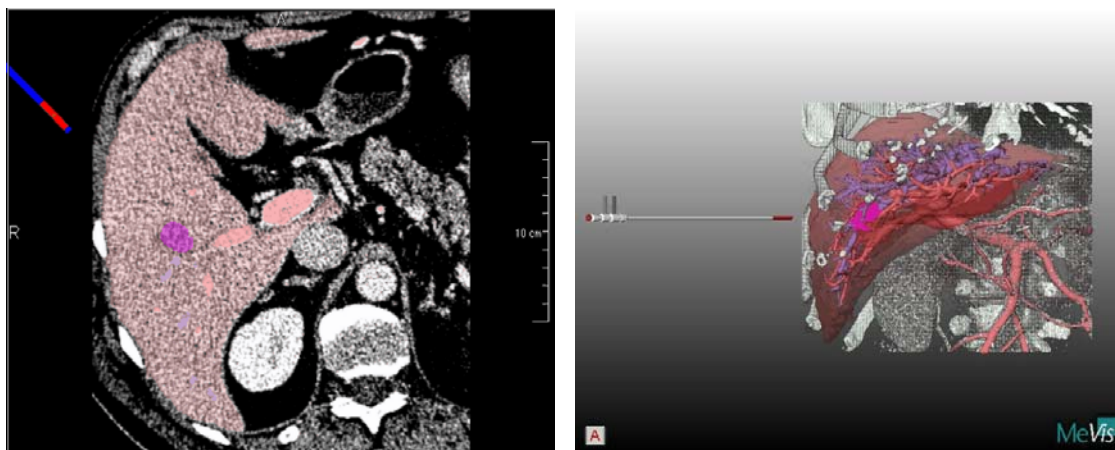
## 2D and 3D Visualization: Placement of Applicators



Images Courtesy Arne Littmann, MeVis Research

- Placement of the applicator into the center of a metastasis in 2D (the active zone is red).
- Placement of the applicator by means of a 3D visualization, whereas the bones are displayed as volume rendering, and the liver surface and the metastases are displayed as isosurfaces.

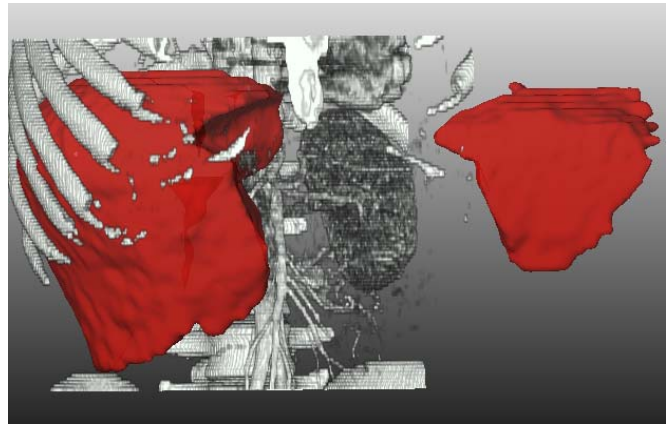
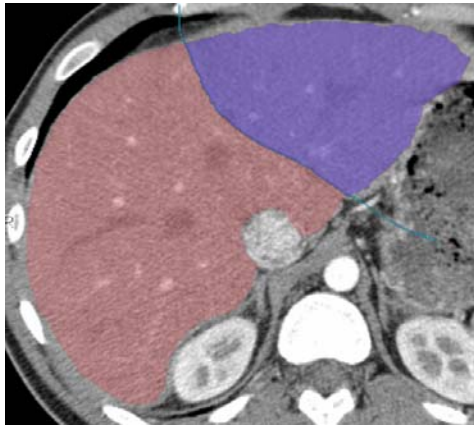
## 2D and 3D Visualization: Placement of Applicators



Videos from Arne Littmann,  
MeVis Research

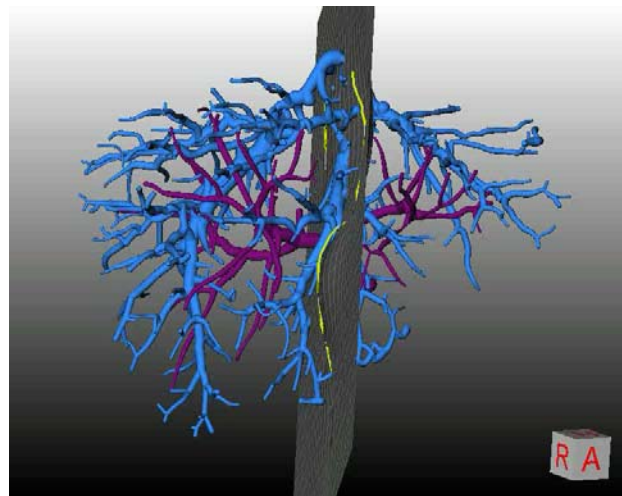
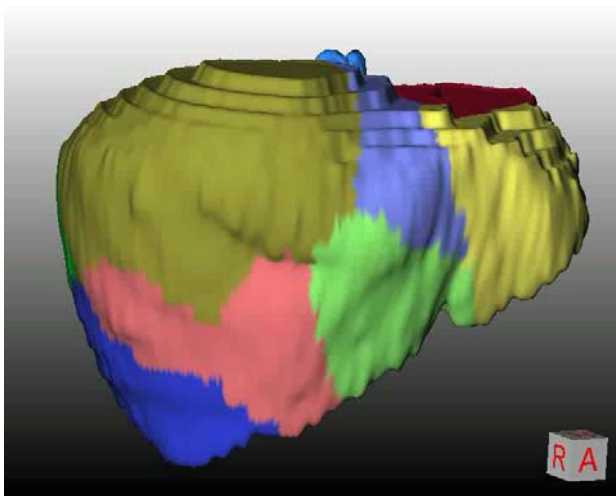
# 2D and 3D Visualization: Virtual Resection

- Virtual resection by drawing into the slices and shape-based interpolation
- Interaction in 2D (precise), evaluation in 3D



Preim et al., *Proc. of SimVis*, 2003

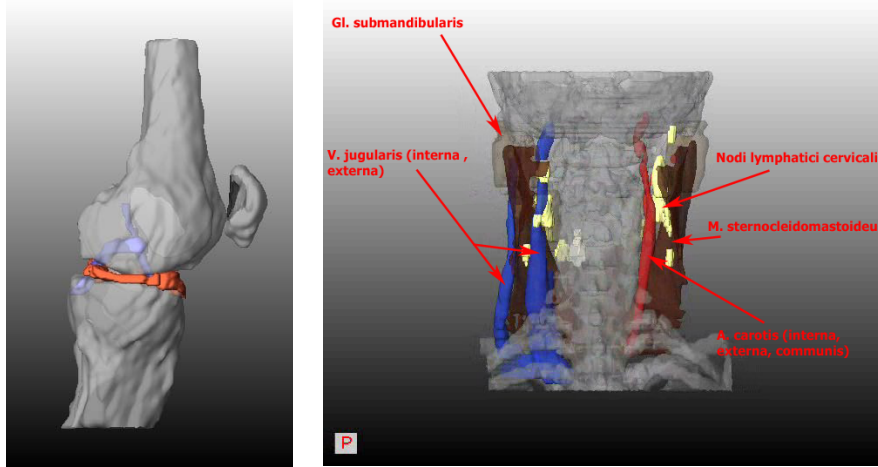
# 2D and 3D Visualization: Virtual Resection



Videos Milo Hindennach, MeVis Research

# Surface Visualization

Visualization of isosurfaces and segmentation results

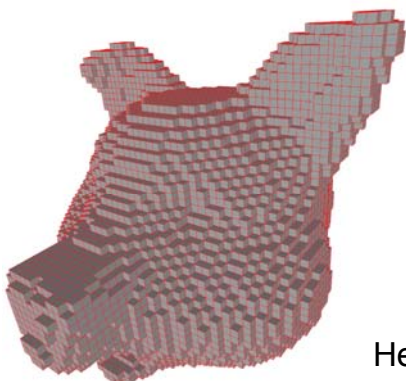


## Surface Visualization: Introduction

Assumption:

- Relevant structures are segmented.
- Segmentation is model-based (Snakes, ...), with “classical” procedures (Region Growing, Watershed, ...), or manually
- Segmentation result is binary represented at the voxel plane (1 for the foreground, 0 for the background).

Visualization: 1<sup>st</sup> idea: presentation of the voxels (“Cuberille” approach)



Herman, Liu (1979)

# Surface Visualization: Introduction

Visualization, better idea:

- linear interpolation, depiction on a polygonal surface (isosurface for the value 0.5)
- definition of vertices, triangulation, definition of normals
- rendering by using the graphics hardware

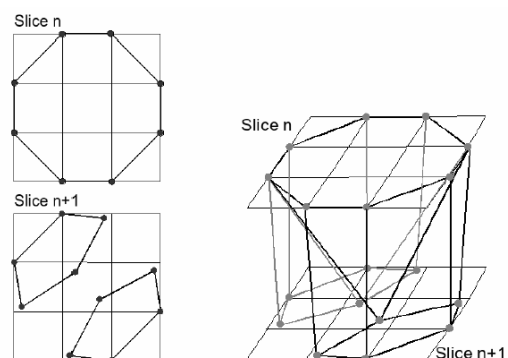
How can this be realized?

- follow the outlines
  - very difficult in 3D, many case distinctions
- Locally independent inspection of the cells. Determine how the cell is cut from the surface.
  - basic idea of Marching Cubes (patented in 1985, published in 1987)

## From Contours in slices to Surfaces

Which problems need to be solved?

- *Correspondence*. (which contour of one slice belongs to a contour at the next slice)
- *Triangulation (Tiling)*.  $C1$  and  $C2$  be corresponding contours. How shall these contours be connected through triangulation nets?
- *Branching problem*. If the number of contours in one slice  $S_n$  is different to the number of contours in the neighbor slice  $S_{n+1}$ .



„Surfaces from Contours“,  
Meyers et al. (1992)

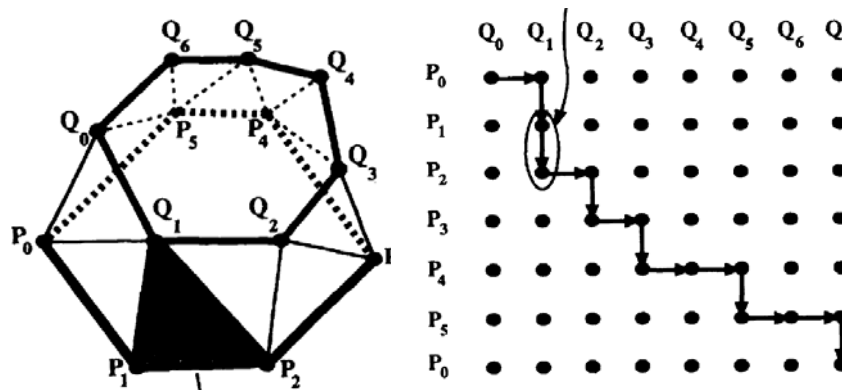
# From Contours in slices to Surfaces

- *Correspondence problem*. Comes up, if the following applies:  
The contours  $C1(S_n)$  and  $C1(S_{n+1})$  belonging to an object do not overlap themselves, and the number of contours belonging to one object is  $> 1$  in  $S_n$  and/or  $S_{n+1}$ .
- What does Marching Cubes do?
  - An overlapping of contours in neighbored slices is assumed.
  - When does this procedure not work? In case of a large slice distance or thin objects which proceed diagonal to the slices.
  - If the requirements are not fulfilled, separate surfaces are generated.
- In such cases, correct solutions are complex.



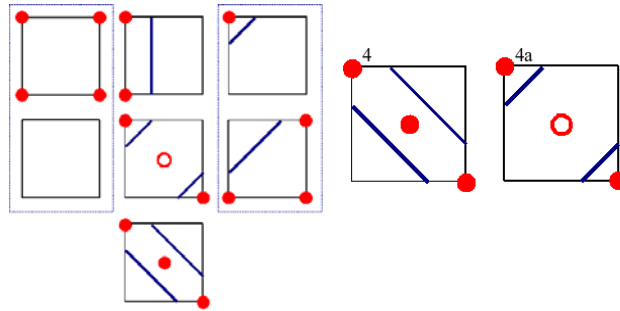
# From Contours in slices to Surfaces

- “Tiling” problem. Connect  $n$  endpoints of the contour in a slice  $P_i$  with  $m$  endpoints of the contour in the neighbor slice  $Q_j$ .
- Criteria (selection):
  - the resulting volume shall be maximal.
  - the resulting plane shall be minimal.
- How can this be solved? Depiction on graph search (Keppel [1972], Fuchs [1977])

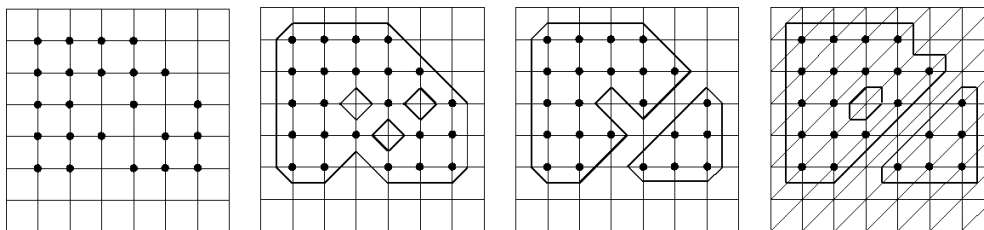


# Surface Visualization: Marching Cubes

- Consideration of the 2D case (Marching Squares). Isoline for  $\text{iso}=0.5$ .



- Ambiguity:



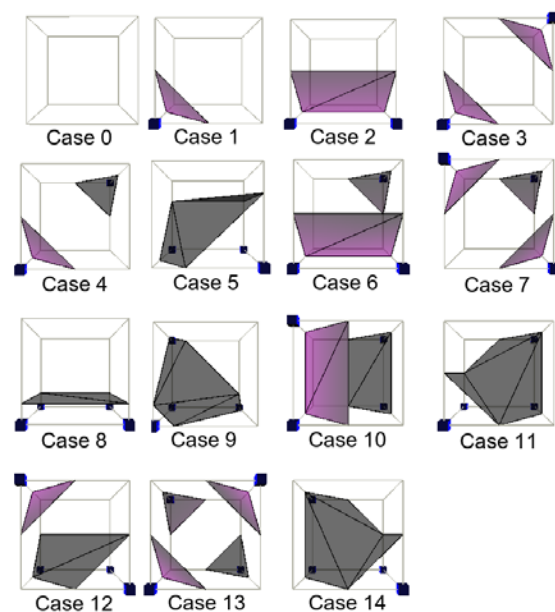
© Dirk Bartz

# Surface Visualization: Marching Cubes

- Extension to 3D:
- there are 14 topologically different cases of how a cell can proceed through a surface.

Procedure (rough):

- determine the case for each cell.
- determine the triangles if the cell is cut.



© Dirk Bartz



# Surface Visualization: Marching Cubes

## Marching Cubes

Purpose: transfer of the voxels of a volume with a given value into a triangulation net (Lorensen *et al.* [1987])

Procedure:

1. Consideration of cubes from 4 voxels of the slice  $k$  and 4 voxels of the slice  $k+1$
2. Check out which vertices are lying above the threshold value, create an index
3. Determine the involved edges
4. Determination of points at these edges through linear interpolation
5. Connection of these points to create triangles

## Indirect Volume Visualization: Isosurfaces

### Marching Cubes

Step 2:

$v_1, v_5, v_6, v_8$  – above,

$v_2, v_3, v_4, v_7$  – below

Index: 1000 1101

Step 4: Linear interpolation

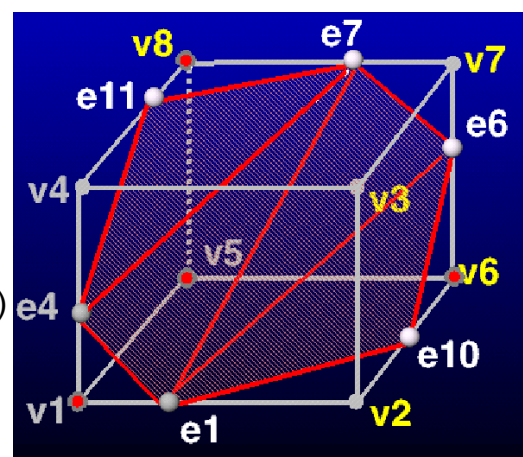
Example: determination of  $e_1$  to the edge  $(v_1; v_2)$

$$e_1 = v_1 + (\text{isoval} - f(v_1)) / (f(v_2) - f(v_1)) * (v_2 - v_1)$$

Step 5: Triangles

$(e_4, e_7, e_{11})$      $(e_1, e_7, e_4)$

$(e_1, e_6, e_7)$      $(e_1, e_{10}, e_6)$



© Alexandre Telea

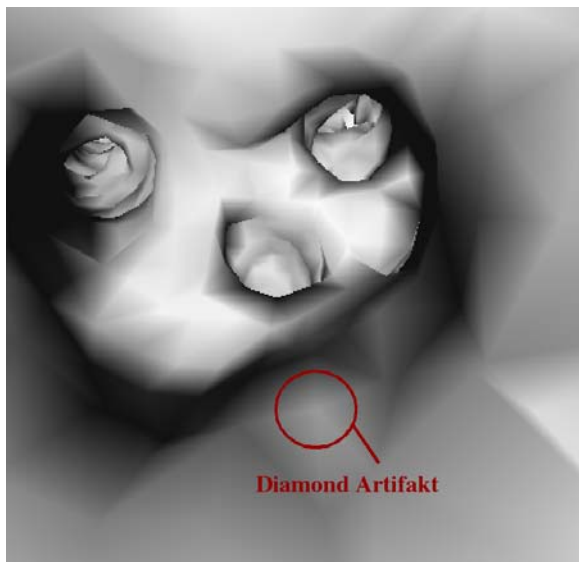
# Surface Visualization: Marching Cubes

What is important about Marching Cubes?

- Very simple
- Compared to Cuberille: Better description through linear interpolation
  - But: Viewers are also sensitive for discontinuities of the first and second derivative
- Ambiguities and inconsistencies, no treatment of the correspondence problem, no optimal solution for the tiling problem
- Relatively precise, but improvable
- Relatively fast procedure
  - But: A lot of time is spent on cells which do not contribute to the surface
- Fast rendering

# Surface Visualization: Marching Cubes

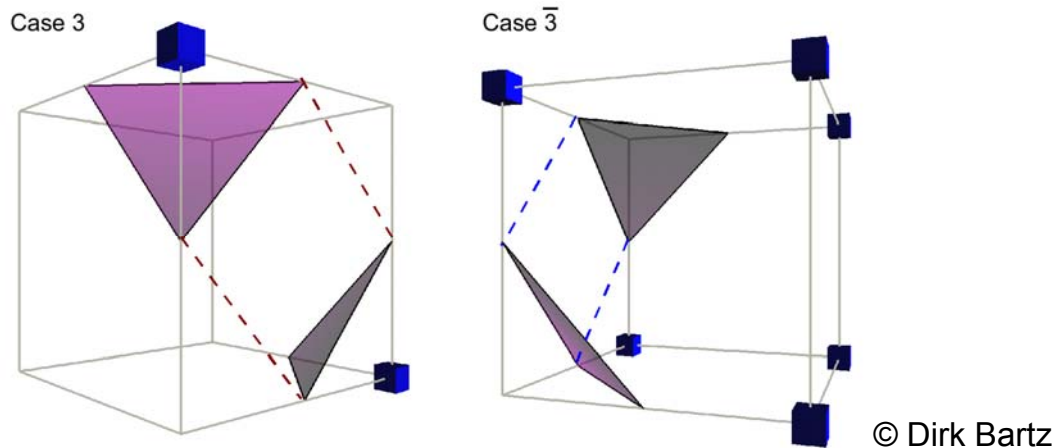
Quality problems through linear interpolation and Gouraud shading



Virtual bronchoscopy

© Dirk Bartz

# Surface Visualization: Marching Cubes



- Holes in the surface arise, if, for the neighbored cells, once the decision is made to divide the intersections and once the decision is made to connect them.

# Surface Visualization: Marching Cubes

- How can this inconsistency be corrected?
  - Rule: e.g., always separate between positive endpoints and connect negative ones
  - Interpolation of points at the interface. The state of this point (above/below) is decisive (Nielsen, Hamann [1991])
  - Usage of the complete case list (Schröder et al. [1998])
  - Decomposition of the cells into tetrahedrons (Shirley, Tuchman [1990])

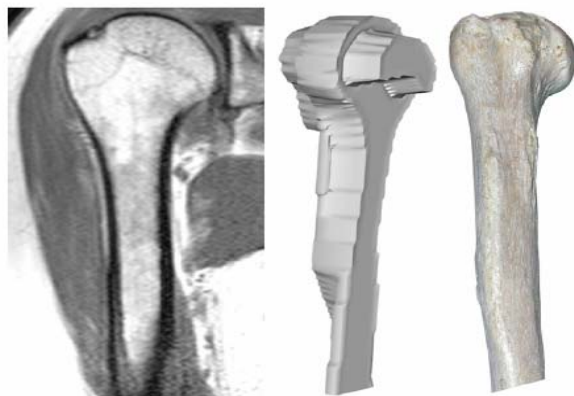
# Surface Visualization: Marching Cubes

- What is used at the most?
  - Usage of the complete case list (among others implemented into VTK)
- How can Marching Cubes be accelerated?
  - Fast recognition of areas that are not affected by the surface.
  - Representation of the scene through hierarchic data structures, e.g., min-max-octrees (Wilhelms, van Gelder [1992])

## Surface Visualization: Smoothing and Noise Reduction

Problem:

Generation of surface models from segmentation results leads to artifacts, especially in case of strongly anisotropic data



MR data,

3D visualization,

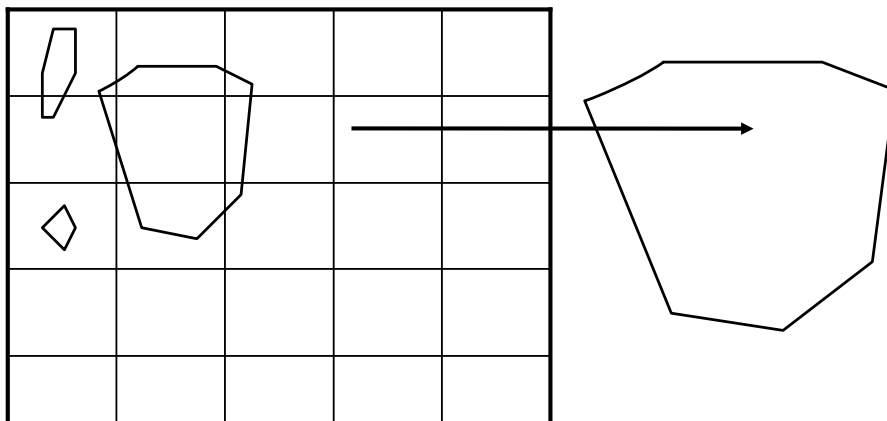
picture

# Surface Visualization: Smoothing and Noise Reduction

- Problem: Development of many small surfaces which represent artifacts
- Purpose: Restriction of the extraction to the largest surface (or a given amount of surfaces)
- Method: Connected Component Analysis (according to Schroeder et al.[1998])
- VTK: *vtkConnectivityFilter*

# Surface Visualization: Smoothing and Noise Reduction

## Connected Component Analysis



Term: Neighborhood: Cells which have common planes, edges or vertices, are neighbored 2,1 or 0

# Surface Visualization: Smoothing and Noise Reduction

## Algorithm Connected Component Analysis:

While there are cells which are not “visited”,

start with any cell  $z$  and mark it as „visited“.

Initialise the component  $k$

While there are still neighbored cells  $z_n$  of  $z$  which contribute to the surface and are not “visited” yet, add  $z_n$  to the component  $k$  and mark it as “visited”.

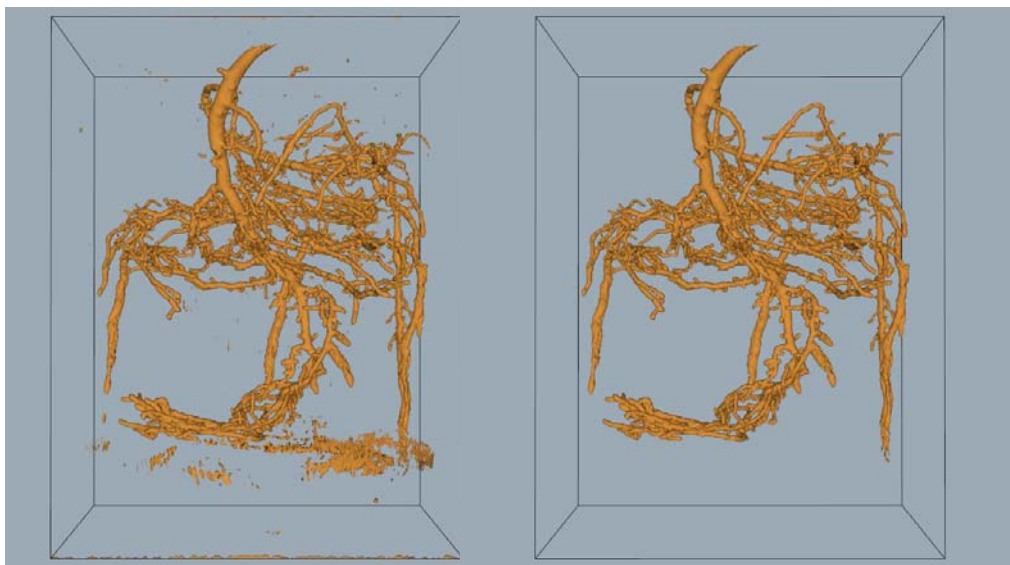
Continue recursively as long as there are still cells which are neighbored (2,1,0) and not visited yet.

Result: all connected components

Selection of the largest (n) component(s) according to the surface area or length of the object contour

# Surface Visualization: Smoothing and Noise Reduction

Connected Component Analysis. Illustration of the largest component.



Digitalized photograph of a pine root

(Source: Schroeder et al. [1998])



# Surface Visualization: Smoothing and Noise Reduction

## General practice:

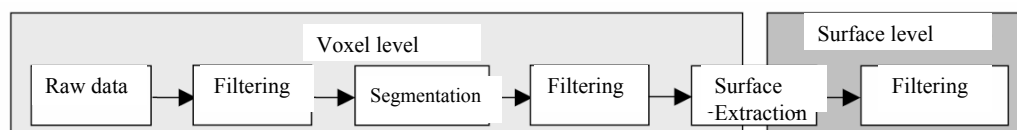
- Interpolation of intermediate slices
- “Manual” smoothing  
e.g., in vtk (vtkSmoothPolyDataFilter), itk, 3D Studio, Amira

## Disadvantages

- complex trial-and-error process
- not reproduceable, not standardized
- only visual control

# Surface Visualization: Smoothing and Noise Reduction

## Extraction of surfaces



## Long-term goal:

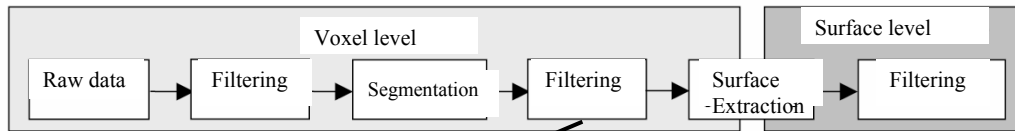
Pipeline of algorithms for the post-processing of segmentation results (e.g., closure of holes), surface generation and subsequent smoothing

## Adaptation of the respective procedures to

- the class of anatomic structure (e.g., tumor, organ, ...)
- imaging or segmentation parameters (e.g., slice distance, model-based segmentation)

# Surface Visualization: Smoothing and Noise Reduction

- Smoothing of the segmentation result through smoothing filters (e.g., Gauss) or morphologic methods



0	0	0	0	0	0	0
0	0	0	100	100	100	0
0	100	100	100	100	100	0
0	100	100	100	100	100	0
0	0	0	100	100	100	0
0	0	0	0	0	0	0

0	6	26	33	33	26	6
20	33	54	66	66	54	26
33	66	66	100	100	66	33
33	66	66	100	100	66	33
20	33	54	66	66	54	26
0	6	26	33	33	26	6

Source: Neubauer et al., IEEE Visualization 2004

- First of all, erosion and modification:

$$v = v_2 - (v_2 - v_1) * \frac{1}{3}$$

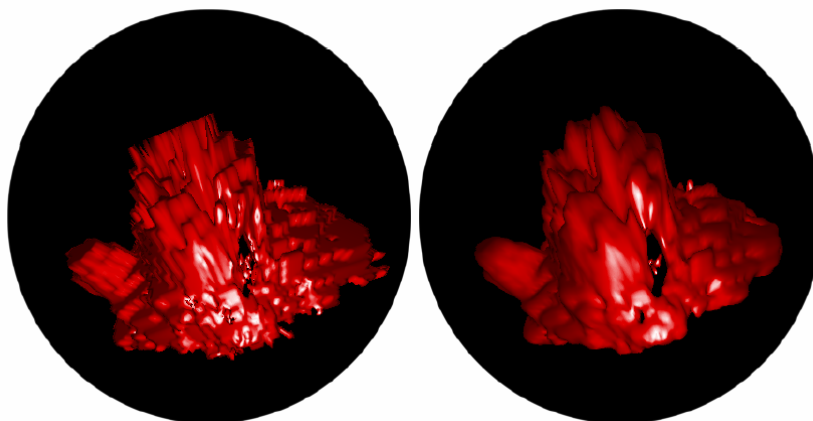
- Afterwards, twice dilatation and modification:

$$v = v_{ref} - (v_2 - v_1) * \frac{d}{3}$$

- d Eucl. Distance,  $v_{ref} = 50$

# Surface Visualization: Smoothing and Noise Reduction

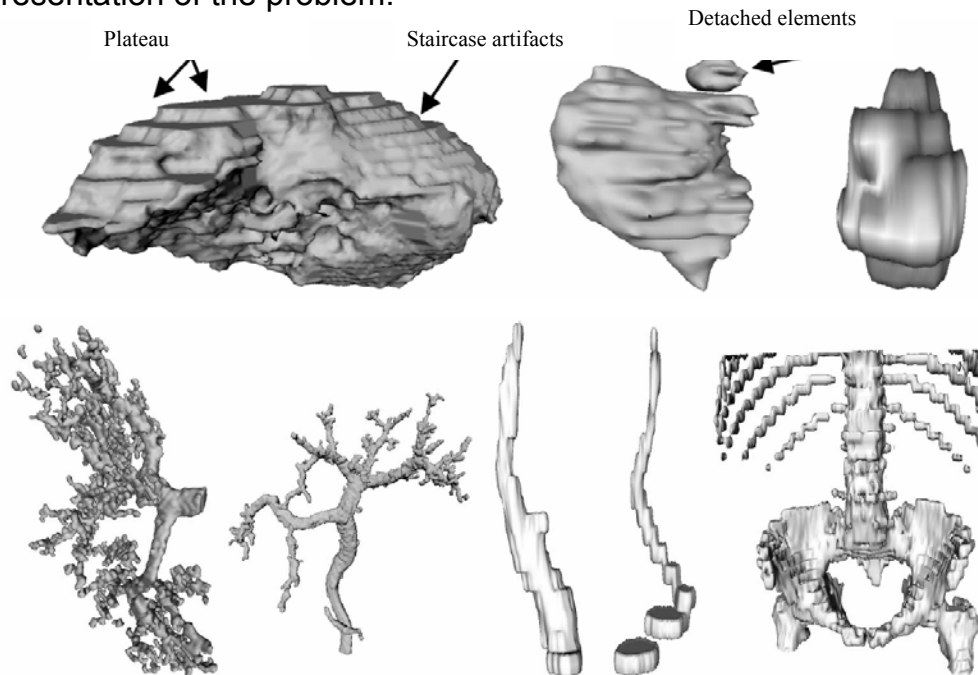
- Smoothing of the segmentation result through morphological methods



Source: Neubauer et al., IEEE Visualization 2004

# Smoothing of Polygonal Surfaces

Presentation of the problem:



## Smoothing of Surfaces

- Large amount and diversity of methods
- Very often an academic procedure: smoothing of artificial noise test data
- Clear application in the CAD area and for the smoothing of models which have been acquired with the laser scanner.
- CAD area: preservation of sharp (orthogonal) edges with preferably optimal smoothing of planar areas
- Medical surface models: barely sharp edges, curvatures are partly changing very fast, "large" models

# Smoothing of Polygonal Surfaces: Requirements

Analog to the smoothing of image data:

- Elimination of high frequency noise at the receipt of features

Measures/Evaluation:

- curvature plots, total curvatures

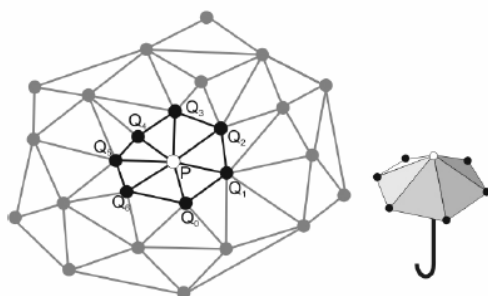
- Speed
- Accuracy

Measures:

- slight distances between the original surface and the smoothed surface
- volume maintenance

## Smoothing of Polygonal Surfaces

- Iterate over all vertices and replace each vertice through a weighted average from its former value and the vertices from the surrounding
- Which surrounding?
  - vertices in a specific distance (Euclidean distance)
  - vertices which are connected to the current vertice (directly or through a path of length  $n$ ) (topological distance)
  - Typical: vertices in the topological distance of 1 or 2



Direct neighbors



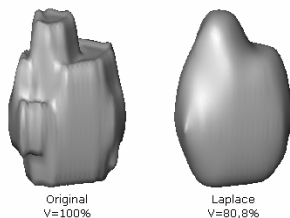
Second order neighbors

# Smoothing of Polygonal Surfaces: Laplace Smoothing

- Considers the points  $q_i$  in the topological distance of 1
- Parameter: smoothing factor  $\alpha$  and number of iterations

$$p' = p + \frac{\alpha}{n} \sum_{i=0}^{n-1} (q_i - p)$$

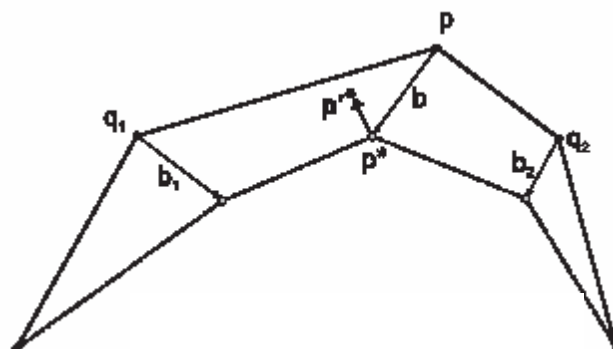
- Realized in vtk (vtkSmoothPolyDataFilter), ...
- Simple, fast realization
- Causes strong (uncontrolled) shrinkage and the favored smoothness is often only achieved through total smoothing of minor features



smoothing with  $\alpha = 0.5$  and 20 iterations

# Smoothing of Polygonal Surfaces: Laplace Smoothing with Correction

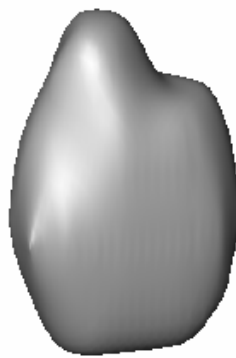
- Correction to maintain the volume
- In each step, modified nodes are shifted back about a certain value (the average of all shiftings in the considered surrounding)
- Additional parameters:
  - How strong is the shifting in direction to the original point?
  - How is the shifting of the neighbors considered?



# Smoothing of Polygonal Surfaces: Laplace Smoothing with Correction



Original  
V=100%



Laplace  
V=80,8%



Laplace+HC  
V=99,8%

Literature: Vollmer et al., „Improved Laplacian Smoothing of Noisy Surface Meshes“, Eurographics, 1999

# Smoothing of Polygonal Surfaces: Low-pass Filtering

- Alternating implementation of two filterings similar to Laplace with different factors  $\alpha$  and  $\mu$

$$p' = p + \lambda \sum_{i=0}^{n-1} w_i (q_i - p)$$

- Filtering: usually  $1/n$  (all neighbors have the same influence; like Laplace)
- Selection of  $\mu$ : a bit smaller than  $\alpha$
- Default:  $-\mu = -1.02 \alpha$  (Taubin, 1995)



# Smoothing of Polygonal Surfaces: Comparison of Elementary Methods

Criteria: Quality, volume maintenance (measurement in Amira), run time

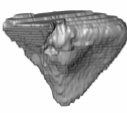

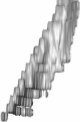

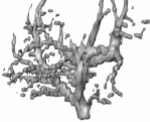

Methods/parameters:

Laplace, Laplace with correction, Low-pass

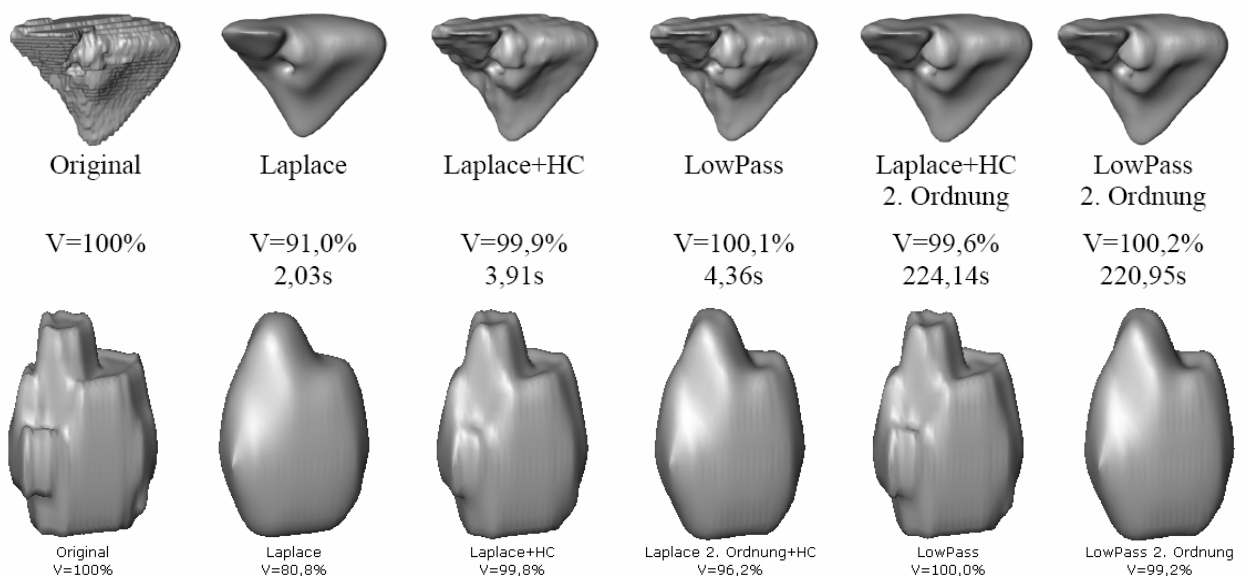
Different iteration steps: 5, 10, 20, 50

Different weighting factors: 0.05, 0.1, 0.3, 0.5, 0.7, 0.9

Different neighborhood: 1, 2 (topological)

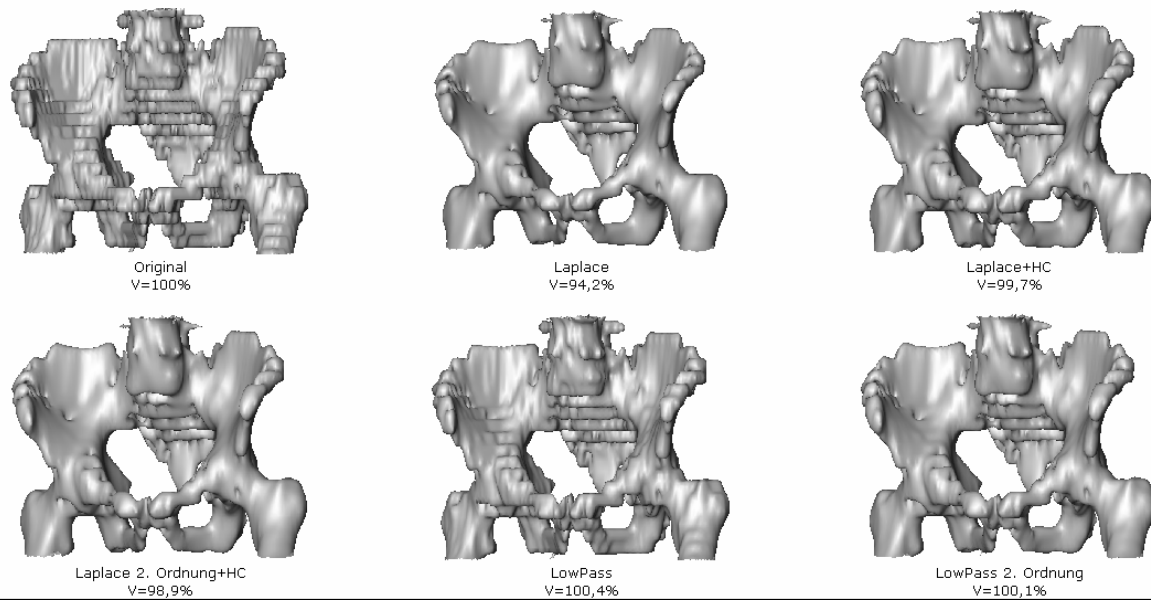
						
	Leber	Lymphknoten	Kopfwendemuskel	Beckenknochen	Gefäßbaum	Halsschlagader
Faces	37.148	3.412	9.616	53.930	23.236	1.956
Vertices	18.576	1.708	4.804	27.211	11.820	982
Voxel	1.696.250	1.664	101.035	430.318	96.807	16.404

## Smoothing of Polygonal Surfaces: Comparison of Methods



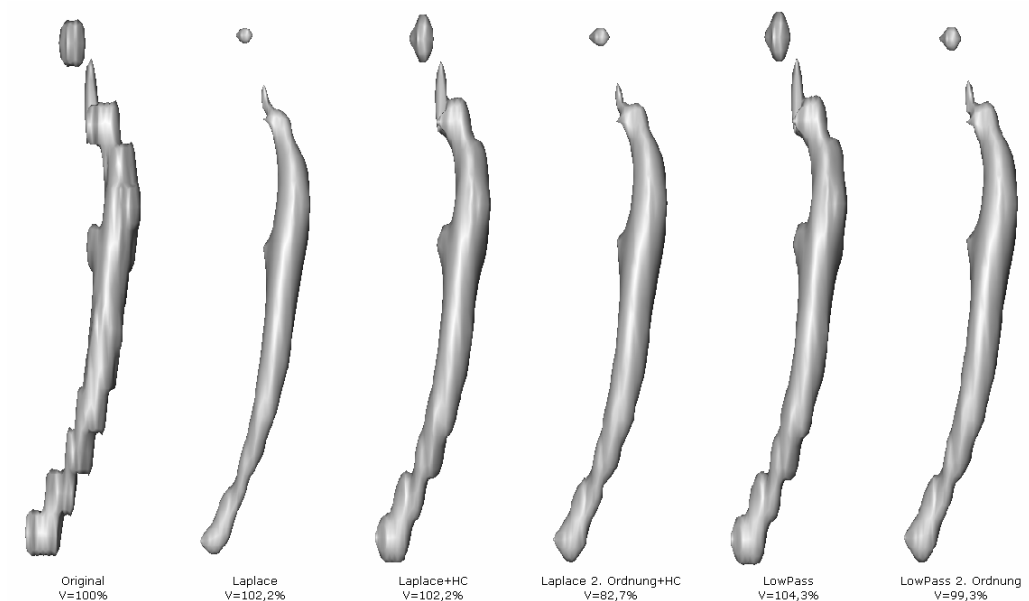
Smoothing factor: 0.5, 20 iterations

# Smoothing of Polygonal Surfaces: Comparison of Methods



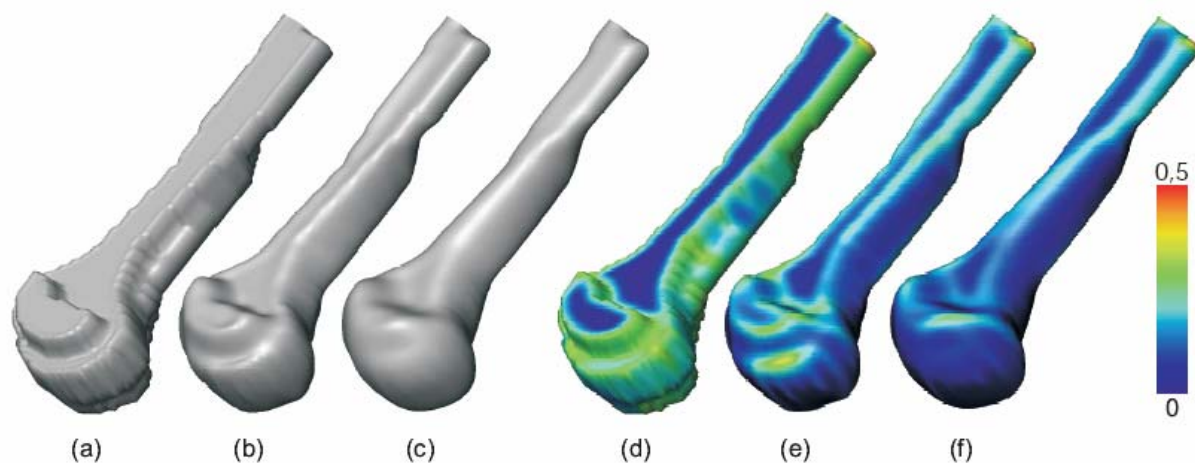
All images with smoothing factor 0.5 and 10 iterations

# Smoothing of Surfaces: Comparison of Methods



Carotid artery: Smoothing factor: 0.7 and 10 iterations

# Smoothing of Surfaces: Comparison of Methods



Original, low-pass filtering with one neighborhood and extended neighborhood as well as the corresponding curvature values.

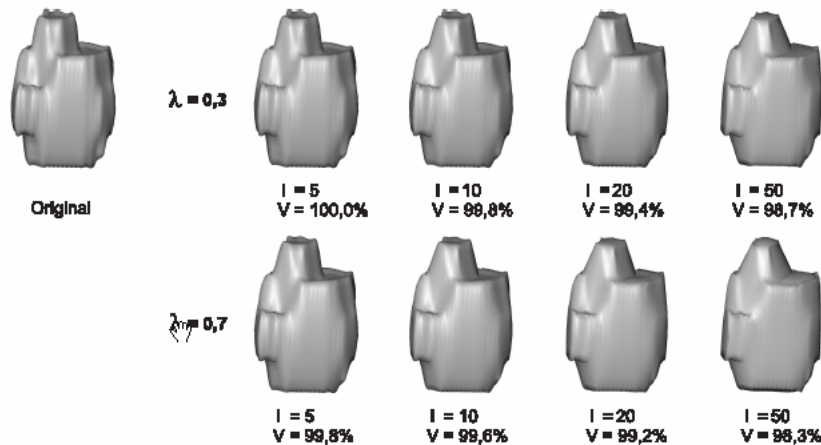
## Smoothing of Surfaces: Further Methods

- Average Value Filtering
  - replaces the surface normal for the current point by the average normal of the considered surrounding and adapts the coordinates.
- Median Filtering
  - Sorts the normals in the neighborhood according to the angle of the current normal and - during the sorting - replaces the current normal by the normal which lies in the middle.
- Mean Curvature Flow
  - Uses curvature measures for the modification of vertices.

# Smoothing of Surfaces

## Average value filtering

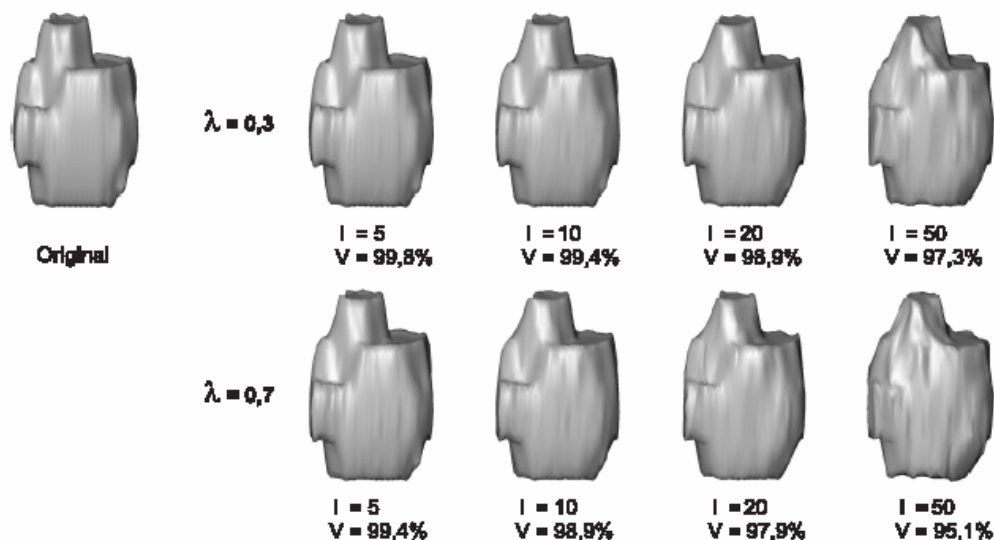
- Good volume maintenance, good smoothing for large and compact objects.
- New artifacts arise in case of smaller objects, especially for a high factor and a large amount of iterations



# Smoothing of Surfaces

## Median Filtering:

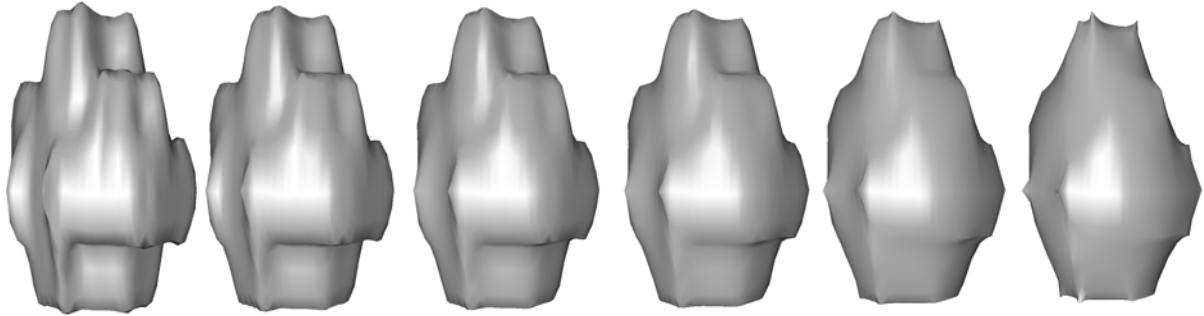
- Main application: maintenance of sharp edges in noise data
- problems similar to the average value filter, partly more distinctive



# Smoothing of Surfaces

## Mean Curvature Flow

- Problematic especially for compact objects in case of stronger smoothing factors



Original, smoothing after 5, 10, 20, 50 and 100 iterations.  
No correction for volume maintenance.

## Smoothing of Polygonal Surfaces: Recommendations

- A low-pass filter is the best solution for all object classes.
- For smaller objects
  - Topological neighborhood of the size 2, 20-50 iterations, weighting: 0.7
- For even objects, especially with problem points:
  - Topological neighborhood: 1, approx. 20 iterations
- For elongated, branching objects:
  - No really good filter (-> Vessel Visualization part will provide appropriate methods)
  - Low-pass filter with topological neighborhood of 1, weighting factor: 0.5 and 10 iterations

# Surface Visualization: References

- M. Desbrun, M. Meyer, P. Schröder, and A. Barr (1999). "Implicit Fairing of Irregular Meshes Using Diffusion and Curvature Flow". In Proc. of ACM SIGGRAPH, pp. 317–324, 1999
- GT. Herman and HK. Liu (1979). „Three-dimensional Display of Human Organs From Computed Tomograms“, Computer Graphics and Image Processing, 9(1):1–21
- D. Meyers, S. Skinner, K. Sloan (1992). „Surfaces from contours“, ACM Transactions on Graphics, Vol. 11(3), pp. 228-258
- A. Neubauer, S. Wolfsberger, M. Forster, L. Mroz, R. Wegenkittl, and K. Bühler (2004). STEPS - An Application for Simulation of Transsphenoidal Endonasal Pituitary Surgery. In Proc. of IEEE Visualization, pp. 513–520, 2004
- Will Schroeder, Ken Martin, and Bill Lorensen. The Visualisation Toolkit. Kitware, 3rd edition, 2001.
- Gabriel Taubin (1995). „A Signal Processing Approach to Fair Surface Design“, SIGGRAPH, pp. 351-358, 1995
- G. Nielson and B. Hamann (1991). The Asymptotic Decider: Removing the Ambiguity in Marching Cubes. In Proc. of IEEE Visualization, pp. 83–91, 1991.
- P. Shirley and A. Tuchman (1990). A Polygonal Approximationm to Direct Scalar Volume Rendering. In Proc. of San Diego Workshop on Volume Visualization, pp. 63–70, 1990.

# Surface Visualization: References

- R. Bade, J. Haase, and B. Preim (2006). „Comparison of Fundamental Mesh Smoothing Algorithms“, *Simulation and Visualization*, pp. 289-304
- All 864 measurements:  
<http://www.wisg.cs.uni-magdeburg.de/cv/projects/LST/smoothing/>
- J. Vollmer, R. Mencil, and H. Müller (1999). „Improved Laplacian Smoothing of Noisy Surface Meshes“. In *Proc. of Eurographics*, pp. 131–138, 1999.
- J. Wilhelms and A. van Gelder. Octrees for Faster Isosurface Generation. ACM Transactions on Graphics, 11(3):201–227, 1992
- Yagou et al., Mesh Smoothing Via Mean and Median Filtering, *Geometric Modelling and Processing*, 2002, pp. 124-131

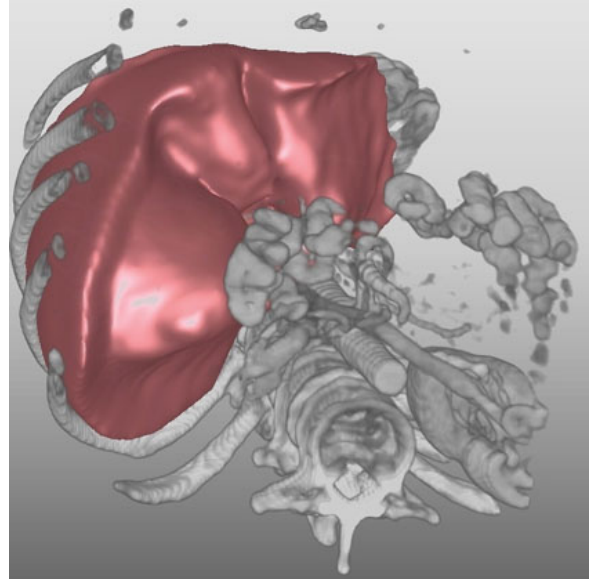
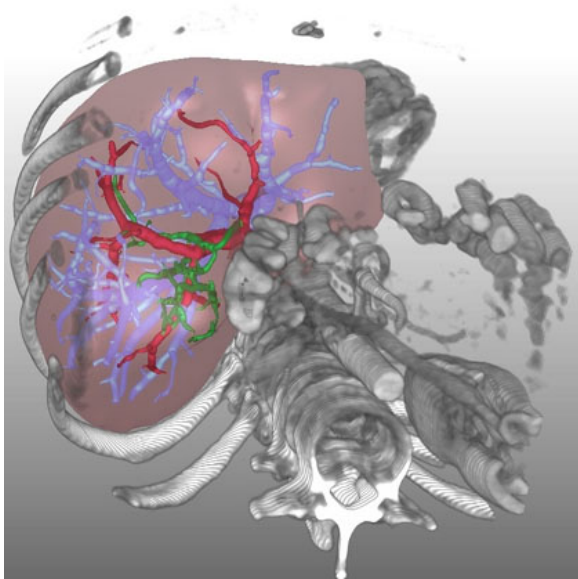
## Overview:

Gabriel Taubin. „Geometric Signal Processing on Polygonal Meshes“, *Eurographics, State of the Art-Report*  
<http://mesh.caltech.edu/taubin/publications/taubin-eg00star.pdf>

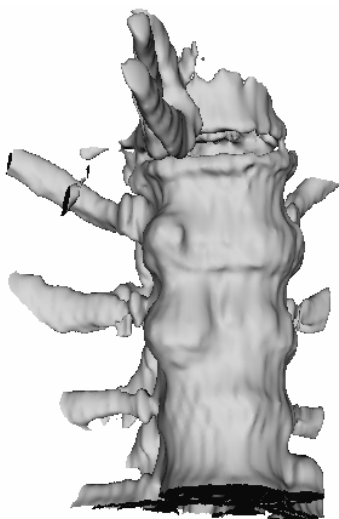


# Surface Visualization: Examples

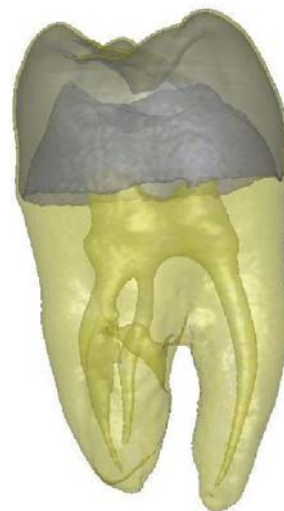
- Embedding of segmented objects (isosurfaces, strongly smoothed) into the anatomic context (DVR)



# Surface Visualization: Examples



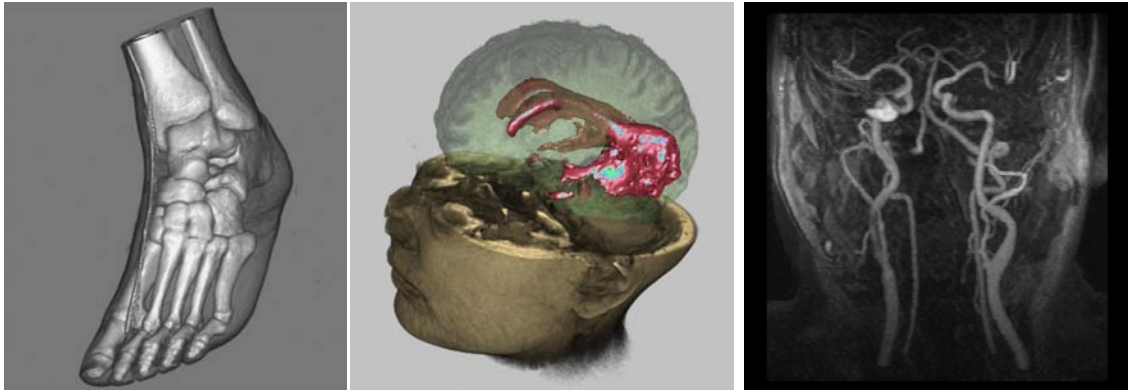
© Wolf Spindler, MeVis Bremen



© Thomas Gerstner, University of Bonn

- Good illustration of bony structures in CT data. Combination of several isosurfaces through an appropriate transparency adjustment.

# Direct Volume Visualization



## Direct Volume Visualization: Structure

### Direct Volume Visualization

- Introduction
- Image-based Volume Visualization
- Texture-based Volume Visualization
- Projection Methods



# Direct Volume Visualization: Introduction

## Requirements:

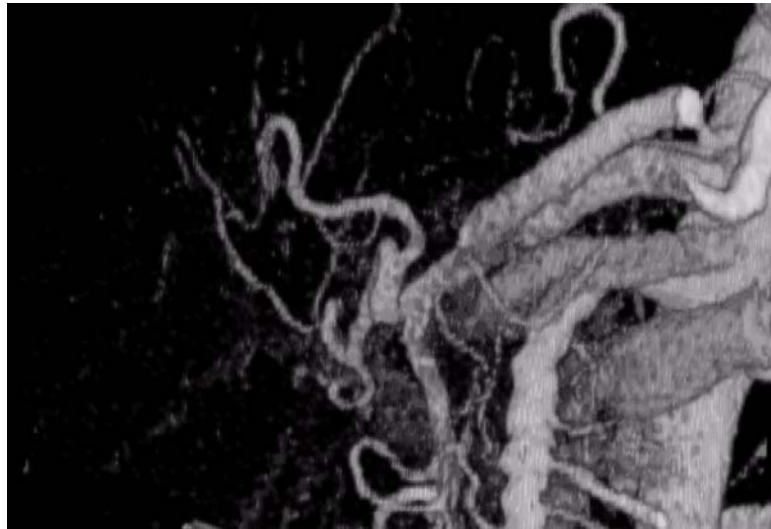
- detailed visualization of the original data (relevance for diagnostic and therapeutic purposes)
- Good rendition of the spatial relations (visual cues like shadows, highlights, depth cueing)
- High presentation speed
- Integration of surface and volume data (*hybrid rendering*)

# Direct Volume Visualization: Introduction

## DVR procedure for medical visualization:

- *Image-based procedures* which (re)trace a ray for each pixel in the scene and compound the colors/the grey value from the hit voxels (*back to front*), weighted with transparency
- *Object-based procedures* which sample the voxels and determine how the voxels contribute to the image (*front to back*), and (splatting, Westover [1990], Hanrahan [1991])
- *Texture-based procedures* which use a 3D texture memory and hardware support for the texture mapping.

# Direct Volume Visualization: Introduction



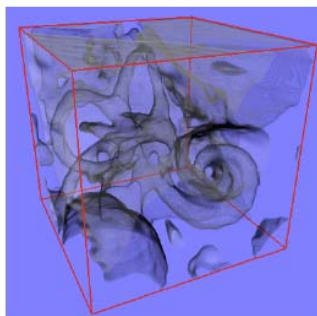
Volume rendering to evaluate liver vessels, Video by Christoph Wald, Lahey Clinic Boston

# Direct Volume Visualization: Introduction

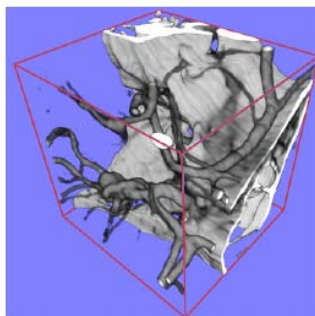
## Examples:

Inner ear with HRCT: matrix: 512x512, thickness: 1 mm,  
slice dist: 0.5 mm, 64 slices, resolution: 0.12 mm

Intracranial vessels, CTA: 512x512x256, resolution: 1 mm,  
thickness: 1 mm



**CT Inner Ear Detail**  
1 MB (128 x 128 x 64)



**CTA Aneurysma Detail**  
2 MB (128 x 128 x 128)

What is typical?

Many transparent or semi-transparent voxels

How is this specified?

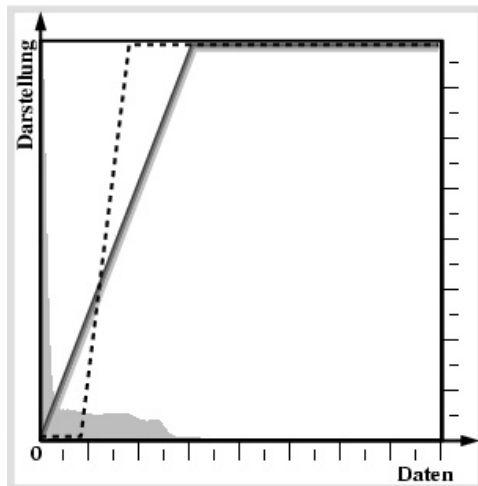
Through an appropriate transfer function

Source: Rezk-Salama, 2002

# Direct Volume Visualization: Introduction

Setting of TFs for grey values and transparency (very often a linear function).

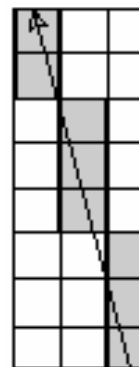
Histogram displayed as context in a graphic editor.



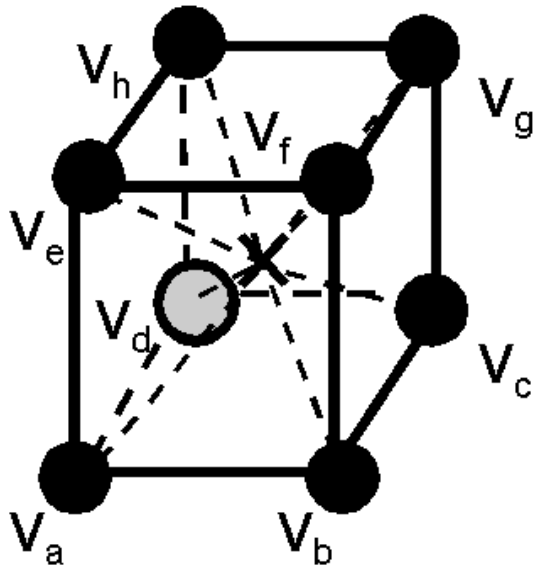
Source: Hastreiter, 1999

## Direct Volume Visualization: Image-based Methods

- Pursuit of rays in the scene (ray casting)
- Per sampling point:
  - Rounding up to the next voxel (nearest neighbor)
  - Trilinear interpolation from the 8 surrounding voxels



## Direct Volume Visualization: Image-based Methods



Trilinear interpolation

$I(x)$ : Intensity/density at the point  $x$

$$\begin{aligned}
 I(V_p) = & I(V_a)(1-x_p)(1-y_p)(1-z_p) \\
 & + I(V_e)(1-x_p)(1-y_p)z_p \\
 & + I(V_b)x_p(1-y_p)(1-z_p) \\
 & + I(V_f)x_p(1-y_p)z_p \\
 & + I(V_c)x_py_p(1-z_p) \\
 & + I(V_g)x_py_pz_p + \\
 & + I(V_d)(1-x_p)y_p(1-z_p) \\
 & + I(V_h)(1-x_p)y_pz_p
 \end{aligned}$$

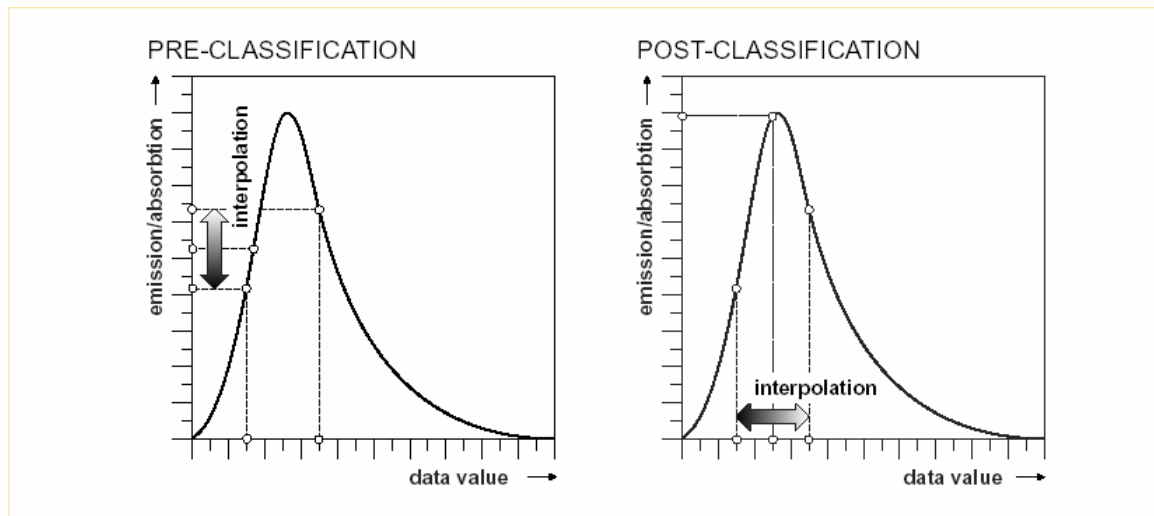
## Direct Volume Visualization: Image-based Methods

Interpolation and application of the transfer function

- 1<sup>st</sup> variant: Application of the TF (classification) to all vertices near the filter (result: RGBA quadruple) and afterwards (tri)linear interpolation of these quadruples (*pre-classification*)
- 2<sup>nd</sup> variant: Interpolation of the intensity values from the data (e.g., Hounsfield Units) and afterwards application of the transfer function to the interpolated result (*post-classification*)

Problem of the first variant: Color perception is non-linear in RGB and interpolation for up to 4 channels. But this variant is very often supported through hardware lookup tables.

# Direct Volume Visualization: Image-based Methods

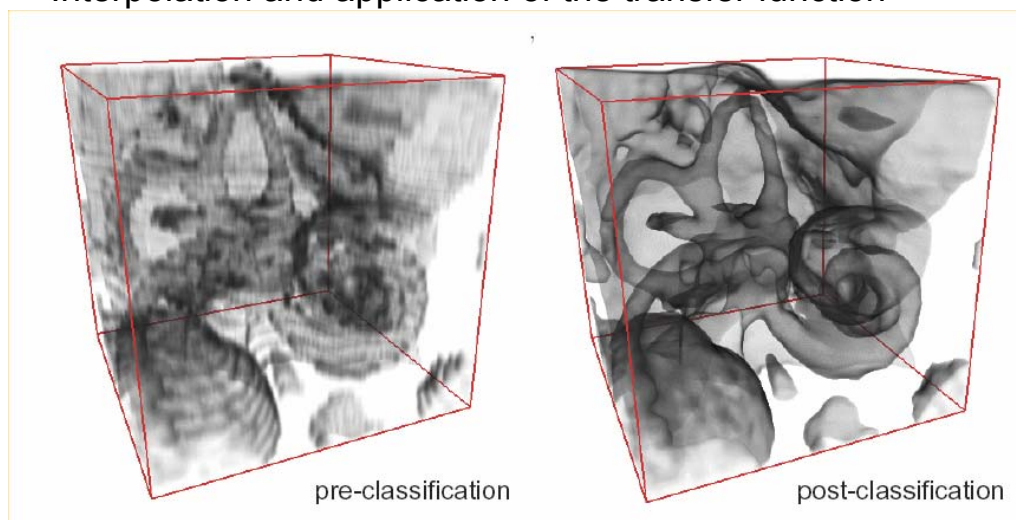


A late application of the TF is more precise!

Source: Rezk-Salama, Dissertation, 2002

# Direct Volume Visualization: Image-based Methods

Interpolation and application of the transfer function



Source: Rezk-Salama, 2002



# Direct Volume Visualization: Image-based Methods

Basic algorithm ray casting:

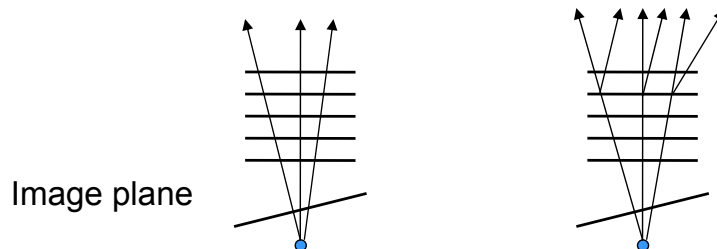
```
for  $y_i = 1$  to ImageHeight
  for  $x_i = 1$  to ImageWidth
    for  $z_i = 1$  to RayLength
      foreach  $x_o$  in ResamplingFilter ( $x_i, y_i, z_i$ )
        foreach  $y_o$  in ResamplingFilter ( $x_i, y_i, z_i$ )
          foreach  $z_o$  in ResamplingFilter ( $x_i, y_i, z_i$ )
            add contribution of Voxel [ $x_o, y_o, z_o$ ] to ImagePixel [ $x_i, y_i$ ]
```

The resampling filter corresponds to the interpolation (often 2x2x2 values)

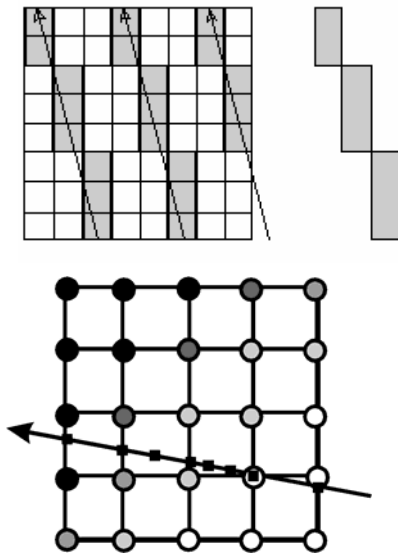
Problem: The volume is not traversed in the order in which it lies in the memory. Often, voxels which are not in the cache or in the central memory, are required.

# Direct Volume Visualization: Image-based Methods

- Problem: consistent sampling of the volume in case of perspective projection (diverging rays)
- Possible solution:
  - Splitting of the rays
  - The ray integrates a broader area for slices that are further away



# Direct Volume Visualization: Image-based Methods

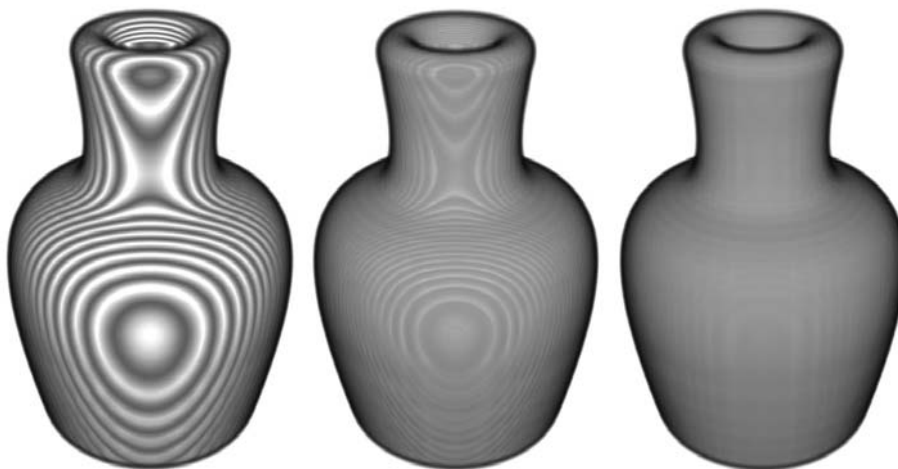


## Methods of acceleration

- Ray templates in case of parallel ray casting (Yagel et al. [1992])
- Early ray termination (e.g., at 95% opacity, acceleration approx. factor 2) (Levoy [1990])
- Adaptive ray sampling (increase of the sampling rate in very transparent areas or with increasing distance) (Danskin, Hanrahan [1992])

# Direct Volume Visualization: Image-based Methods

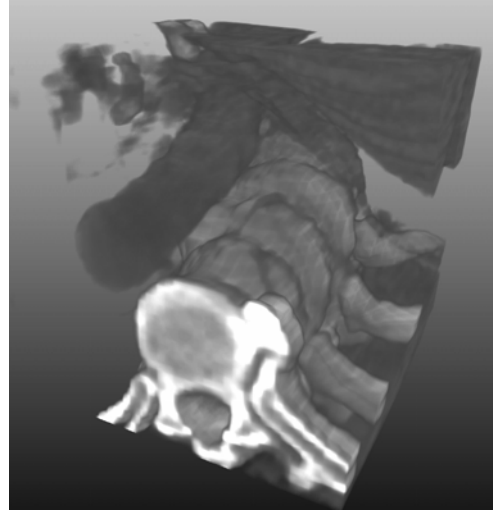
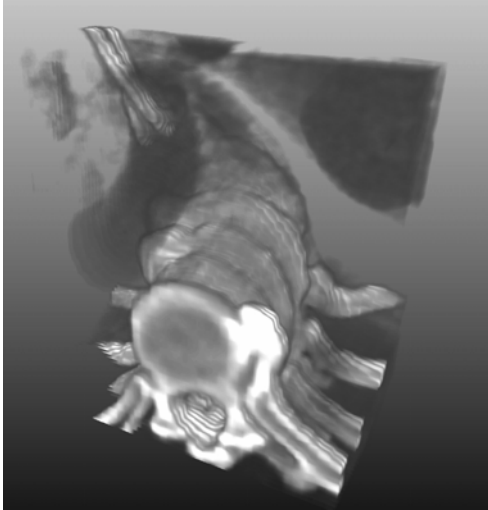
Influence of the sampling rate on alias effects (increment: 2.0 voxel, 1.0 voxel, 0.1 voxel), (© Schroeder et al. [1998])



Suggestion: increment  $< 0.5$  voxels (according to the sampling theorem: sampling at least with the double frequency which is present in the discrete data).

# Direct Volume Visualization: Image-based Methods

Influence of the sampling rate on alias effects  
(increment: 1.0 voxel, 0.2 voxels)



# Direct Volume Visualization: Texture-based Methods

## Volume Definition

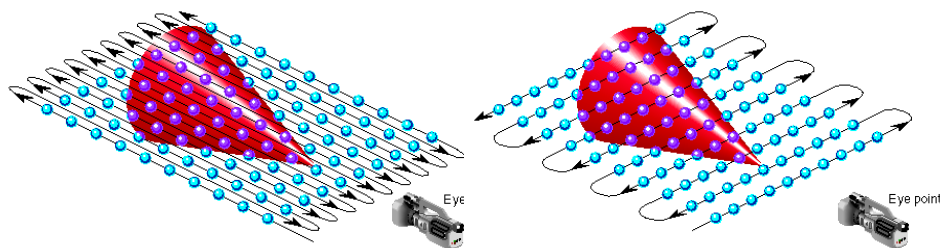
- The volume is loaded into the 3D texture memory.
- Application of a (hardware-based) lookup table, in which the data can be scaled and shifted and be mapped to RGBA values (transformation into an internal format)
- If volume > texture memory
  - partition of the volume into bricks
  - overlapping of the brick ends for a correct interpolation at the edges

# Direct Volume Visualization: Texture-based Methods

## Basic Approach:

- The volume is cut through equidistant planes
- Textured polygons are generated for each slice plane. They are drawn from back to front and overlaid semi-transparently.
- If volume > texture memory
  - sorting of the blocks according to the distance
- Hardware: 3D texture memory in PC graphics cards, ATI Radeon since 10/2000 and NVidia from GForce 3 (2/2001)

# Direct Volume Visualization: Texture-based Methods



Source: Silicon Graphics

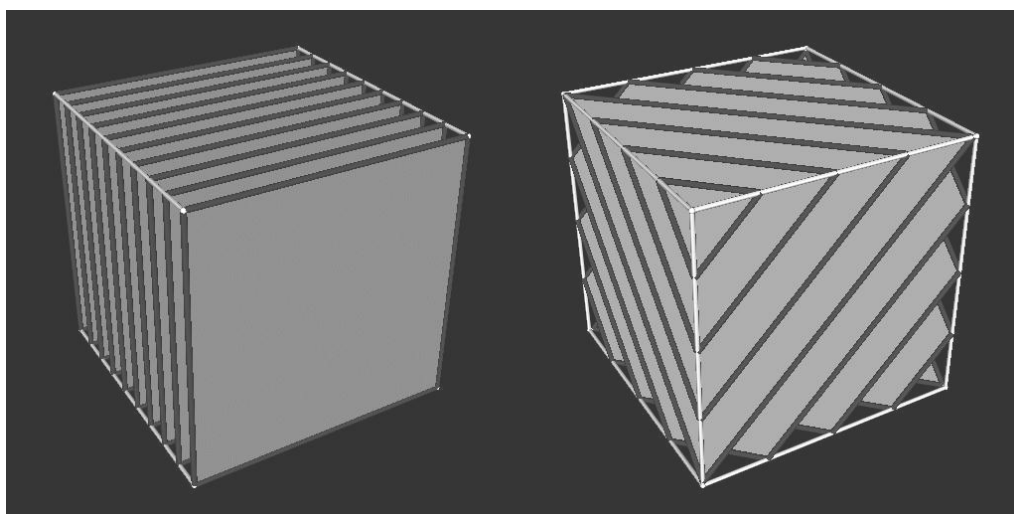
Comparison of the procedures of the image-based volume visualization (ray casting, left) and of texture based procedures (right)

# Direct Volume Visualization: Texture-based Methods

## Usage of 2D texture mapping hardware

- Volume is loaded into the texture memory 3 times (always one copy for each orthogonal direction)
- In case of rotation one uses the copy whose angle between viewing direction and the corresponding orthogonal direction is minimal.
- Problems:
  - Switching effects between the 3 flow directions (artifacts, delay)
  - Memory requirements

# Direct Volume Visualization: Texture-based Methods



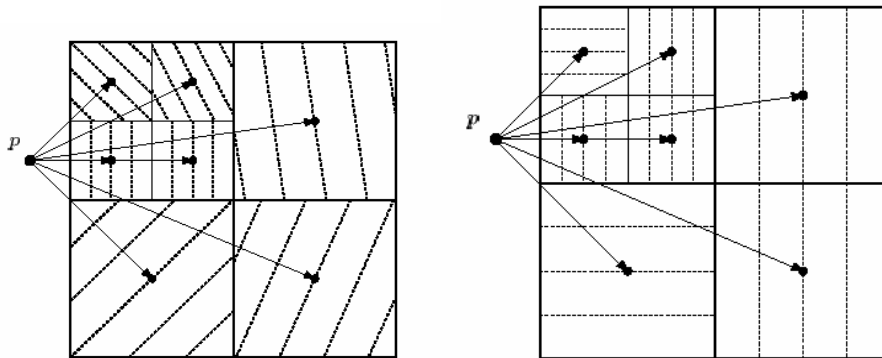
Source: Silicon Graphics

2D texture mapping and 3D texture mapping with sectional planes which proceed parallel to the view plane. (viewport-parallel)

# Direct Volume Visualization: Texture-based Methods

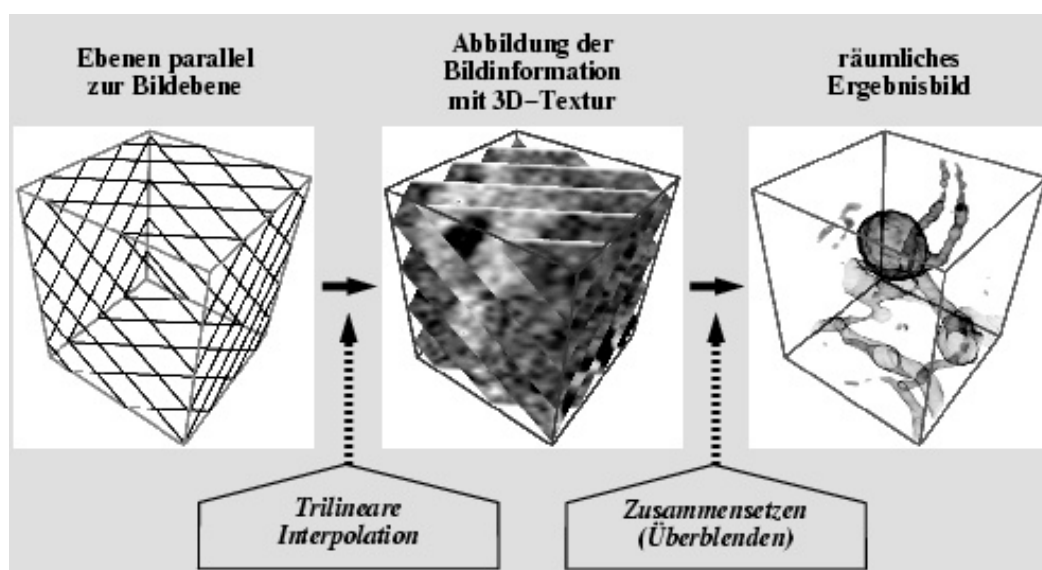
Viewport-parallel and axial-parallel rendering

- Viewport-parallel rendering improves the quality remarkably.
- In connection with hierarchic data structures and sceneography, different slice directions for parts of the data are useful. Left: vp-parallel, right: axial-parallel



Source: LaMar et al. (1999)

# Direct Volume Visualization: Texture-based Methods

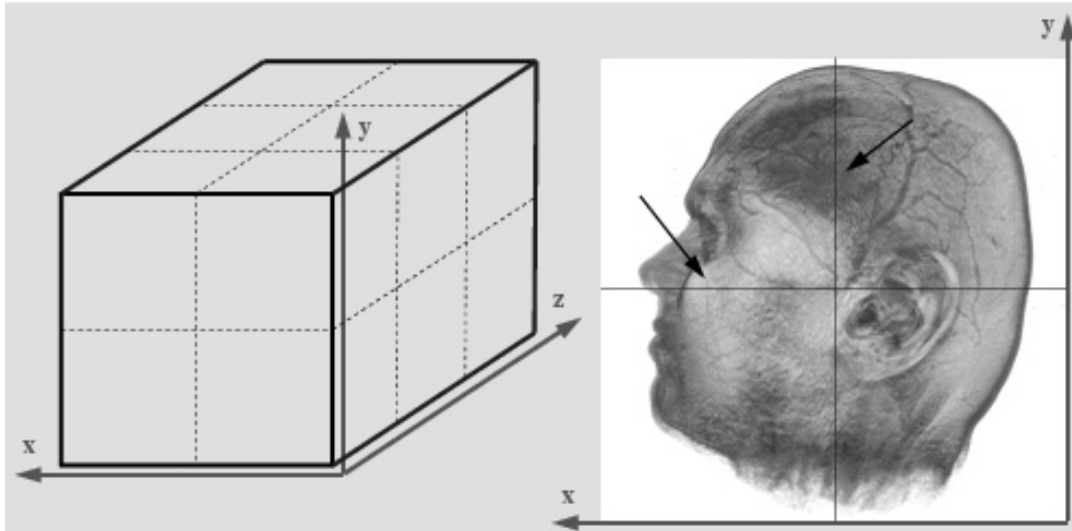


Procedure for the use of 3D textures

(© Peter Hastreiter, University of Erlangen)

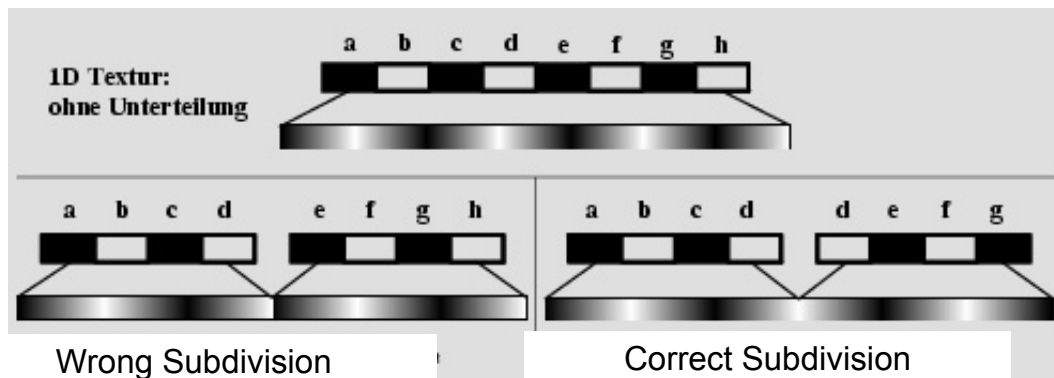
# Direct Volume Visualization: Texture-based Methods

Division of the volume into bricks, artifacts (black stripes)  
in case of non-observance of the boundaries  
(© Peter Hastreiter, University of Erlangen)



# Direct Volume Visualization: Texture-based Methods

Division into bricks. Thus, the data overlap about one voxel in each dimension and continuous transitions raise at the boundaries.



© Peter Hastreiter, University of Erlangen



# Direct Volume Visualization: Texture-based Methods

## Interpolation of slices

- Problem: in case of strongly anisotropic data, the amount of slices is not sufficient to ensure a good quality.
- Interpolation of additional slices is possible, but increases the memory requirements.
- Possible solution with a modern graphics hardware:
  - use of multitextures (for one sampling point, two textures are considered and linearly interpolated in between).
  - An additional slice is generated temporarily.

# Direct Volume Visualization: Projection Methods

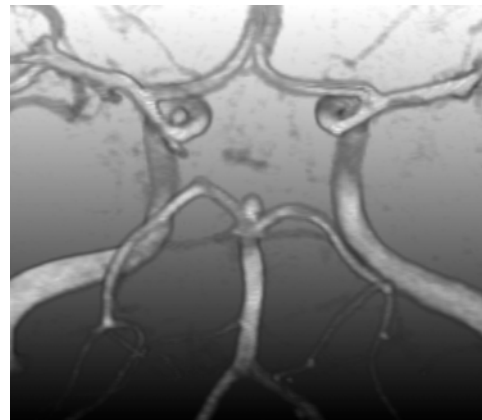
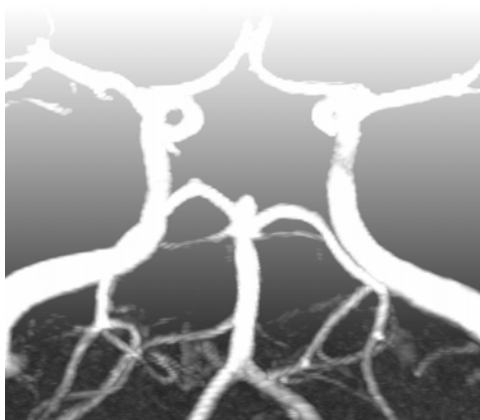
Average Projection	Average of all hit voxels per ray	Simulation of x-ray projections
Maximum (minimum) Intensity Projection (M(m)IP)	Brightest and (darkest) voxel hit per ray	Illustration of vessels, noise-added data
Closest Vessel Projection (Zuiderveld [1995])	First hit voxel per ray above a threshold	Illustration of vessels

## Direct Volume Visualization: Projection Methods



MIP (Data: MR angiography)

## Direct Volume Visualization: Projection Methods



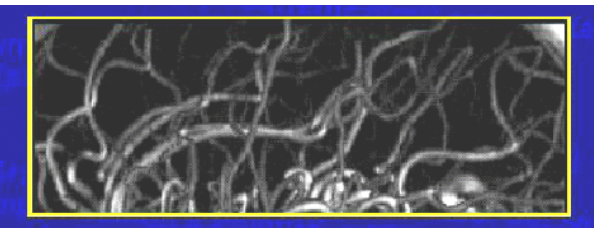
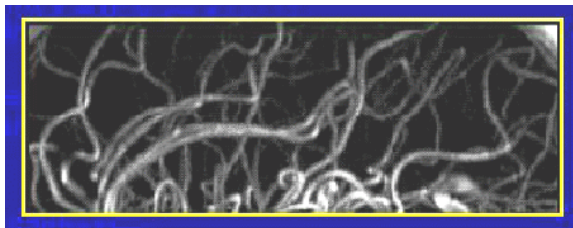
Comparison of MIP and DVR, cerebral vessels, purpose: diagnosis of aneurysms (Data: MR angiography, Prof. Terwey, Bremen)

# Direct Volume Visualization: Projection Methods

Restriction of the data on which a MIP is applied:

- (1) Remove certain structures which disturb the MIP interaction.  
Example: Removal of bones (interactively by placing a seed point and Region Growing).
- (2) Apply the MIP to a certain partial volume.  
Example: MIP illustration in a segmented organ for the selective evaluation of this organ

# Direct Volume Visualization: Projection Methods



MIP and CVP of brain vessels (© Karel Zuiderveld)

To evaluate spatial relations, movies with rotations of MIP and CVP in a central perspective are often used.

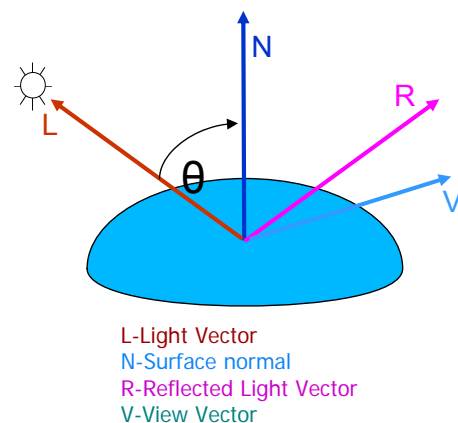
# Direct Volume Visualization: Projection Methods

Thin-Slab-MIP

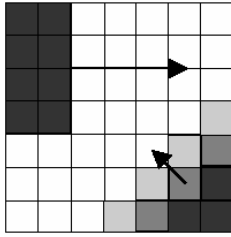


## Direct Volume Visualization: Lightning

- Angle of incidence  $\theta$ : angle between  $L$  and  $N$  (determines the diffuse reflection)
- Reflection angle  $r$ : angle between  $R$  and  $N$ .
- Angle  $\phi$  between  $V$  and  $R$  determines the intensity of the incident light.
- If  $V = R$  (respectively  $\phi = 0$ ), the light is reflected maximal to the viewer.



# Direct Volume Visualization: Lightning



- Approximation of the surface normal by calculating the gradient (grey level gradient shading, Source: Höhne and Bernstein [1986])
- Problem: Memory requirements: 4 Byte \* 3 per voxel
- Indirect storage of the normals as indices in a field of normalized vectors (rounding)  
→ Discretization of the normal in a gradient lookup table



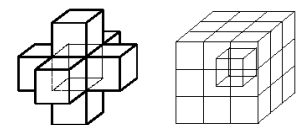
- Illuminated illustration of an MRT data set (high sampling rate and trilinear interpolation)

Problems:

- High noise sensibility (possibly smooth gradients) or ignore small gradients (use the threshold value)
- No consideration of the gradient strength

# Direct Volume Visualization: Shading

Common variants of gradient estimation:



- (1) central differences (6 neighbors):  

$$\nabla V(X) = (\partial V / \partial x, \partial V / \partial y, \partial V / \partial z)$$

$$\nabla V(x_i, y_j, z_k) = \left( \frac{1}{2} (V(x_{i+1}, y_j, z_k) - V(x_{i-1}, y_j, z_k)), \right.$$

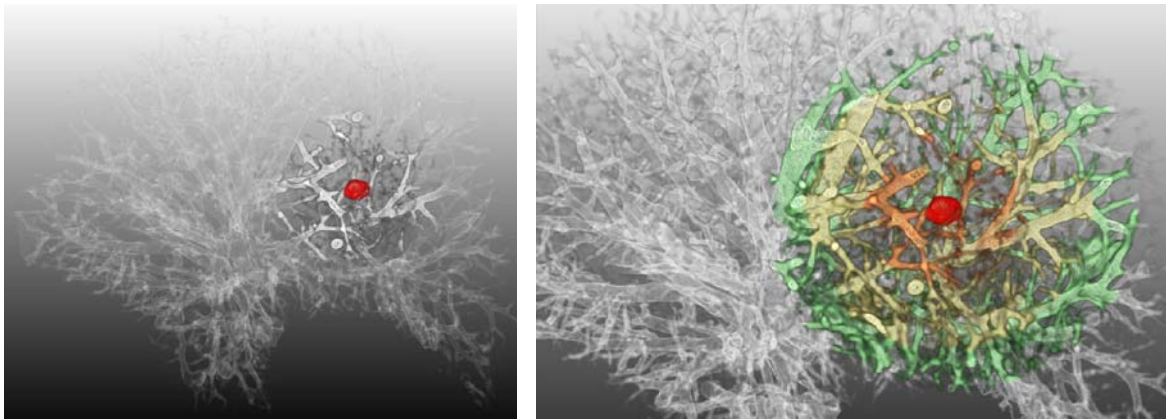
$$\left. \frac{1}{2} (V(x_i, y_{j+1}, z_k) - V(x_i, y_{j-1}, z_k)), \right.$$

$$\left. \frac{1}{2} (V(x_i, y_j, z_{k+1}) - V(x_i, y_j, z_{k-1})) \right)$$
- (2) Gradient estimation of from the 26 neighbors (weighting according to the distance from the central voxel)
- (3) Gradient calculation, not from direct neighbors, but from  $x_{i+2}, x_{i-2}, y_{i+2}, y_{i-2}, z_{i+2}, z_{i-2}$ ,

The second variant is more complex than the first one, but qualitatively better.

Problems: treatment of boundaries, line structures

# Direct Volume Visualization: Tagged VR



Tappenbeck [2006]

Segmentation: Tumor

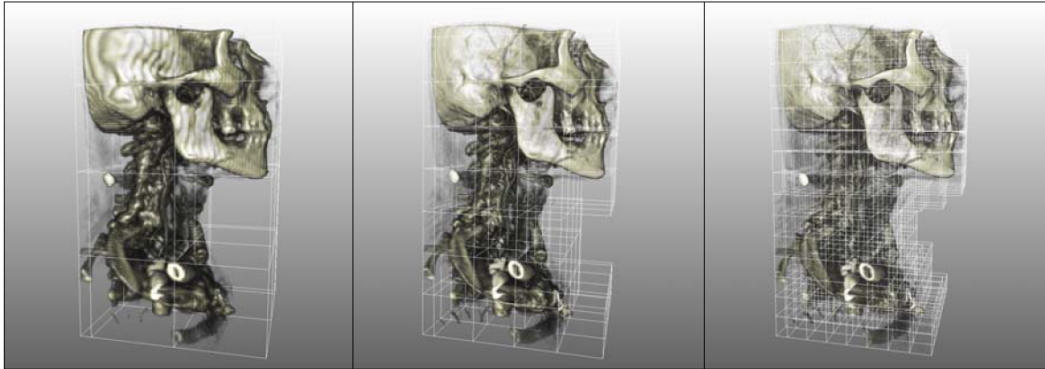
Visualization: Distance-based TFs (distance to tumor mapped to opacity and color)

## Direct Volume Visualization: Hierarchical Methods

- Goal: restrict rendering to visible portions and/or importance
- Typical data structure: Octree
- Node size, 16x16 .... 64x64
- Requires resampling, e.g. by means of a rank filter
- Overlap of the nodes for correct interpolation (1 voxel)
- Moderate additional memory load

# Direct Volume Visualization: Hierarchical Methods

- Octree nodes are rendered back to front
- Order of nodes depends on the viewing direction
- Lower resolution may be used for interactive rendering



Link [2006]

## Validation in Medical Visualization

- Accuracy of the generated visualizations (with given image data) depends on a variety of parameters:
  - type and parameter of the interpolation
  - distances of the sampling points
  - used gradient filters
  - treatment of boundaries in texture-based procedures
  - implementation faults!

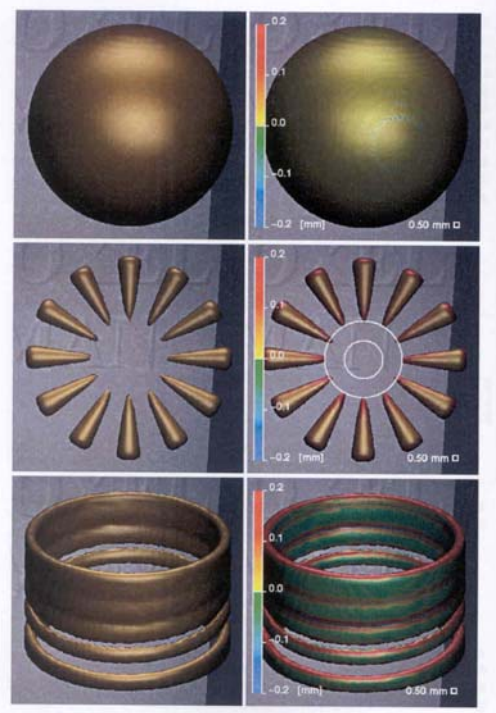


# Validation in Medical Visualization

- Essential parameters of accuracy:
  - Position fault: distance between a displayed point (e.g., border between 2 materials) and its precise location
  - Fault of normals: deviation of the approximated normal from the actual normal (angle in degree)
- How can accuracy be evaluated?
  - Qualitatively through the viewing of pictures. Problem: An exact solution is unknown.
  - Quantitatively through the volume visualization of phantoms: exact results are known. Problem: Transferability to clinical data.

# Validation in Medical Visualization

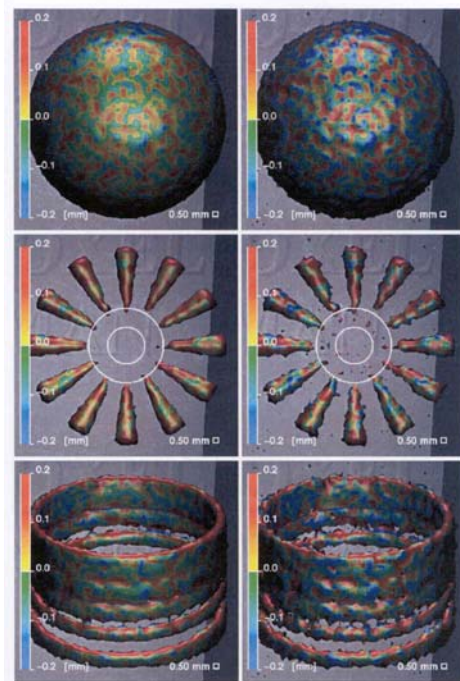
- Test piece: ball, SIEMENS star, and disconnected cylinder.
- Left: surface visualization.
- Right: volume visualization after discretization (1 mm<sup>3</sup>). Color coding of the arising position faults.



© Pommert [2004]

# Validation in Medical Visualization

- Simulation of additive noise in the image data. Color coded illustration of the position fault.
- Interpretation: Which variations can arise at a certain noise level (convolution core).

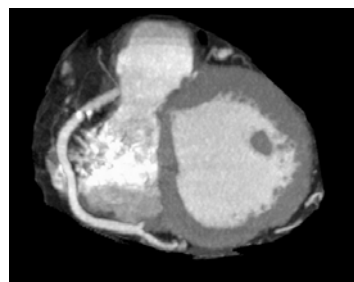


© Pommert [2004]

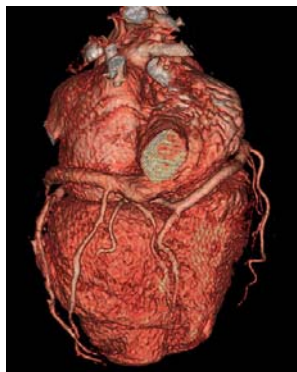
## Tools for Volume Visualization: Volume per 1000 – Image Gallery



CTA of the  
abdominal  
vessels



MIP restricted to a  
subvolume (slab)  
Data: Cardiac CTA

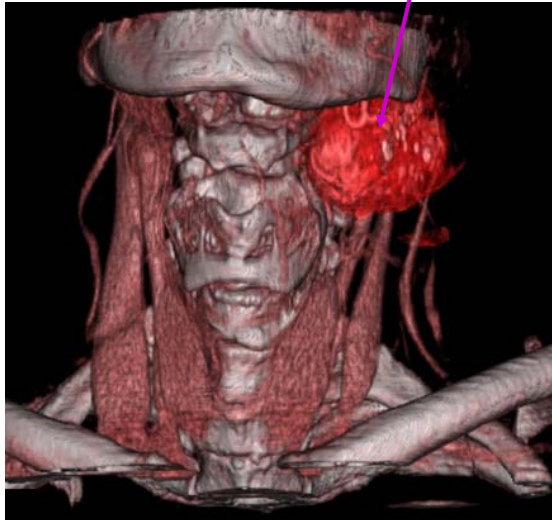


Aneurysm of  
the abdominal  
aorta



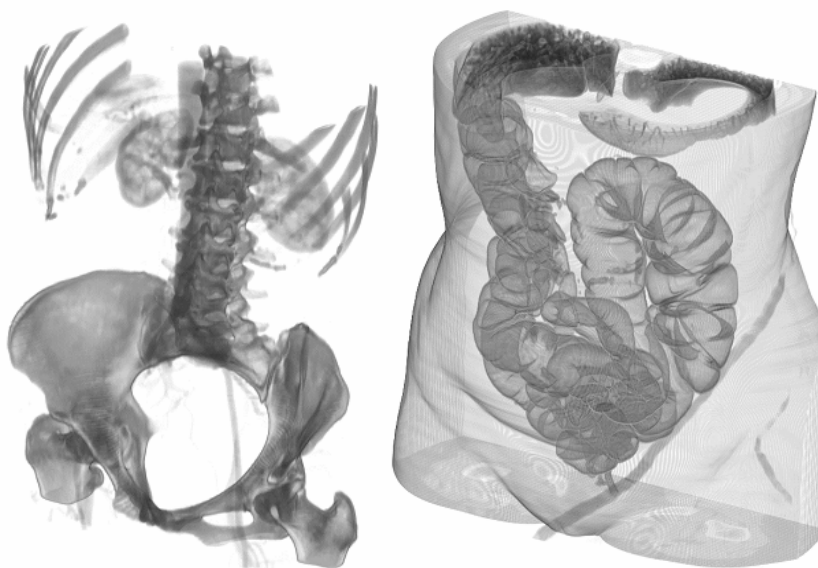
## Tools for Volume Visualization: Volume per 1000 – Image Gallery

tumor in the neck area



MIP illustration of the kidney (vessels)

## Tools for Volume Visualization: Volume per 1000 – Image Gallery



Images Courtesy,  
Hoen-Oh Shin,  
Medical School  
Hannover

Direct volume rendering with gradient-based TFs and VolumePro.

# Literature: Volume Rendering

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- M Chen, AE Kaufman, R. Yagel (Hrsg.) (2000) *Volume Graphics*, Springer
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- S Fang and H Chen (2000) "Hardware Accelerated Voxelisation", In: Chen et al. [2000], p. 302-315
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- KH Höhne and R Bernstein (1986) "Shading 3D-images from CT using gray level gradients", *IEEE Trans. Med. Imaging* MI-5, (1986), p. 45-47

# Literature: Volume Rendering

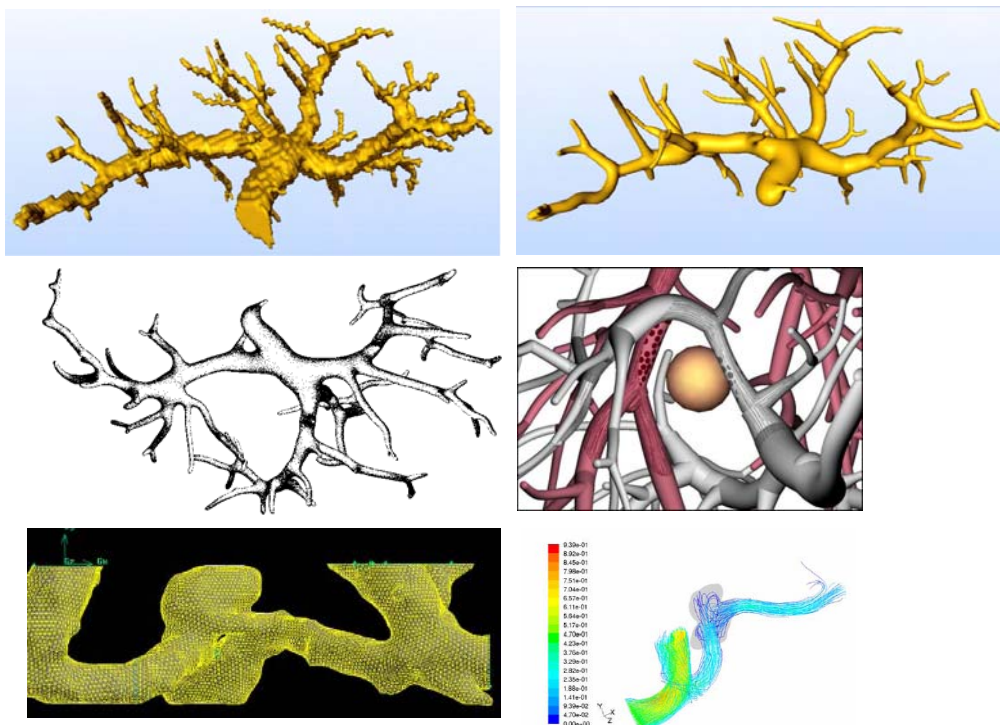
- P Lacroute and M Levoy (1994) "Fast Volume Rendering Using a Shear-Warp Factorization of the Viewing Transformation", *Proc. of SIGGRAPH '94*, p. 451-458
- P Lacroute (1995) *Fast Volume Rendering Using a Shear-Warp Factorization of the Viewing Transformation*, PhD-Thesis, Stanford (available online)
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- F Link, M Koenig, H-O Peitgen (2006). „Multi-Resolution Volume Rendering with per Object Shading“, *Proc. of Vision, Modelling and Visualization*
- H Noordmans, A Smeulders, and H Van der Voort (1997) "Fast Volume Render Techniques for Interactive Analysis", *Visual Computer*, Vol. 13(8), p. 345-358



# Literature: Volume Rendering

- J Oikarinen, R Hietala, and L Jyrkinen (2000) "High Quality Volume Rendering Using Seed Filling in View Lattice", In: Chen et al. (2000), p. 199-210
- A Pommert (2004) *Simulationsstudien zur Untersuchung der Bildqualität für die 3D-Visualisierung tomografischer Volumendaten*, Dissertation at the Institute of Mathematics and Data Processing in Medicine, University Medical Center Hamburg-Eppendorf
- C Rezk-Salama (2002) *Volume rendering techniques for general purpose graphics hardware*, Dissertation, Techn. Faculty, University of Erlangen-Nürnberg
- A Tappenbeck, V Dicken, B Preim (2006) "Distance-based transfer functions", Proc. of Simulation and Visualization, pp. 259-274
- L Westover (1990) "Footprint Evaluation for Volume Rendering", *Proc. of SIGGRAPH '90*, p. 367-376, August 1990
- R. Yagel, A. Kaufman, and Q. Zhang (1991) "Realistic Volume Imaging", *IEEE Visualization '91*, p. 226-231
- R Yagel, (1992) "Template-Based Volume Viewing", *Proc. of Eurographics*, Computer Graphics Forum, Vol. 11(3), p. 153-157
- KJ Zuiderveld, AH Koning, M Viergever (1992) "Acceleration of Ray Casting using 3d Distance Transforms", *Proc. of Visualization in Biomedical Computing*, p. 324-335
- KJ Zuiderveld (1995) *Visualization of multimodality medical volume data using object-oriented methods*, PhD-thesis, University of Utrecht

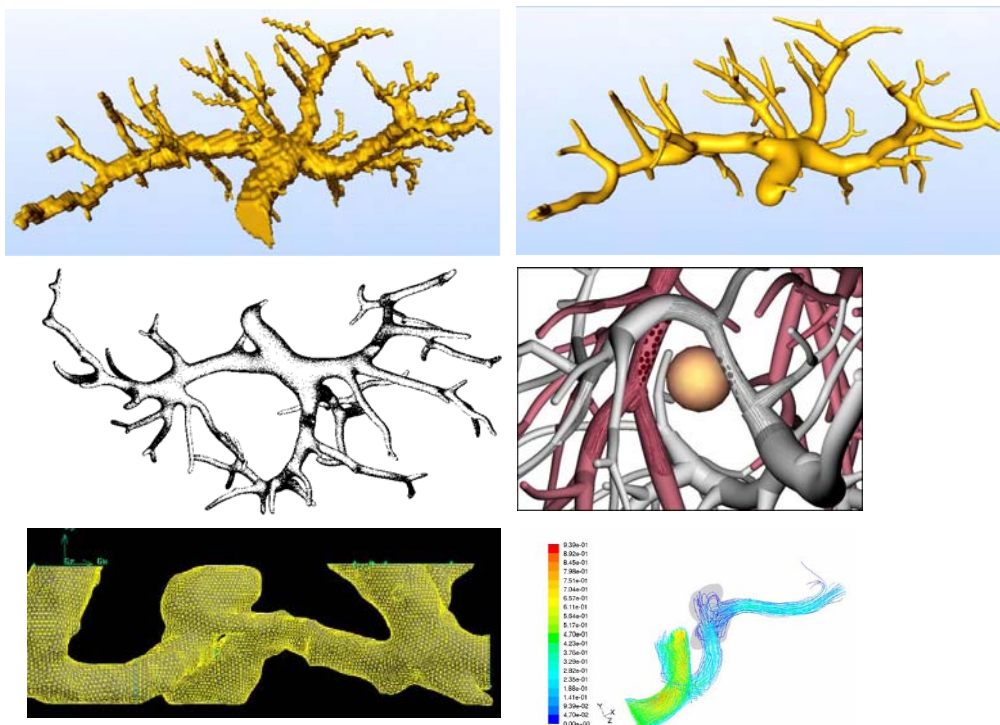
## Visualization of Vascular Structures



# Literature: Volume Rendering

- J Oikarinen, R Hietala, and L Jyrkinen (2000) "High Quality Volume Rendering Using Seed Filling in View Lattice", In: Chen et al. (2000), p. 199-210
- A Pommert (2004) *Simulationsstudien zur Untersuchung der Bildqualität für die 3D-Visualisierung tomografischer Volumendaten*, Dissertation at the Institute of Mathematics and Data Processing in Medicine, University Medical Center Hamburg-Eppendorf
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- R. Yagel, A. Kaufman, and Q. Zhang (1991) "Realistic Volume Imaging", *IEEE Visualization '91*, p. 226-231
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- KJ Zuiderveld, AH Koning, M Viergever (1992) "Acceleration of Ray Casting using 3d Distance Transforms", *Proc. of Visualization in Biomedical Computing*, p. 324-335
- KJ Zuiderveld (1995) *Visualization of multimodality medical volume data using object-oriented methods*, PhD-thesis, University of Utrecht

## 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

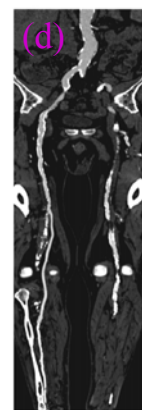
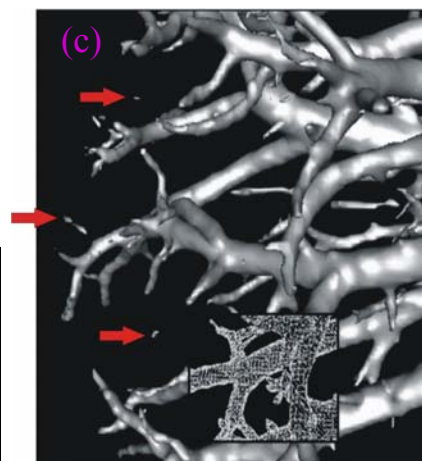
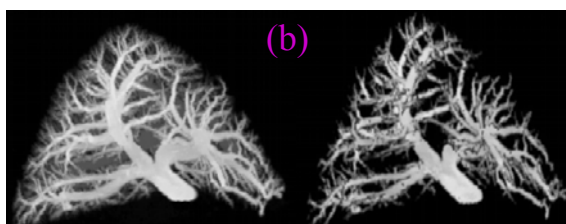
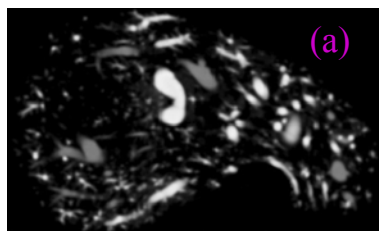
- Traditional approaches:

(a) slice-based examination

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

(c) Isosurface Rendering

(d) Curved Planar Reformation



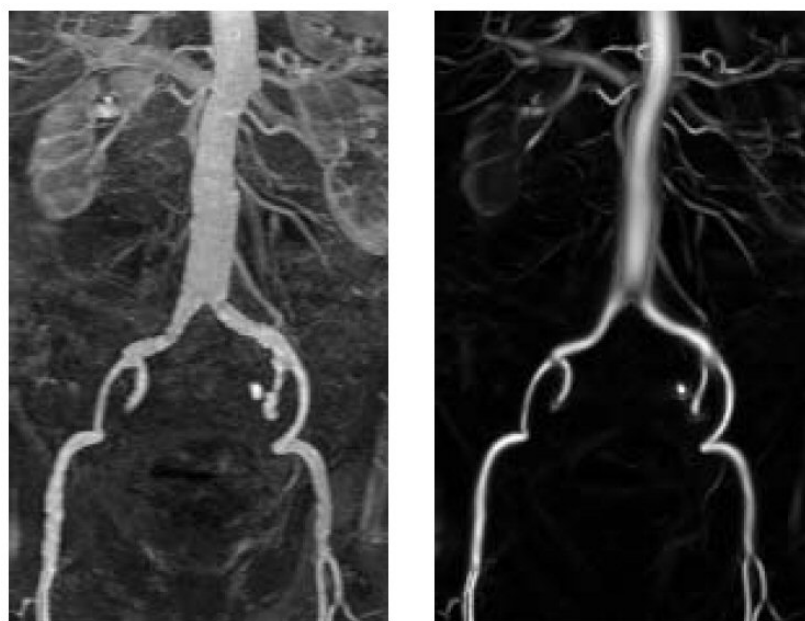
[Kanitsar, 2001]



# Vascular Diagnosis vs. Surgery Planning

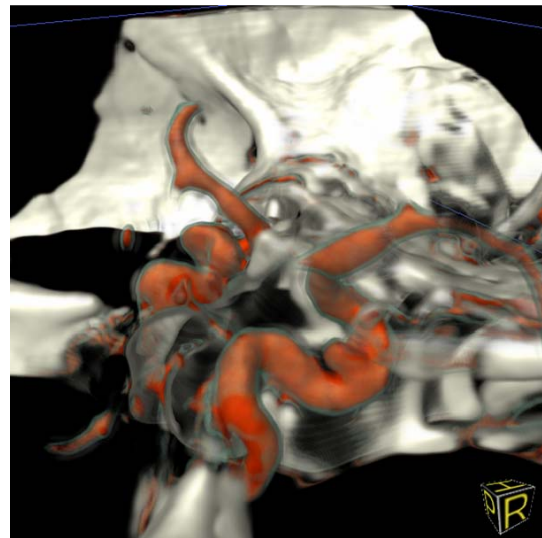
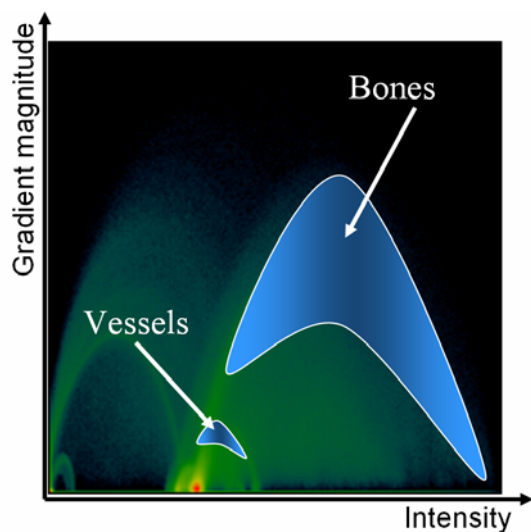
- Visualization in vascular diagnosis and vascular surgery:
  - Close adherence to the image data (vascular cross section)
  - Mostly slice-based examination, Curved Planar Reformations
  - 3D visualization must be accurate
  - Vascular surgery: bypass surgery, endoscopic treatment of aneurysms
- Visualization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

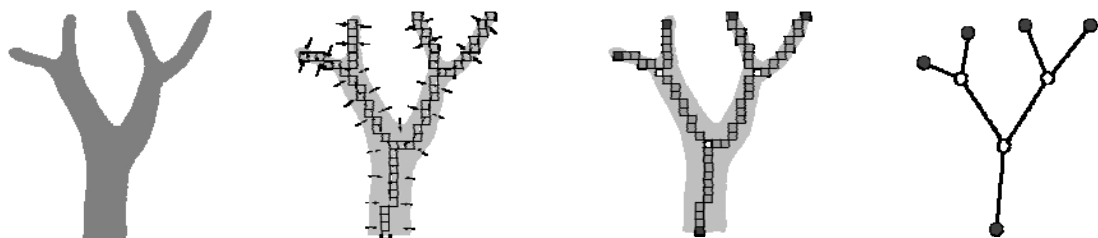
# Direct Volume Rendering



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

## Image Data and Vessel Analysis

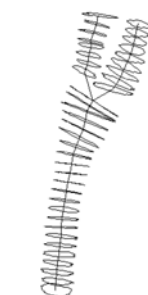
- High resolution CT- or MR-data → Segmentation → Skeletonization → Analysis of shape and branching pattern



[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



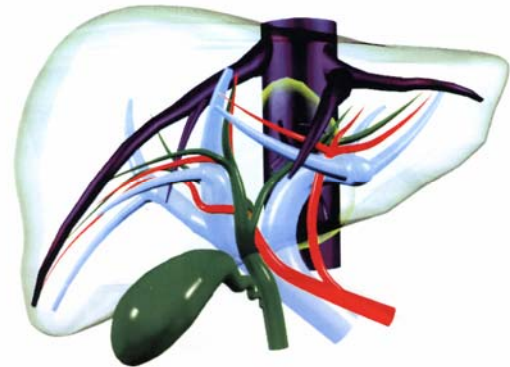
[Ehricke, 1994]

# 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



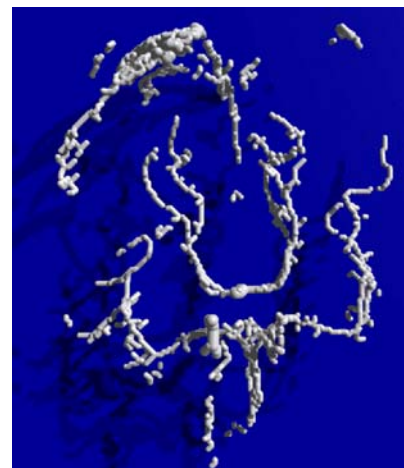
Requirements:

- Correct representation of the vessel diameter
- Smooth, organic looking vessel shape
- Closed vessel ends
- Avoidance of structures inside the vessels

[Mazziotti, 1997]

## Model-based Visualization – Cylinder Fitting

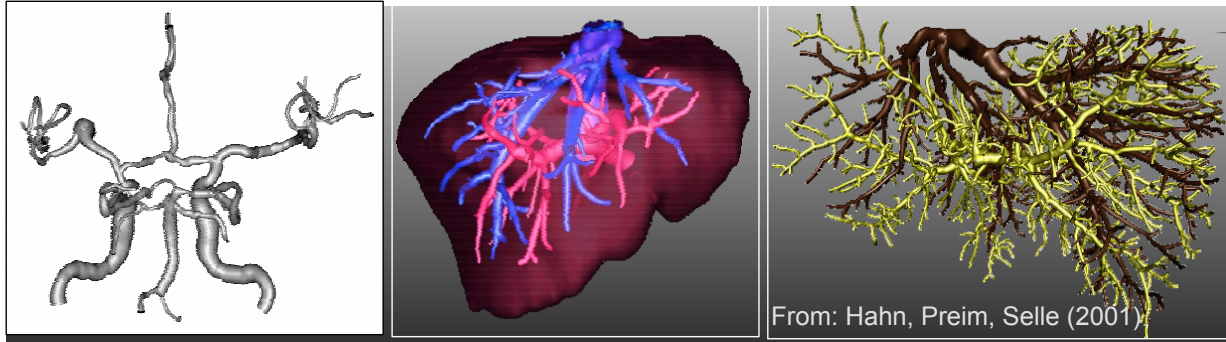
- Gerig et al., 1993: “Symbolic Description of 3d structures applied to cerebral vessel tree obtained from MR angiography volume data”.
- Graph representation (edges, nodes) of the vessel tree for structural analysis, e.g. identification of subtrees
- Representation of the local vessel diameter by means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



[Gerig, 1993]

# Model-based Visualization – Truncated Cones Fitting

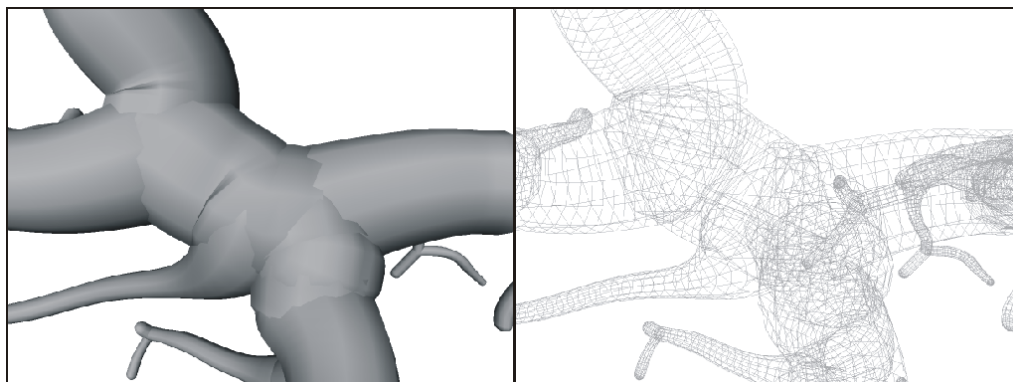
- Filtering: Smoothing of the skeleton and radius (Binominal filter)
- Mapping:
  1. Concatenation of truncated cones along the skeleton
  2. Mapping of truncated cones to polygons



- 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)

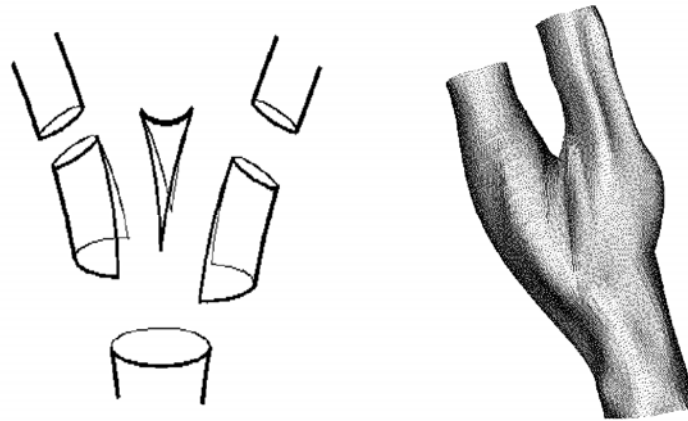
# Model-based Visualization – Truncated Cone Fitting

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



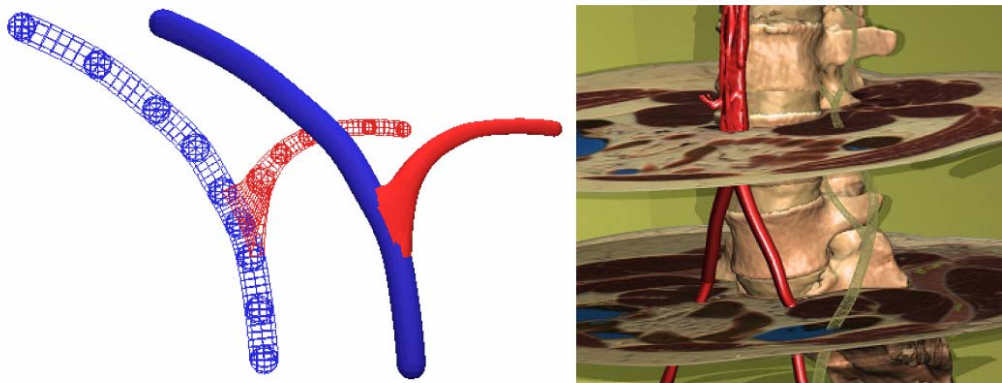
# Model-based Visualization – Freeform Surfaces

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



[Ehricke, 1994]

# Model-based Visualization – Freeform Surfaces

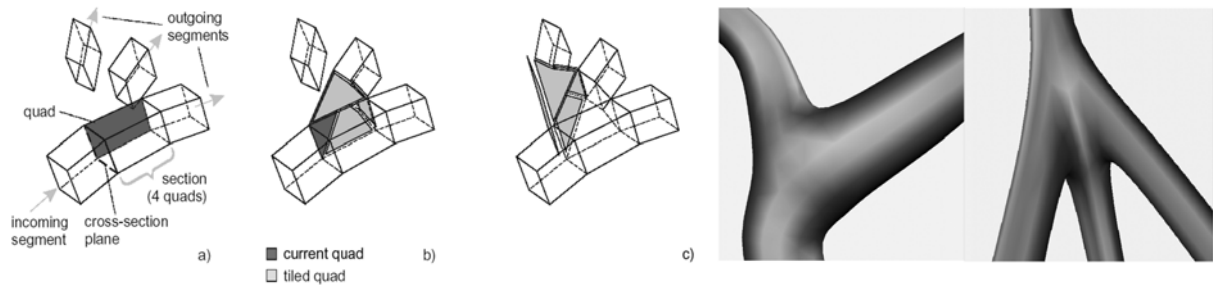


Modelling incompletely segmented nerves and vascular structures with B-splines. Application within the VoxelMan  
[Pommert, 2001]



# 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

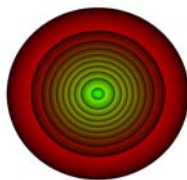
Visualization in two steps [Bornik, 2005] :

- 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

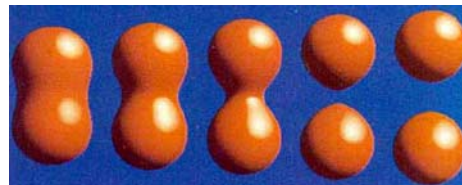
Idea (exploration of implicit surfaces):

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



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

$\omega = \text{width coefficient}$



Implicit surfaces for the visualization of tree structures

[Blinn, 1982]

- 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])

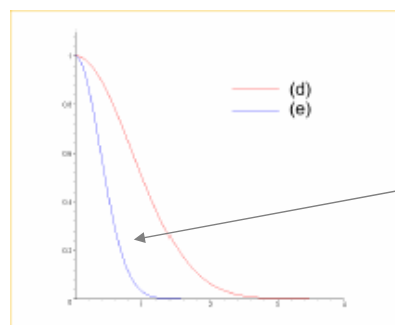
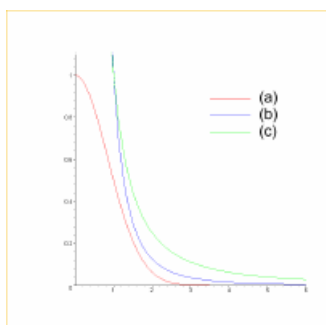
- Convolution of a signal with a filter
- Here: Convolution of line segments with a 3d-lowpass filter

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



- Polygonization with an isovalue depending on the filter

# Visualization of Vascular Structures: Convolution Surfaces



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

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

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

Exploration of filter functions.

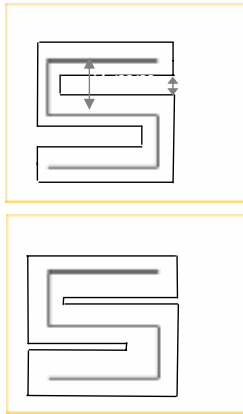
Selection guided by the following criteria:

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

Result:

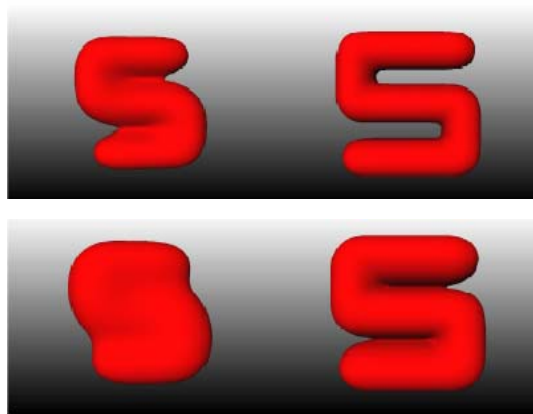
- A narrow Gaussian filter is a good choice.
- For even narrower filter kernels the implicit surface converges against the truncated cone visualization.

## Visualization of Vascular Structures: Convolution Surfaces



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

Below: radius: 1.37 mm  
( $3 - 1.37 \times 2 = 0.26$  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

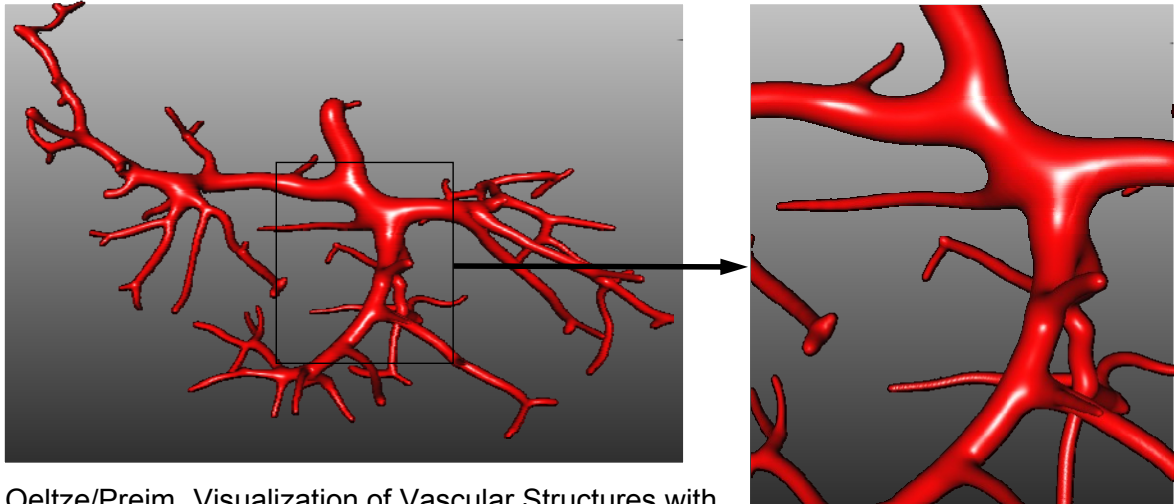


- Bulging



# Visualization of Vascular Structures: Applications of Convolution Surfaces

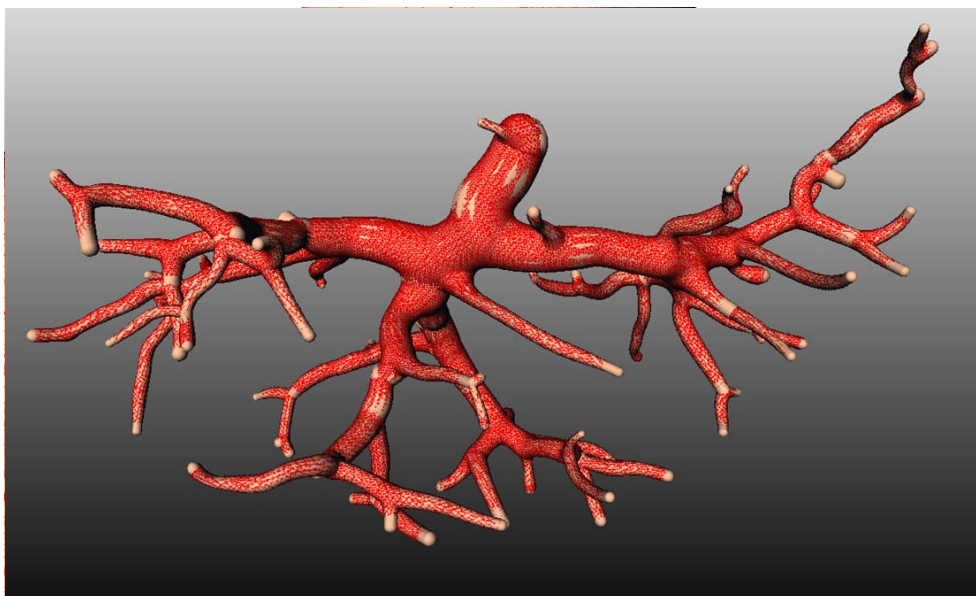
Portal vein of a human liver



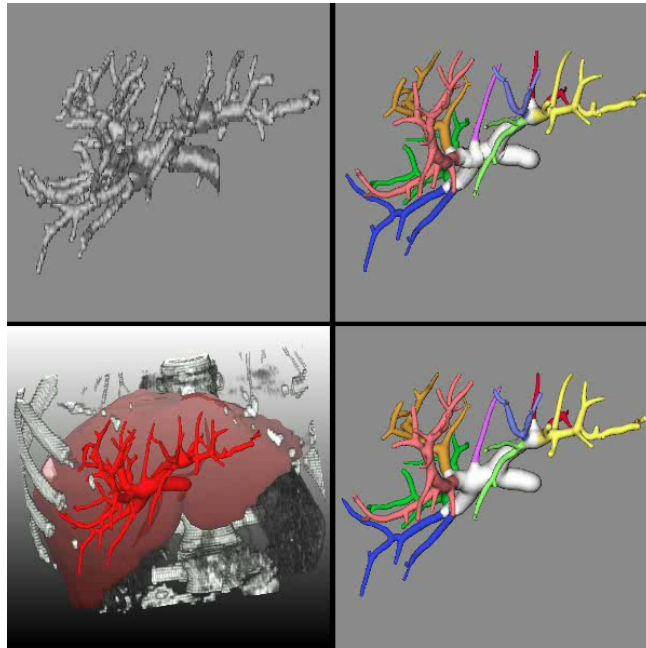
Oeltze/Preim „Visualization of Vascular Structures with Convolution Surfaces“, IEEE Transactions on Medical Imaging

## 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



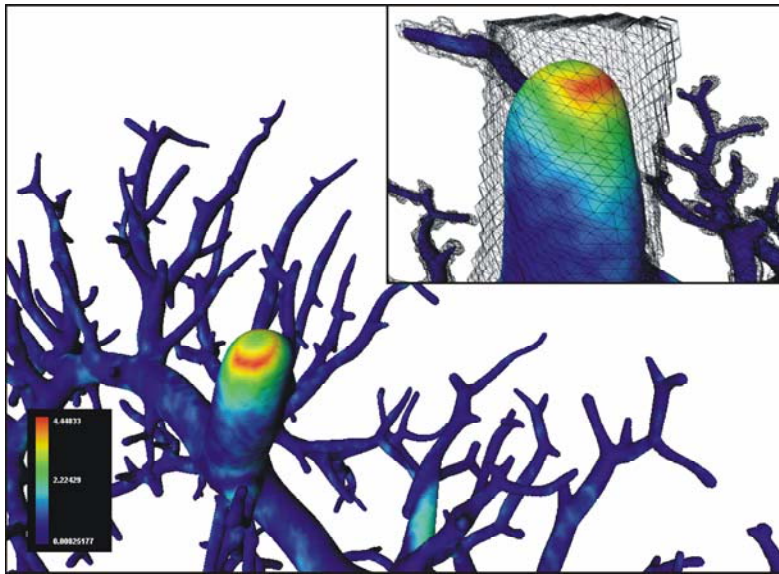
# Visualization of Vascular Structures: Validation of Convolution Surfaces

- 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:

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

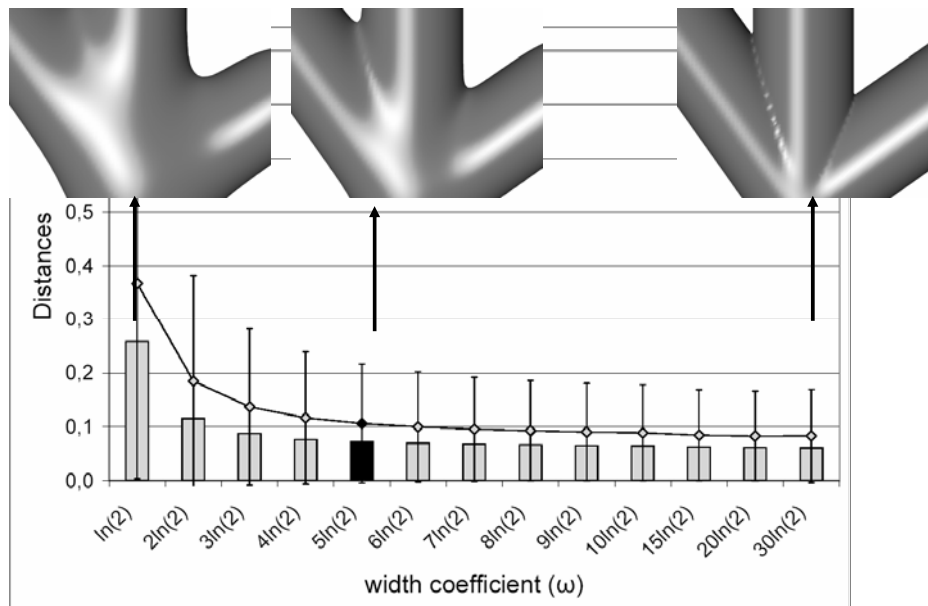
- Results:
  - Quantitative visualization (color coding)
  - Histogrammes of distances
  - Statistic Evaluation (mean, standard deviation, ...)

# Visualization of Vascular Structures: Validation of Convolution Surfaces



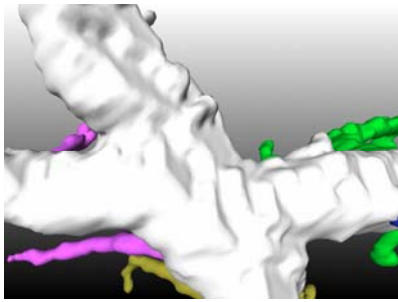
CS → Isosurface: Large distances only at the root of vascular trees

# Visualization of Vascular Structures: Validation of Convolution Surfaces

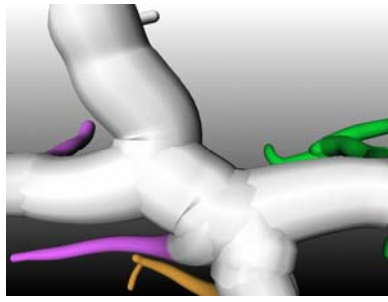


Width Coefficient versus accuracy (average and standard deviation of directional distances to isosurface)

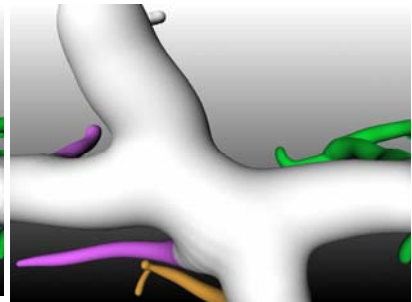
# Visualization of Vascular Structures: Evaluation of Convolution Surfaces



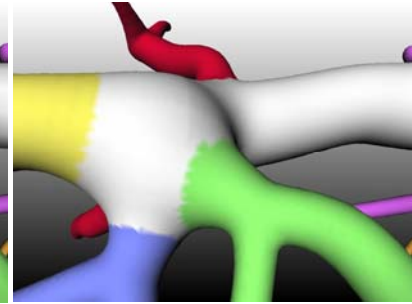
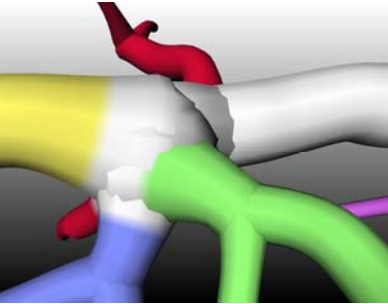
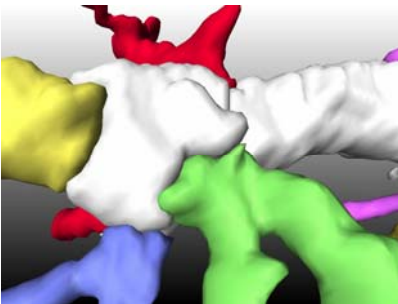
Isosurface of the  
segmentation result



Truncated Cones



Convolution Surfaces



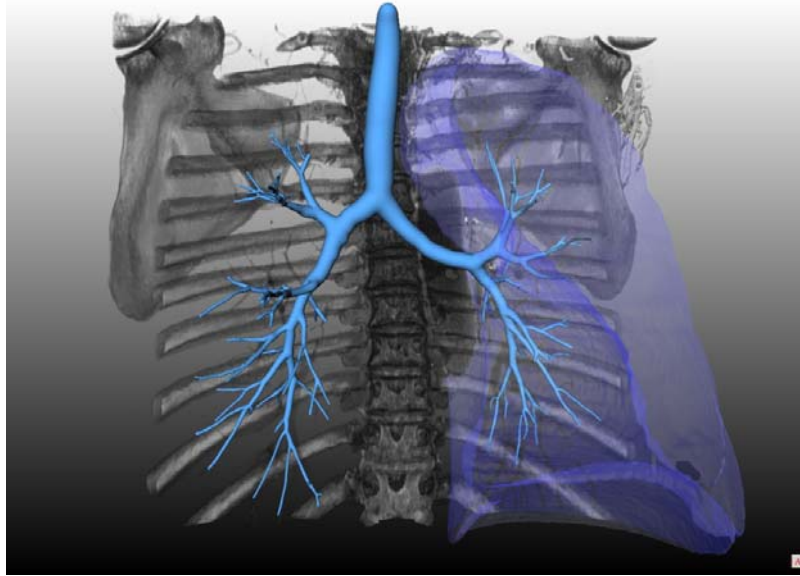
# Visualization of Vascular Structures: Evaluation of Convolution Surfaces

Method	Clarity (n=11)		Comprehensibility (n=11)		Similarity to operative Views (n=8)		Visual Quality (n=11)	
	$\bar{O}$	$\sigma$	$\bar{O}$	$\sigma$	$\bar{O}$	$\sigma$	$\bar{O}$	$\sigma$
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



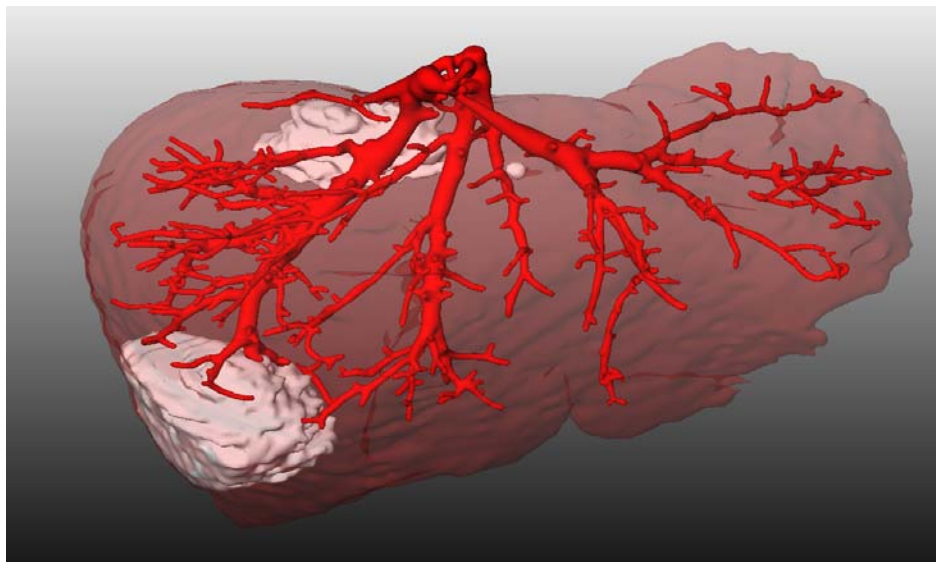
## Application Scenarios – Analysis of the Bronchial Tree

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



## Application Scenarios - Tumor Resection (1)

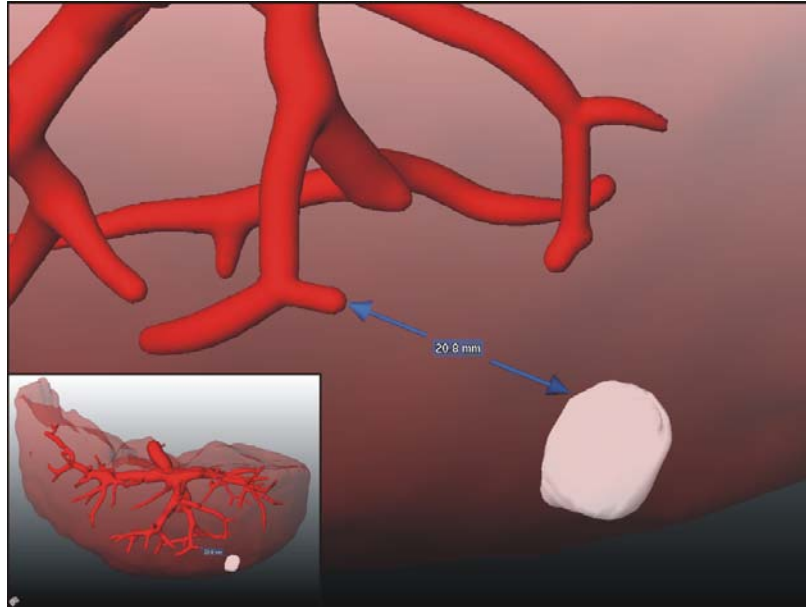
Visualization of the portal vein inside a human liver (with  
three tumors).



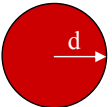


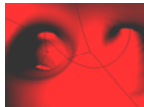


# Application Scenarios – Tumor Resection (2)

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



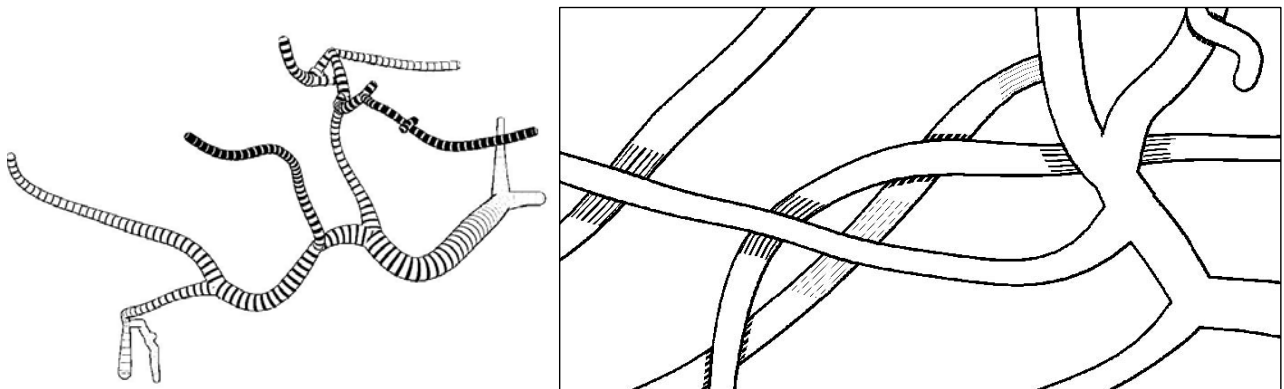
## Model-based Visualization – Comparison

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

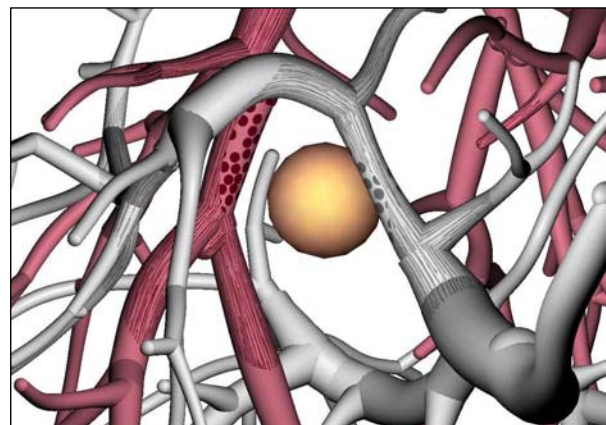
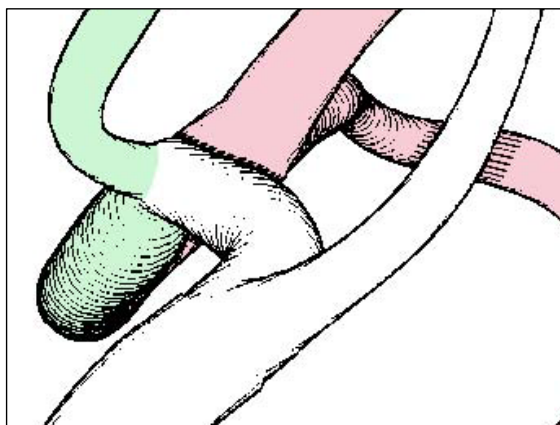
- Intraoperative projection of vasculature on liver surface
- Visualization of distance information by means of procedural textures
- Visualization method: truncated cones

[Ritter et al. 2006]

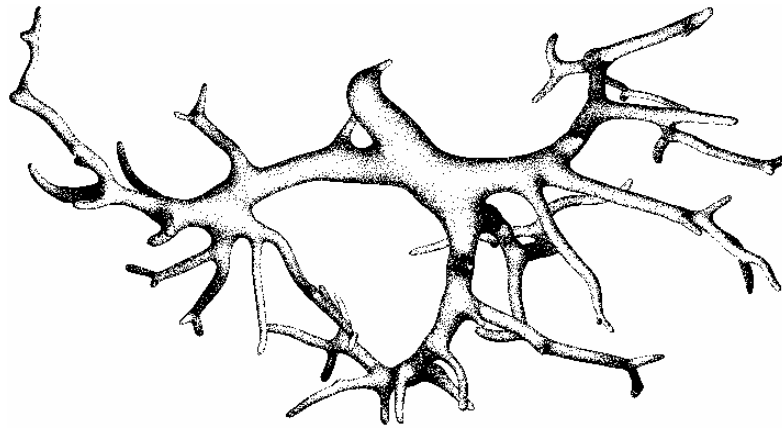


# Illustrative Visualization of Vasculature

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



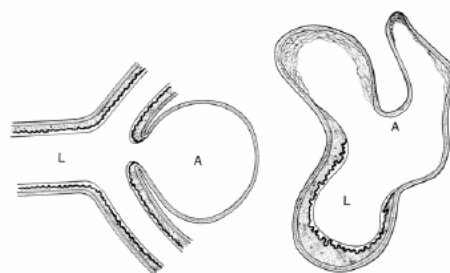
# Illustrative Visualization of Vasculature



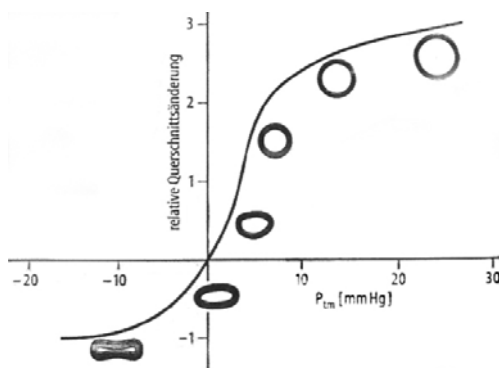
Stippling Convolution Surfaces with Textures. Minimal distortion of the stippling texture by using the PolyCubes-method.  
[Baer, 2007]

## Model-Free Visualization

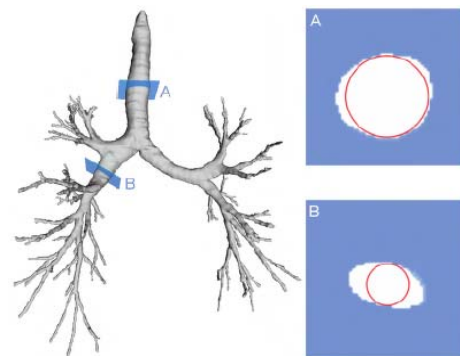
- Simplifying model-assumption of circular cross-sections is invalid for pathologic vessel parts, e.g. aneurysms
- Even Non-pathologic vessels may exhibit non-circular cross-sections



[Osborn, 1999]



[Schmidt, 2004]



[Schumann, 2006]

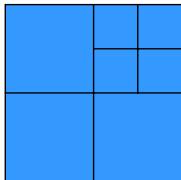
# Model-Free Visualization – Multi-level Partition of Unity Implicits

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

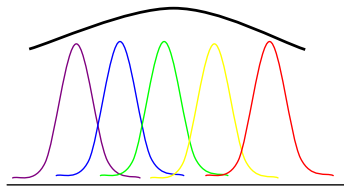
- Visualization of vasculature based on post processed segmentation result (points placed within boundary voxels)
- Arbitrary cross-sections may be reconstructed
- Suitable for vessel diagnosis
- Algorithm:
  - Spatial subdivision of the point cloud by an octree
  - Local approximation by means of surfaces
  - Blending of local approximations results in global approximation

## Multi-level Partition of Unity Implicits

Adaptive  
refinement



Piecewise quadratic  
local approximation



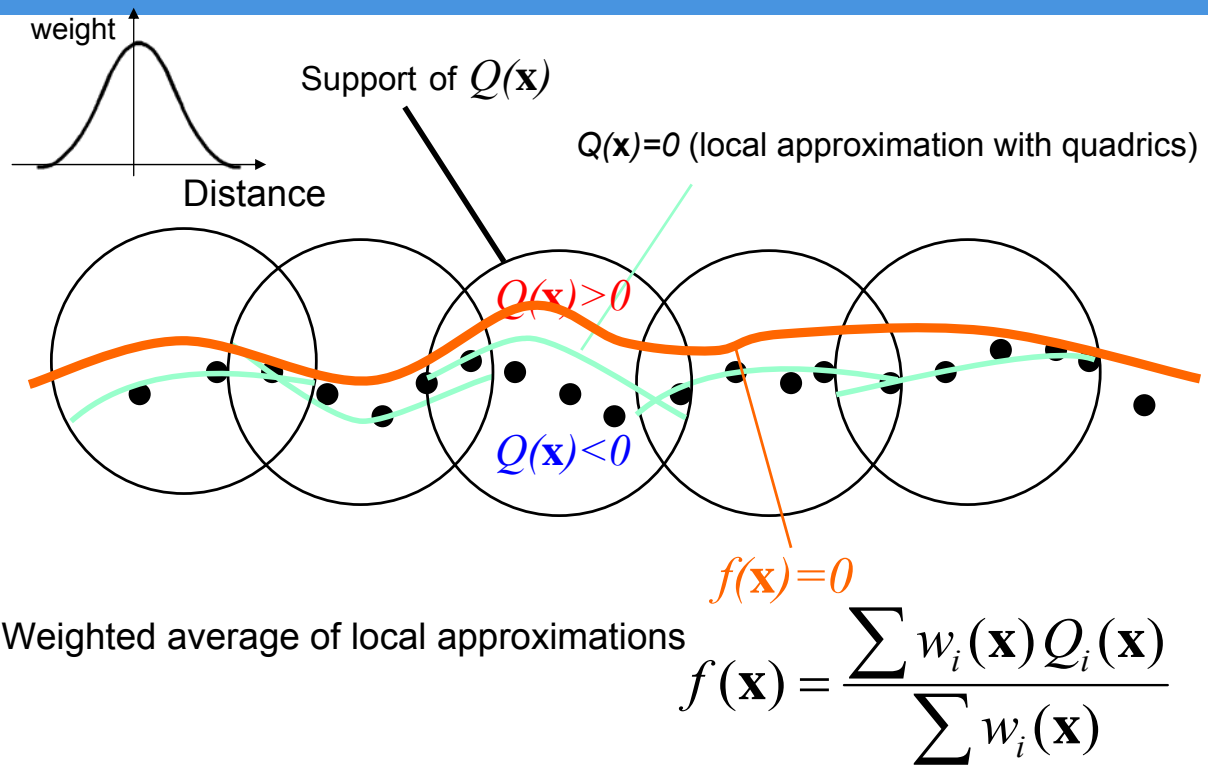
- Fast reconstruction of surfaces from scattered data
- Surface approximation with adaptive error control
- Search for points in spherical regions



Approximation with  
14 million points

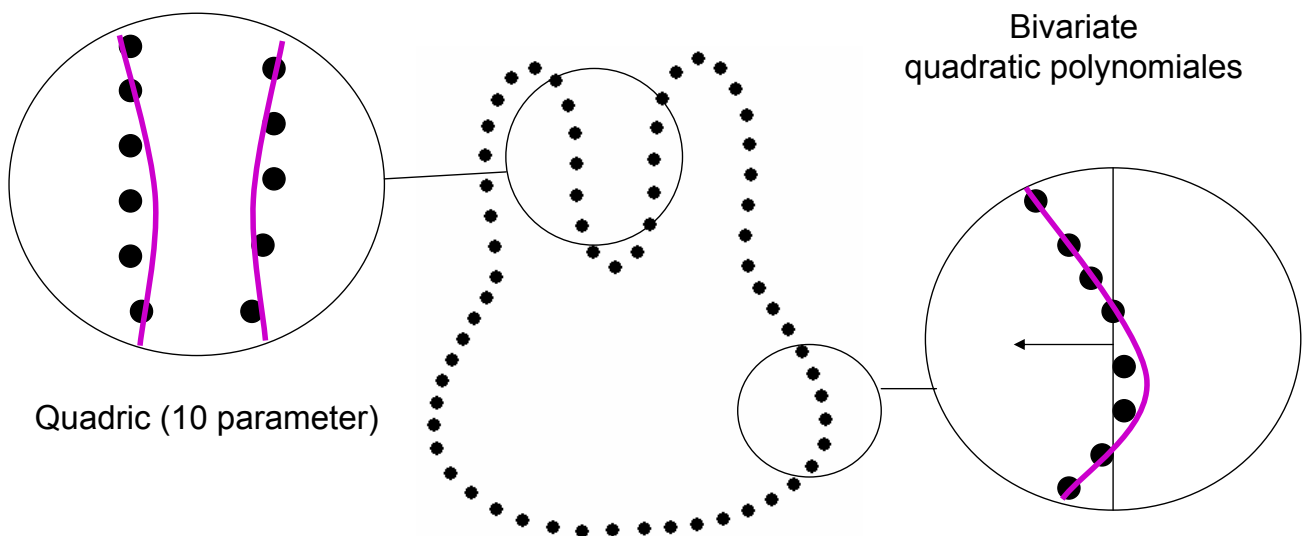
[Ohtake et al. 2003]

# Model-Free Visualization Partition of Unity



## Local Approximations

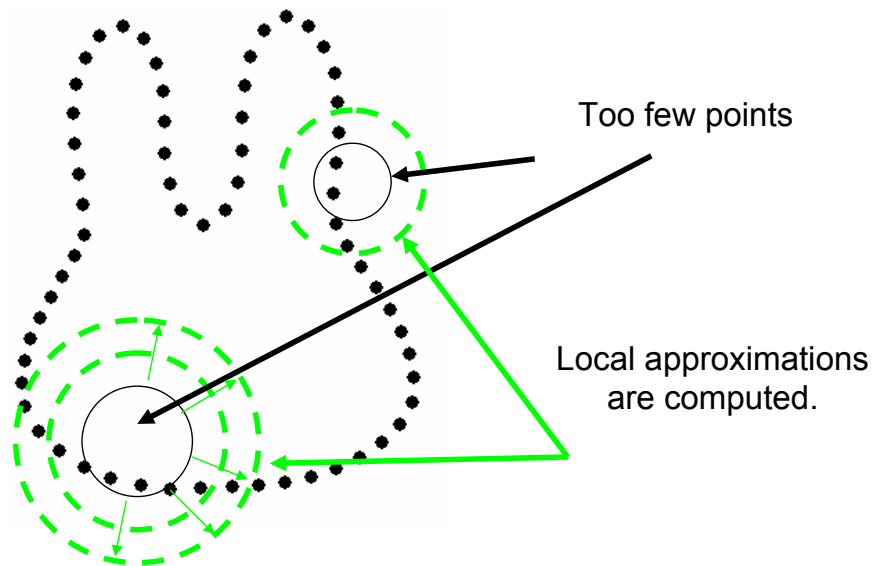
- Polynomial approximation (quadrics) with least square approach.



Adaptive subdivision guided by deviation of the normal

# Local Approximations

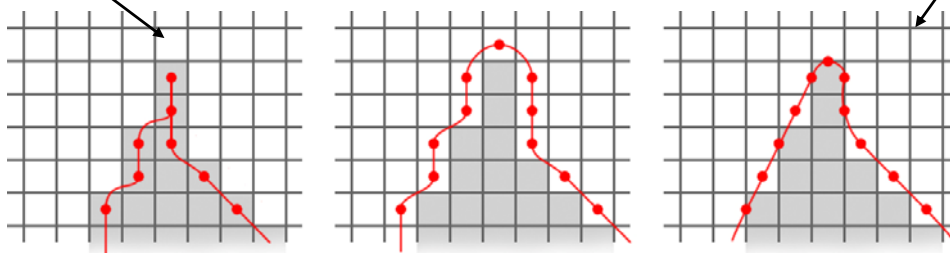
- If not enough points are in the local region → expand it.
- Parameter: Maximum octtree depth, initial size of the region, growth factor



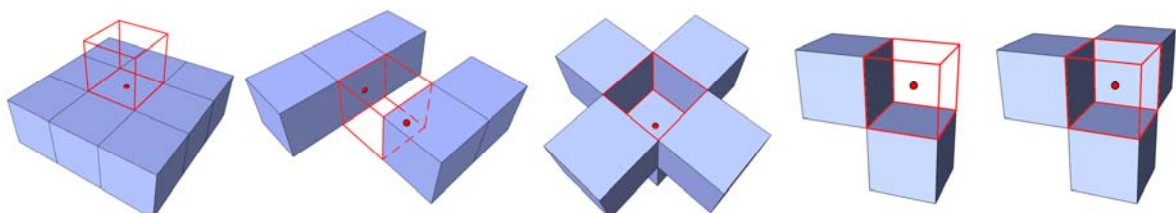
# Model-Free Visualization

- Border voxels as initial places for points

Degenerating of thin vessels



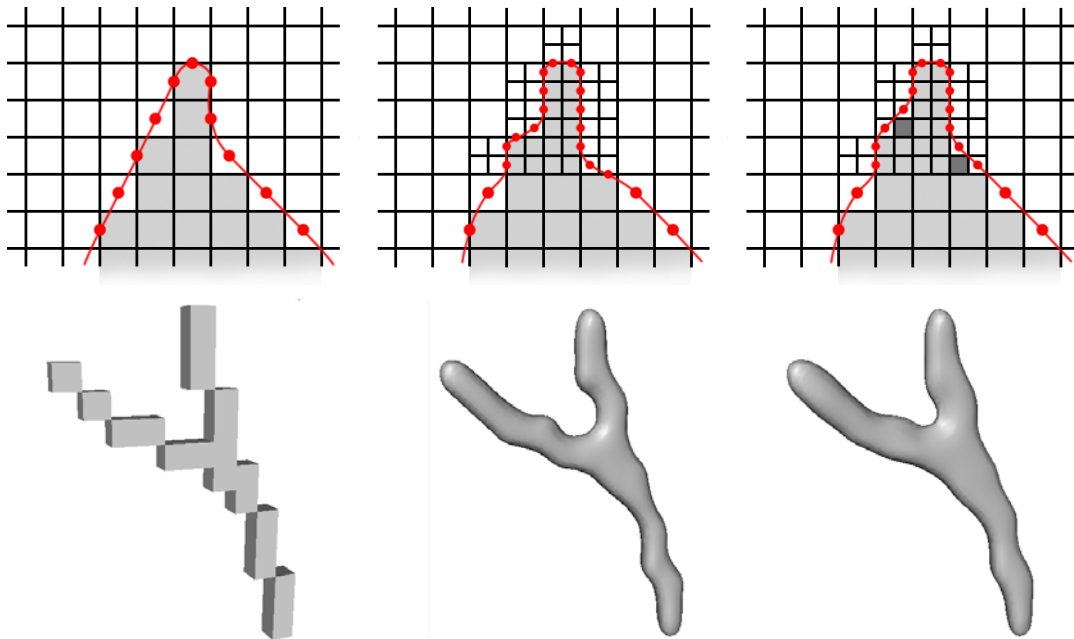
- Different cases for placing points





# Model-Free Visualization

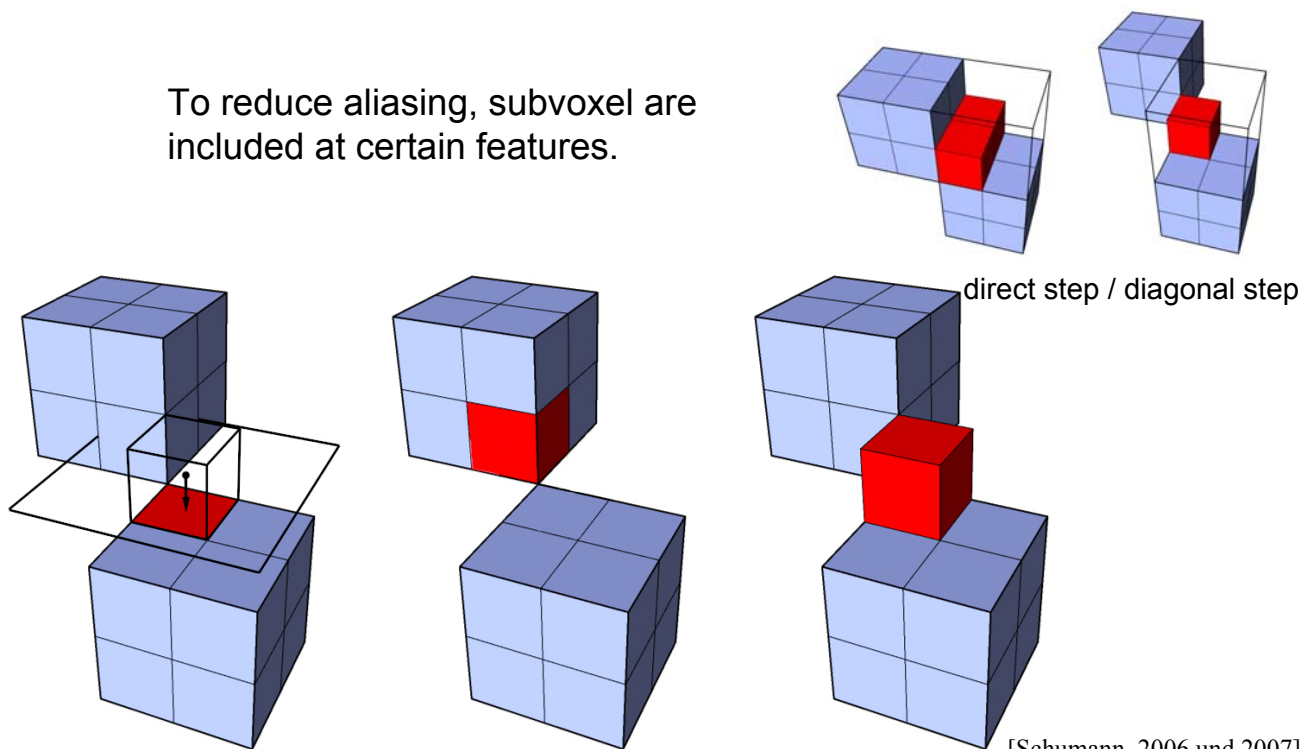
Adaptive subsampling of thin branches



[Schumann, 2006 und 2007]

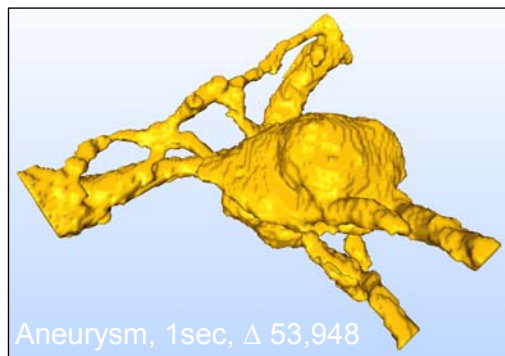
# Model-Free Visualization

To reduce aliasing, subvoxel are included at certain features.

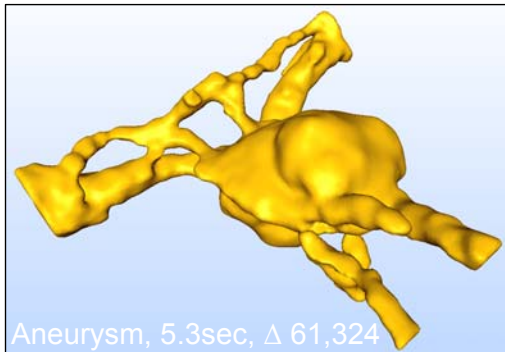
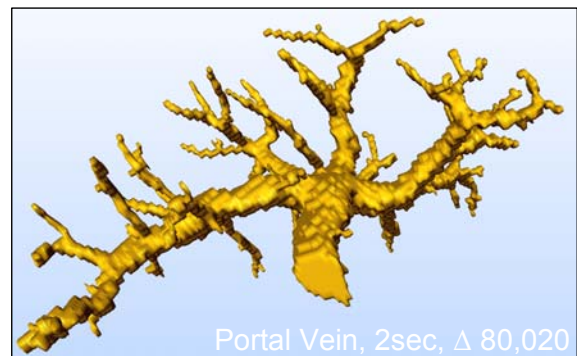


[Schumann, 2006 und 2007]

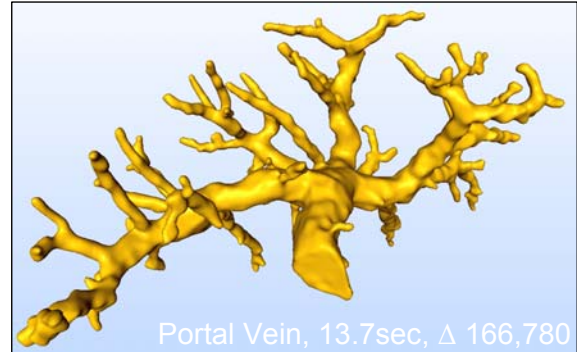
## Model-Free Visualization – Results (1)



MC

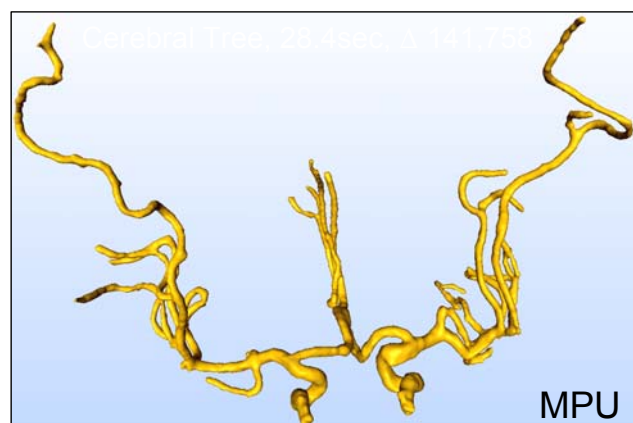
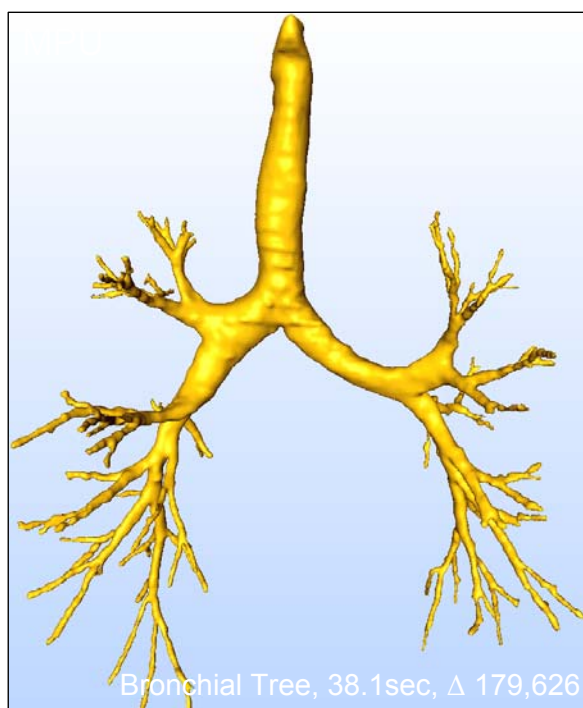


MPU

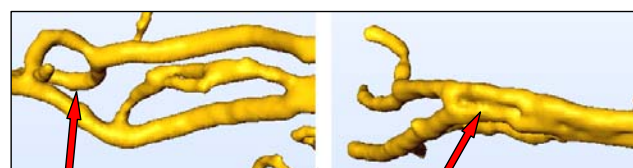


[Schumann, 2006 und 2007]

## Model-Free Visualization – Results (2)



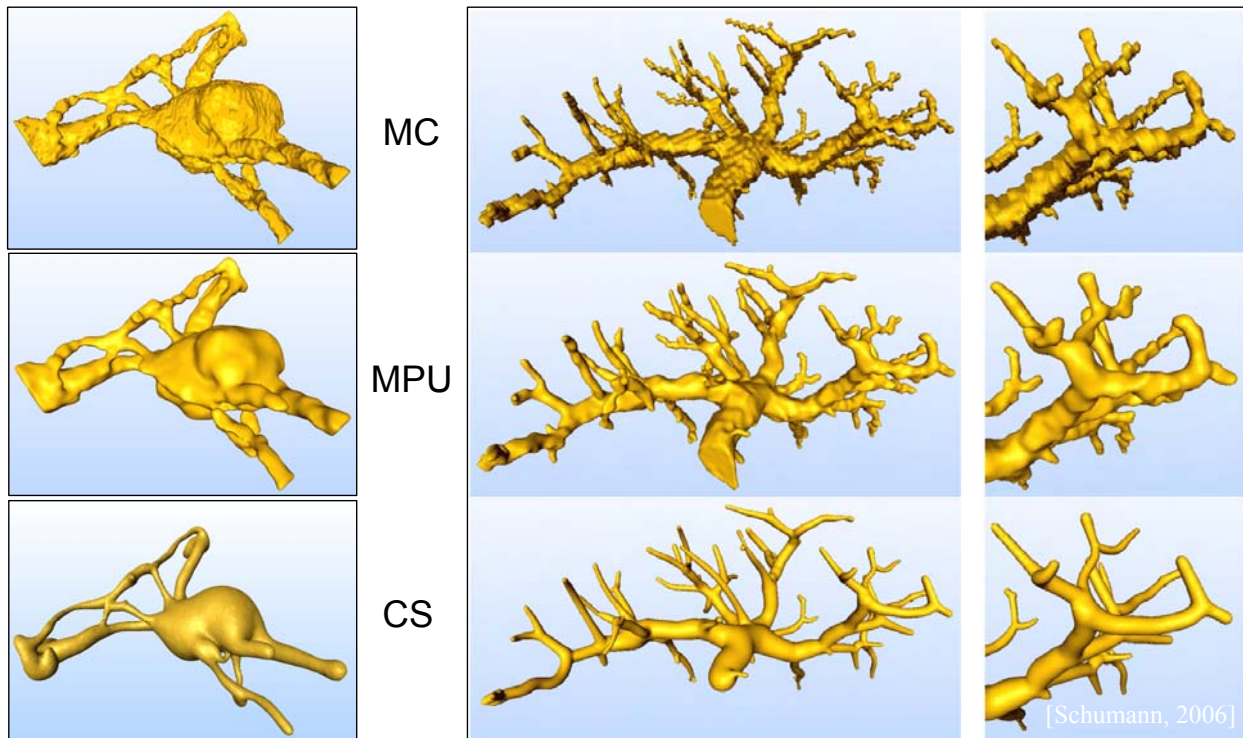
[Schumann, 2006]



Cycle

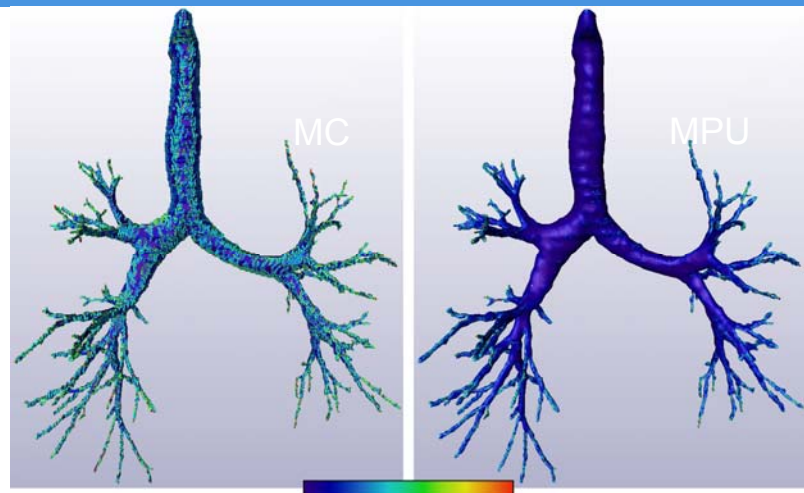
Adjacent Vessels

## Model-Free Visualization – Results (3)



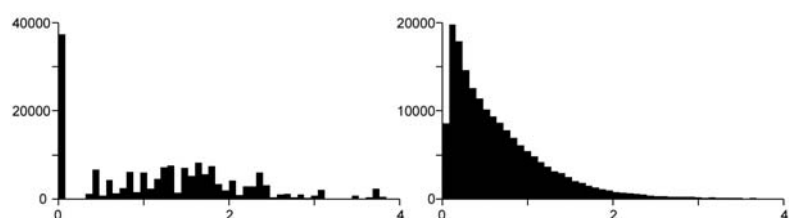
## Model-Free Visualization – Smoothness

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



- Histogram of the curvature values

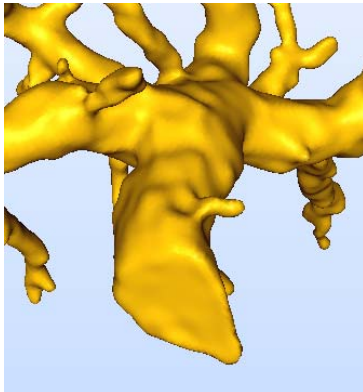
[Schumann, 2006 und 2007]



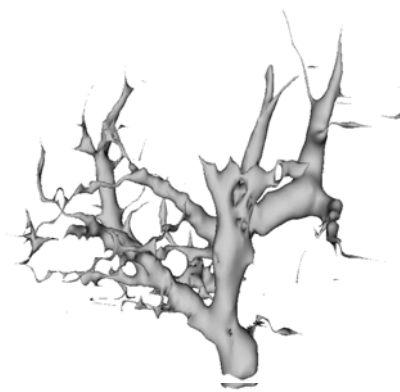
# Model-Free Visualization – Comparison with Marching Cubes

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]

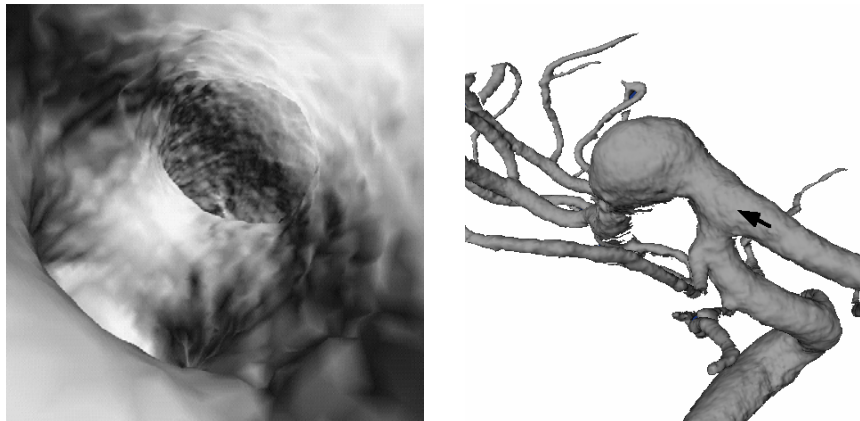
# Model-Free Visualization – Surfaces Distances

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

Dataset	$\phi$	$\sigma$	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

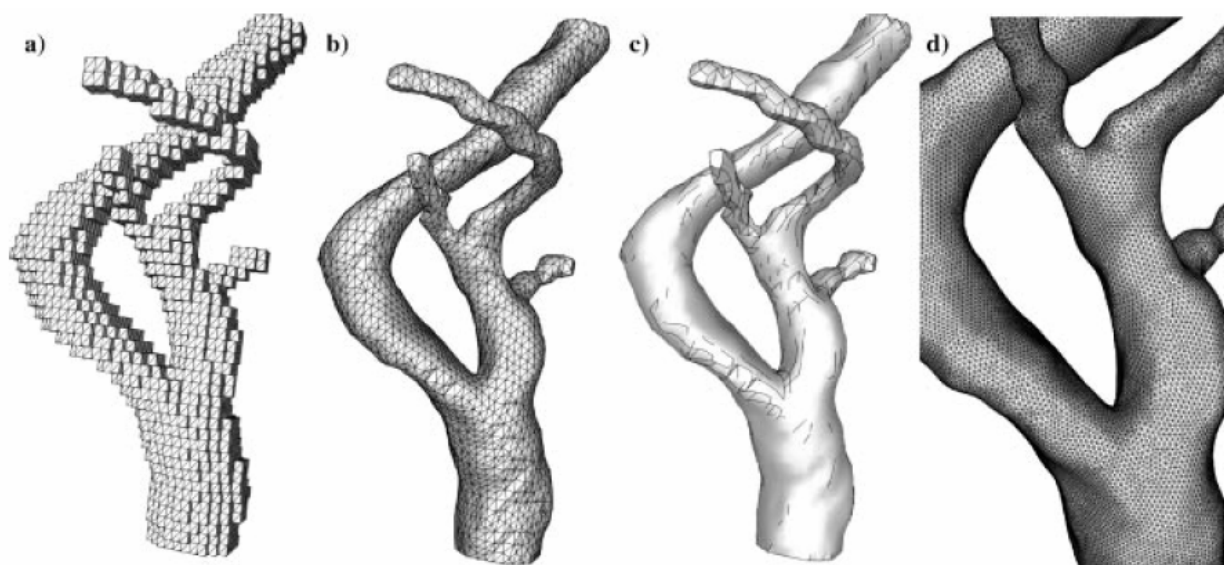


# Virtual Angioscopy



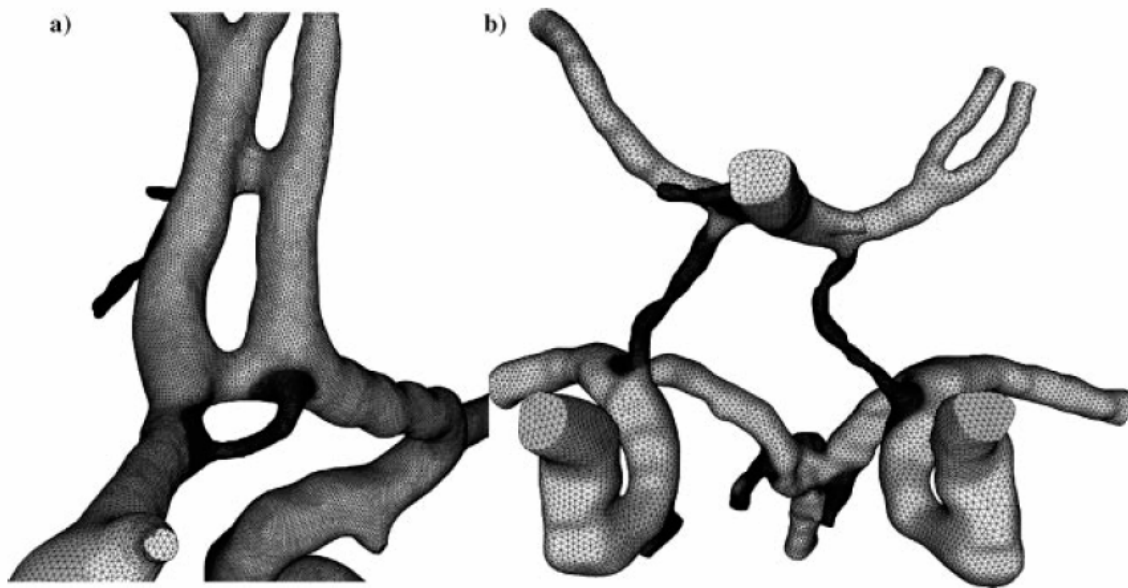
Visualization technique: Isosurface rendering based on smoothed segmentation result. Combination of overview and detail view. Specific application: Planning interventional treatment of cerebral aneurysms. [Bartz 99]

## Simulation and Visualization of Blood Flow: Model Generation



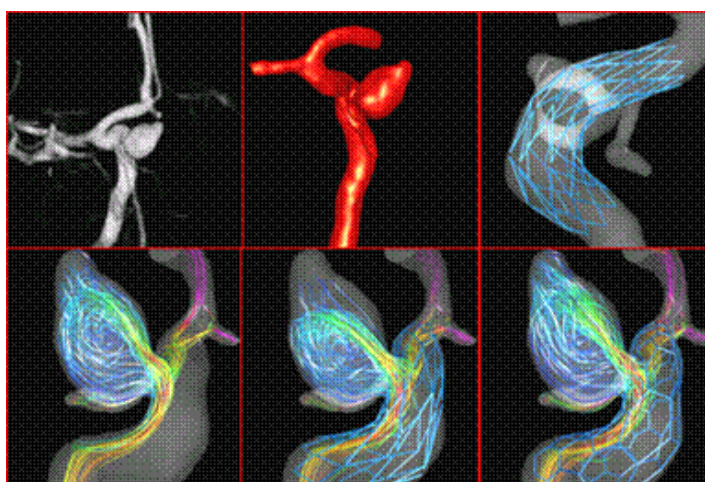
Voxel model – smoothed surface model – feature lines – adaptive refinement by considering Verfeinerung feature lines [Ceb01]

# 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 choice and placement of a stent
- Source: [Webpage Juan Cebal](#)



# 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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# References (2)

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- Ritter et al. [2006]: "Real-time Illustration of Vascular Structures". To appear: IEEE Trans. on Visualization and Computer Graphics.

## References (3)

- Schmidt [2004]: Physiologie des Menschen mit Pathophysiologie. Springer Medizin Verlag, 29th ed.
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## Acknowledgements



Steffen Oeltze



Alexandra Baer



Christian Schumann



Christian Hansen



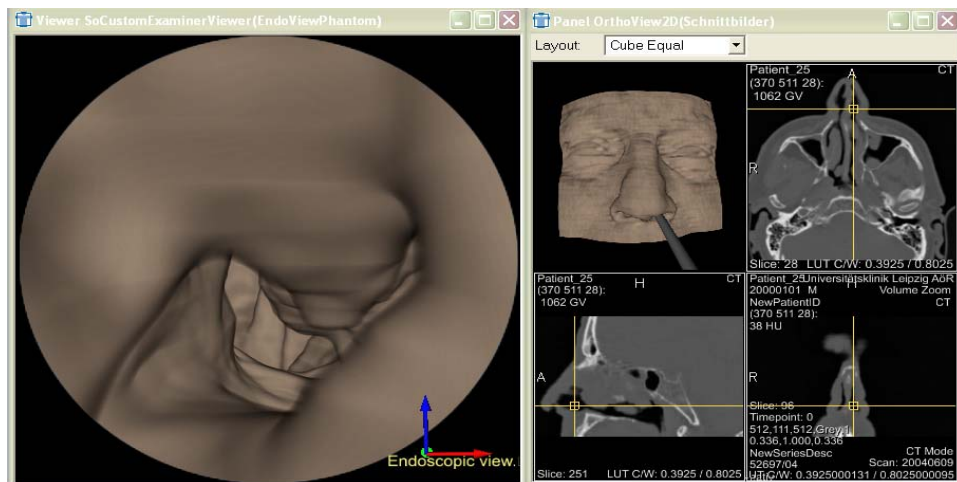
Horst Hahn (MeVis)



Olaf Konrad (MeVis)

We also thank our clinical partners for providing datasets and the Zuse Institute, Berlin (S. Zachow) for supporting the validation of our visualizations with Amira.

# Virtual Endoscopy



## Outline

- Introduction and Motivation
- Rendering Techniques
- Navigation and Interaction Concepts
- Application Areas
  - Virtual Colonoscopy (Diagnosis)
  - Virtual Bronchoscopy (Diagnosis)
  - Virtual Endoscopy for Sinus Surgery (Intervention Planning and Training)
  - Virtual Endoscopy for Minimally-Invasive Surgery of the Pituitary Gland (Intervention Planning)
- Commercial Systems
- Conclusion

# Introduction

- Virtual Endoscopy is based on high-resolution medical image data (often CT) and is a viewing and exploration mode derived from optical endoscopy.
- In optical endoscopy a thin (flexible or stiff) fiber optic is moved to the target area.
- Virtual endoscopy: Virtual camera is moved along air- or fluid filled structures.
- Optical properties of endoscopes are mapped to the virtual camera.

# Introduction

- Endoscopy is used as diagnostic tool and can be combined with interventions, e.g., removal of polyps or taking biopsies.
- Virtual endoscopy is limited to applications without interventions.
- Requirements for virtual endoscopy:
  - Sufficient accuracy
  - Identifiable (segmentable) structures of interest
  - Interactivity (high frame rate)
    - Large amounts of data and interactivity – these aspects are difficult to achieve at the same time. Special emphasis is needed!

# Introduction

Major applications for virtual endoscopy

- Diagnosis: virtual bronchoscopy
- Diagnosis: vascular diseases, such as aneurysms
- Screening for colon cancer prevention (or early detection)
- Treatment planning with respect to endoscopic procedures, such as Functional Endoscopic Sinus Surgery
- Training for endoscopic interventions. Due to the limited visual access there is a high demand for training these procedures.

# Introduction

Instruments for optical endoscopy:

Brochoscope,  
Coloscope



Light source,  
Video processor



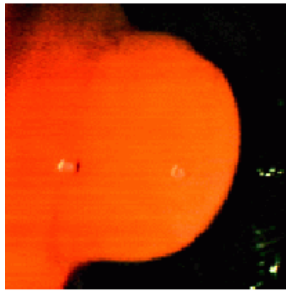
Sources: above – <http://www.olympus.de/endo>  
below – <http://www.info-endoskopie.de>

Nooses,  
Forceps

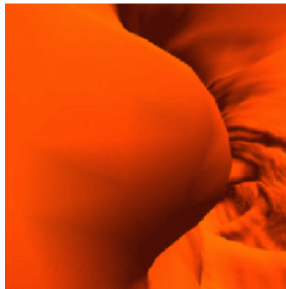
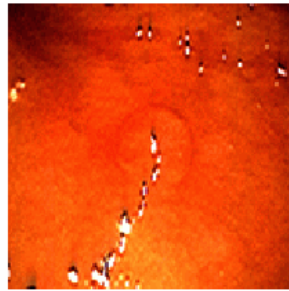




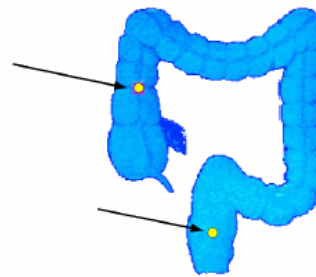
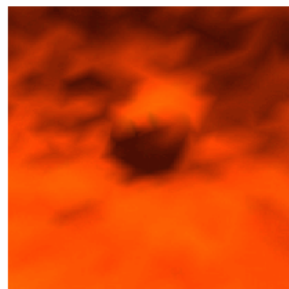
# Introduction



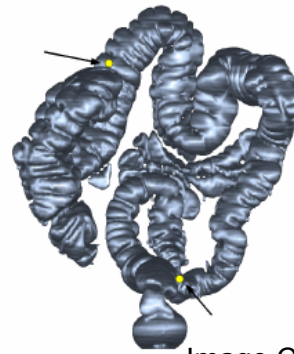
Optical Endoscopy



Virtual Endoscopy



8 mm polyp



4 mm polyp

Image Courtesy Dirk Bartz,  
Univ. of Leipzig

# Motivation

- In contrast to optical endoscopy, virtual endoscopy allows
  - to „look behind the walls“
  - to reduce risks and costs associated with optical endoscopy
- However, virtual endoscopy
  - cannot be combined with interventions
  - does not provide realistic colour and texture information and
  - does not allow physical contact
  - is of limited value if the structure of interest has changed since acquisition, e.g. „brain shift“

# Concept

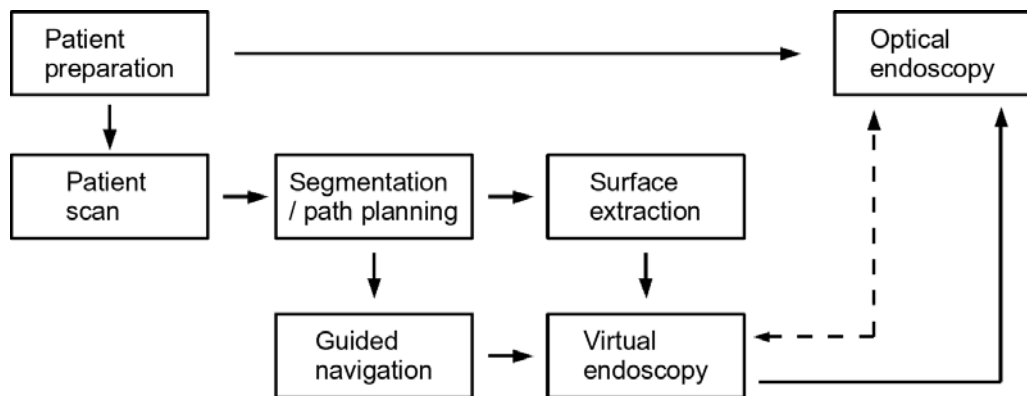
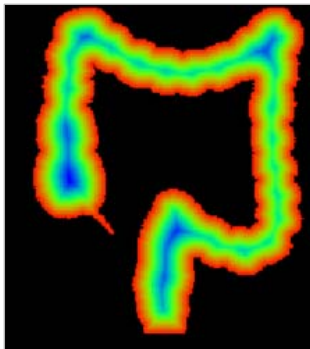


Image Courtesy Dirk Bartz,  
Univ. of Leipzig

## Segmentation/Path Planning

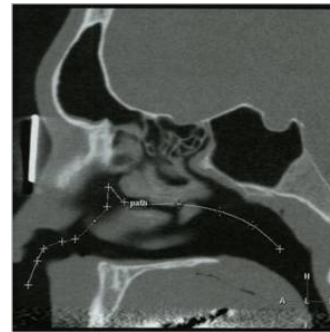
- Accuracy and value of virtual endoscopy depends on segmentation quality.
- Reliable, fast and automatic segmentation in general is very difficult.
- Good results are achieved in case of air-filled structures in CT, such as the colon.
- Path planning often based on the skeleton and/or the distance field of the target structure.

# Segmentation/Path Planning



The distance field in the colon may be used for path computation and supporting guided navigation.

(From: Hong et al. 1997)



Interactive path specification based on coronal slices.

# Rendering Techniques

Surface visualization and Direct Volume Rendering

- Surface visualization requires pre-processing (segmentation).
- Segmentation result is converted to a polygonal mesh, post-processed (smoothing) and efficiently rendered using graphics hardware.
- Perspective rendering is preferred
- Acceleration Techniques:
  - Occlusion culling (restrict rendering to the small visible portion)
  - Empty-Space-Leaping

# Rendering Techniques



Image Courtesy Dirk Bartz,  
Univ. of Leipzig

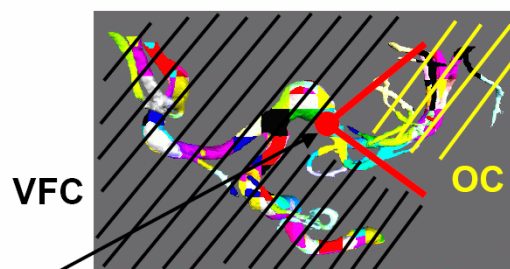
Typical artifacts of surface models generated by means of  
Marching Cubes for virtual endoscopy.

# Rendering Techniques

Occlusion Culling:

Specific possibilities of endoscopic views:

- Endoscopic views have very limited visibility
- Removal of occluded geometry (occlusion culling)
- Frequently achieves culling of 90%



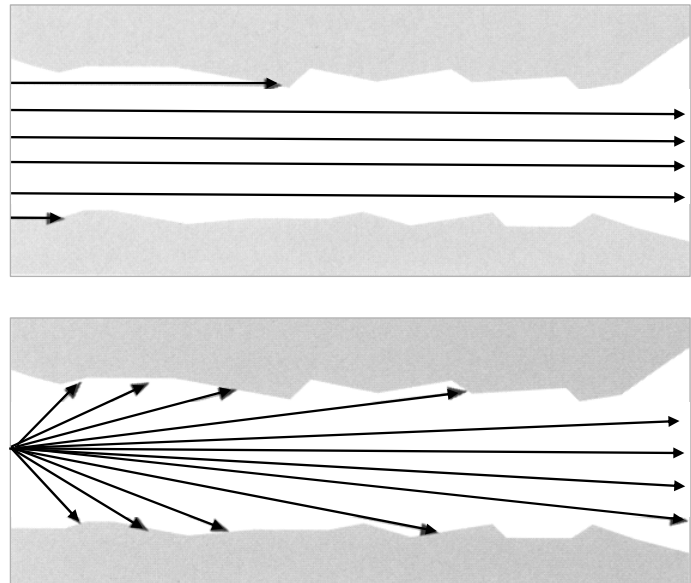
View frustum

Image Courtesy Dirk Bartz,  
Univ. of Leipzig

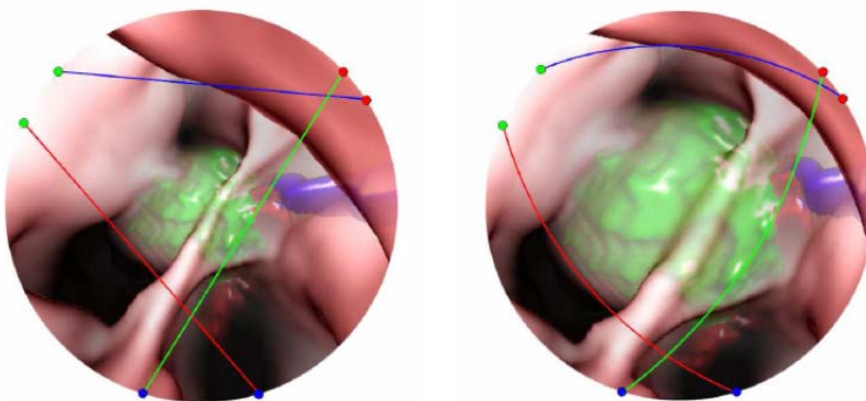
# Rendering Techniques

## Parallel versus Perspective Rendering

More structures are visible with perspective rendering. Although parallel rendering is faster, perspective rendering is preferred.



# Rendering Techniques



For intervention planning and training, it is essential to simulate the distorted view of virtual endoscopy.

To provide a sufficient overview, lenses at the tip of endoscopes use large opening angles (30°, 70°).

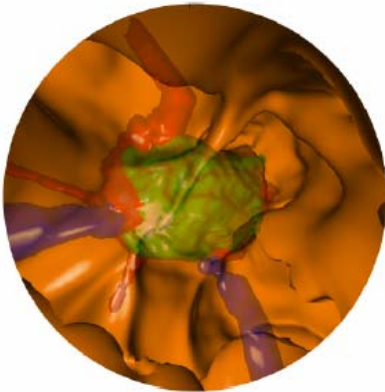
View from the sphenoid sinus to the pituitary gland

Images are courtesy of André Neubauer, VR Vis Vienna

# Rendering Techniques

„Look behind the wall“

Provide additional information compared to optical endoscopy



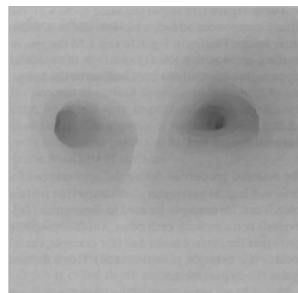
constant blending parameter      Modified blending considering the distance between fore- and background

Blended fore- and background images for first-hit ray casting. Images are courtesy of André Neubauer, VRVis Wien.

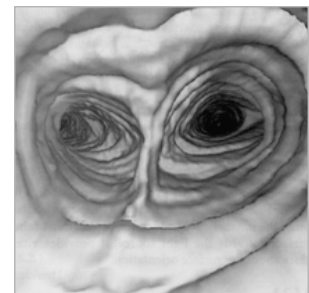
# Rendering Techniques

Illumination

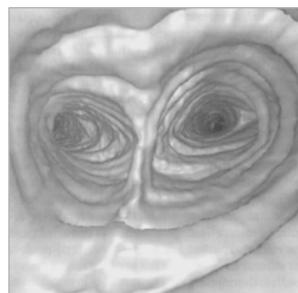
ambient



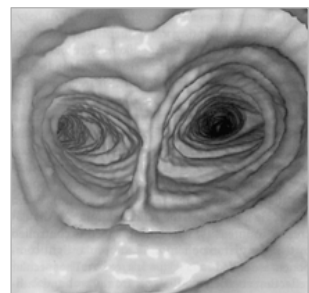
diffuse



diffuse  
+  
low specular



diffuse  
+  
high specular



Source: Virtual Endoscopy  
and Related 3D Techniques,  
Springer 2001



# Rendering Techniques

## Direct volume rendering

- Trilinear interpolation (better than linear interpolation, used in Marching Cubes)
- Special variant of ray-casting, first hit raycasting (Neubauer, 2004), where a predefined number of surfaces along each ray are located.

# Interaction and Navigation

## Navigation Models - Paradigms

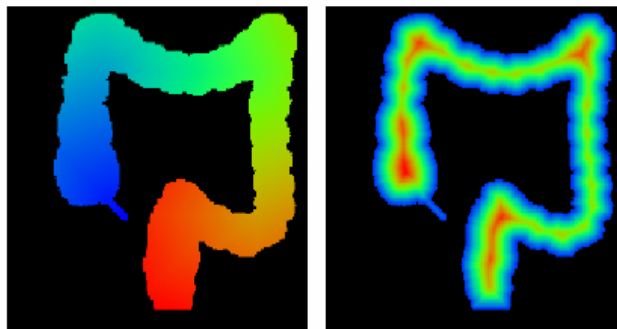
- Planned Navigation (“Autopilot“)
  - Specification of a camera path
  - Camera is more or less fixed to that path
  - VCR-like interaction
  - Costly refinement
  - Some observations: only 70% of all polyps are visible in a typical flight through the colon. 95 % are visible if the flight is also shown in the reverse direction.
- Manual/free Navigation
  - Often difficult to control
  - Requires heavy 3D interaction

# Interaction and Navigation

## Guided Navigation:

- Combines flexibility and guidance
- Interactive and intuitive
- Camera dives through scene like submarine
- Current and thrust through distance fields and kinematic rules
- Principles have been invented in the Vivendi-System (Bartz, 2003)

# Interaction and Navigation



Distance to the target and distance to the vessel wall are employed for guided navigation (Hong, 1997). Images courtesy of Shigeru Muraki, AIST Japan

# Interaction and Navigation



Besides „traditional“ input devices, graphics tablets, force feedback devices as well as tactile input may be employed.

Sources: <http://www.wacom.com>  
<http://www.sensable.com>

# Interaction and Navigation

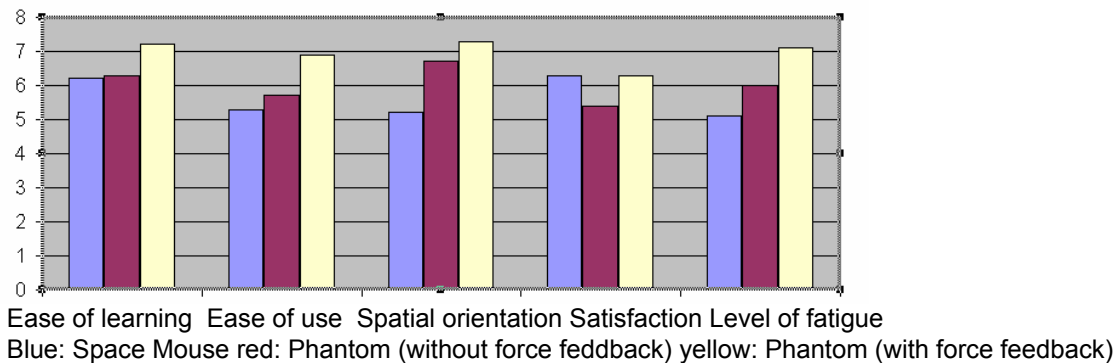
## Comparison of different input devices



(From: [Krüger, 2007])

- Input devices
  - SpaceMouse
  - PHANToM without force feedback
  - PHANToM with force feedback
- Subjective Evaluation
  - Ease of learning, ease of use, spatial orientation
  - Satisfaction and level of fatigue
- PHANToM with force feedback yielded best results

# Interaction and Navigation



Results must be interpreted with care (few users, strong dependency on experience and expectations of users).

Basic conclusion: Not only visualization techniques, but also input devices strongly influence diagnostic performance.

## Applications: Virtual Colonoscopy

Cancer of the colon is a leading cause of death → prevention and early detection is crucial.

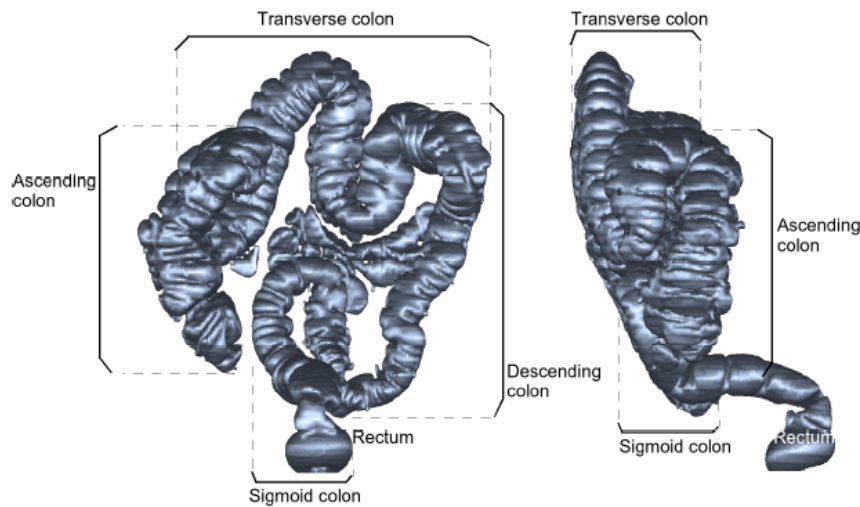
Optical endoscopy is an effective diagnostic procedure to inspect the colon wall for pathologies.

However, it is expensive (sedation of the patient) and suffers from low patient acceptance. → Virtual Endoscopy

Major goals:

- Reliable identification of polyps > 5 mm
- Low rate of false positives (e.g., residual fluid or remaining stool)
- Efficient processing of data for mass screening application of a whole age group

# Applications: Virtual Colonoscopy



Coronal (left) and sagittal (right) view of the colon.

# Applications: Virtual Colonoscopy

## Results:

- The diagnostic performance (sensitivity, specificity) depends on many factors.
- Similar results to optical endoscopy are feasible (high quality data, experienced radiologists).
- It is essential that every part of the colon was inspected. Visibility maps indicate which regions have not been visited.

# Applications: Virtual Brochoscopy

Diagnostic and therapy planning related to diseases of the tracheo-bronchial system, e.g., lung cancer, emphysema, ...

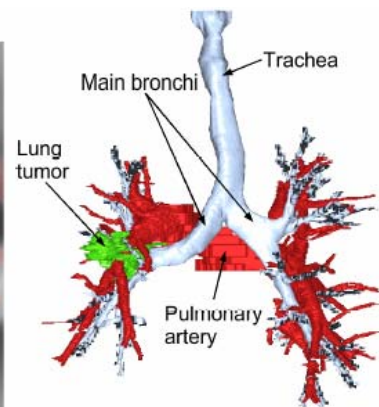
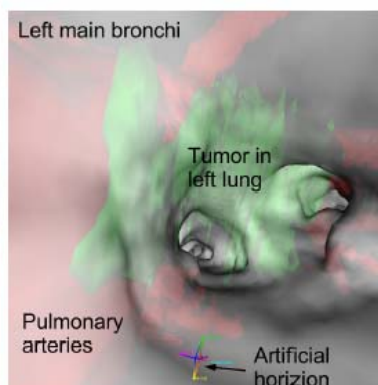
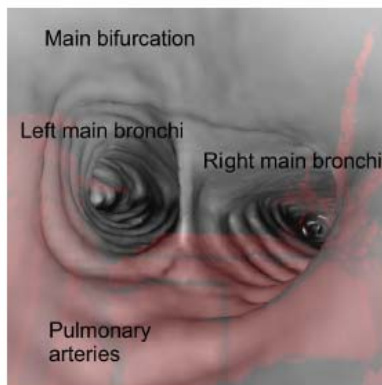
Based on high resolution CT data (300 slices, 512x512)

Target structures: Airways, blood vessels, tumors

Segmentation of all structures requires a complex pipeline [Bartz, 2003].

In particular, reliable identification of the 5th and 6th generation of inner airways is difficult to accomplish.

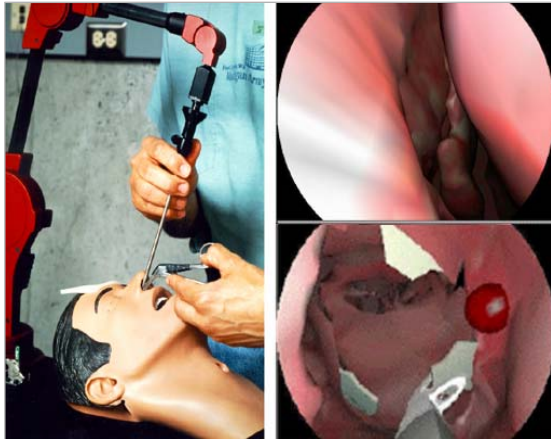
# Applications: Virtual Brochoscopy



Virtual bronchoscopy for surgery planning. Blended visualization of objects is crucial. (From: Bartz et al., 2003)



# Applications: Training



Endoscopic Sinus Surgery Simulator  
[Weghorst, 1997]

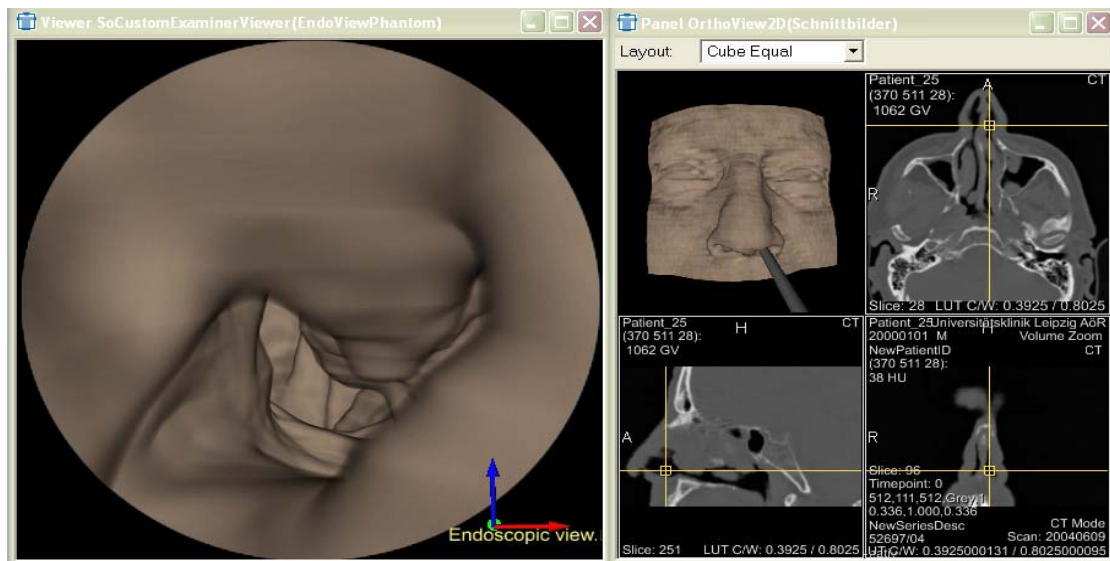
- Teaching anatomy of patients from interior viewpoints.
- Simulating endoscopic interventions, e.g. sinus surgery.
- Challenging application area since instrument-tissue interaction as well as soft tissue deformation must be simulated.

## Applications: Functional Sinus Surgery

Major goals:

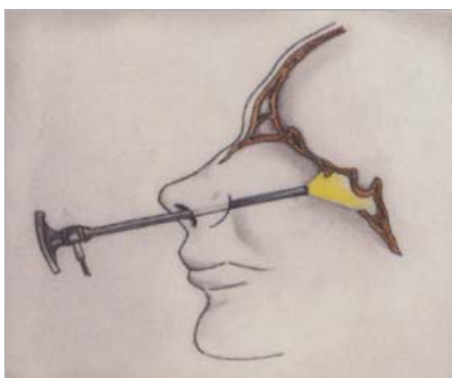
- 3D visualization of relevant structures
- Evaluation of spatial relations, e.g. with respect to risk structures, such as the optical nerve
- Measurement (e.g. to evaluate whether certain structures may be reached)
- Access planning
- Documentation of treatment planning

# Applications



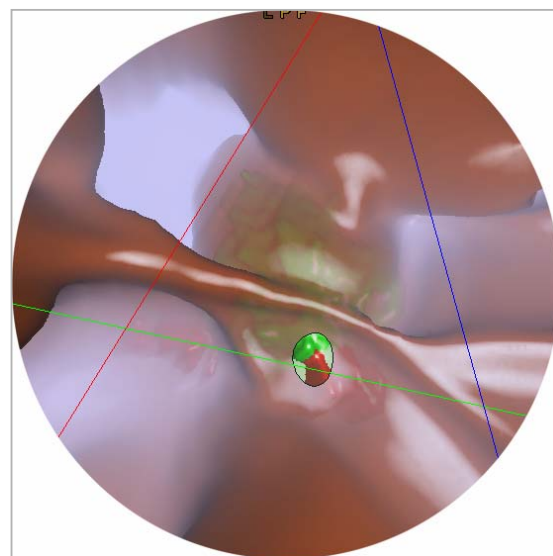
Endoscopic Sinus Surgery Planning System (From: [Krüger, 2007])  
Segmentation and path planning is easy as long as cavities are filled with air. The more extended pathologic swellings are, the more difficult is the segmentation.

# Applications



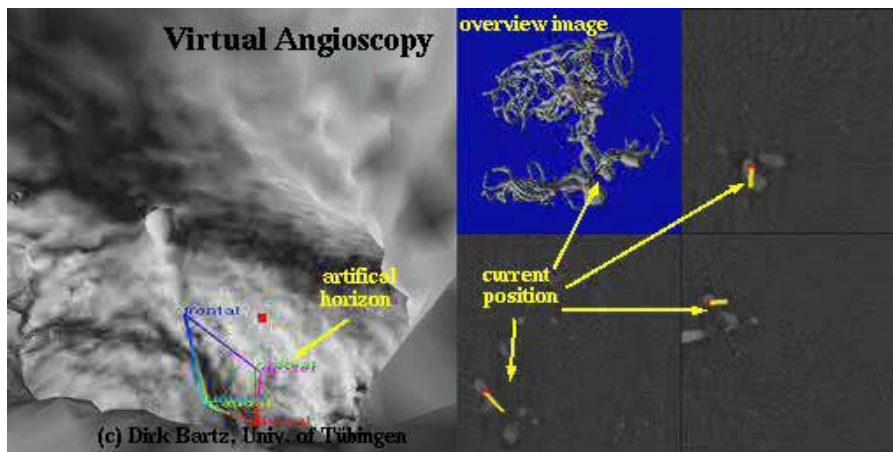
Virtual Endoscopy for Minimally-Invasive Surgery of the Pituitary Gland.

Benign tumors in this region are frequent and minimally-invasive removal is the state-of-the-art treatment. Several risk structures have to be considered.



Images are courtesy of  
André Neubauer, VRVis Wien.

# Applications



Virtual endoscopy for diagnosis of cerebral aneurysms and planning neurointerventions (From: [Bartz et al. 2001])

## Commercial Systems

Rendering, interaction and navigation techniques are similar to research prototypes. Careful integration in hospital information systems and clinical workflows are essential.

In particular, for virtual colonoscopy

- Philips EasyVision Endo 3D
- Viatrox V3D Viewer/Colon
- GE Advantage Winodws
- Vital Images Vitrea2/CT Colonography

Most of them

- use raycasting as rendering mode,
- provide (semi-)automatic path planning and
- guided as well as manual navigation

# Conclusion

- Virtual colonoscopy is still the only successful commercial application.
- Virtual endoscopy for intervention planning has great potential. However, the added planning time hampered wide-spread use so far.
- Requirements, with respect to accuracy, strongly depend on application area.
- Virtual endoscopy cannot be used when examination of tissue sample is necessary.
- Validation and clinical evaluation are crucial aspects. The book by Rogalla et al. (Virtual Endoscopy and Related 3D Techniques) provides an excellent overview on these aspects.

# Acknowledgement

- Dirk Bartz, Univ. of Leipzig
- Ilka Hertel, Gero Strauß, Univ. of Leipzig
- André Neubauer, Katja Bühler, VR Vis Wien
- Arno Krüger, Univ. of Magdeburg

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# Augmented Reality and Intraoperative Visualization

Augmented Reality:

- Overlay of real data („patient“) and virtual data (geometric patient model)
- AR in Intraoperative Visualization:  
Live-data (Op-Video) combined with pre-op. Patient model

Prerequisites:

- Appropriate dataset (not too old)
- Preprocessing (Segmentation, ...)
- Registration (Mapping: Pre-Op – Intra-Op.)
- Tracking of surgical instruments
- Update during surgery
- Appropriate output devices

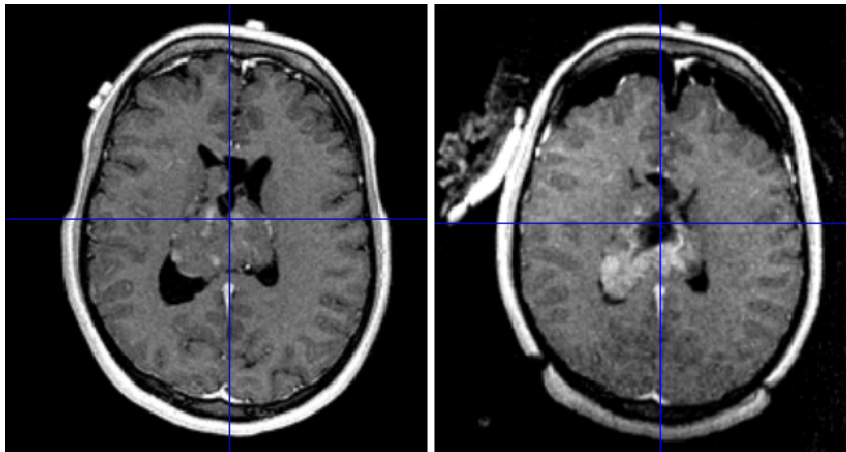
# Augmented Reality and Intraoperative Visualization

Brain shift and tissue deformation:

- Due to influence of surgical instruments and forces exerted on the tissue deformations occur
- Brain shift: Movement of (parts of the brain) after the skull is opened
- Initial registration is still valid in some portions of the brain.



# Augmented Reality and Intraoperative Visualization



Images Courtesy Peter Hastreiter,  
Univ. Erlangen

Tissue deformation due to brain shift.

# Augmented Reality and Intraoperative Visualization

Registration:

- Mapping of patient data to intraoperative position/orientation
- Optimization process guided by landmarks
  - Anatomic landmarks (difficult to locate them reliably and precisely)
  - Fiducial markers attached to the patient at known positions
  - Point cloud of the skin derived with a laser pointer
- Fiducial markers enable highest accuracy
- Point cloud sufficiently precise for a variety of interventions

# Augmented Reality and Intraoperative Visualization

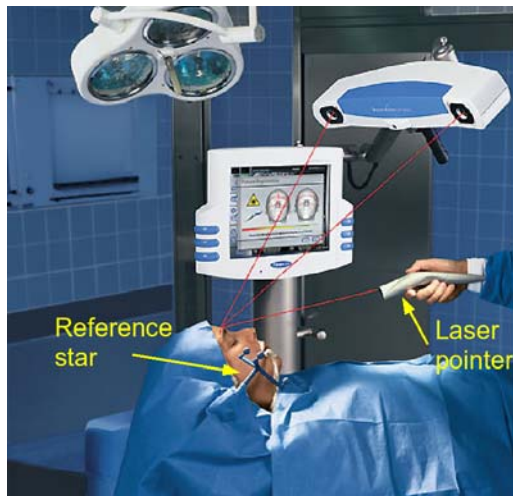


Image Courtesy Jürgen Hoffmann, Univ. Tübingen

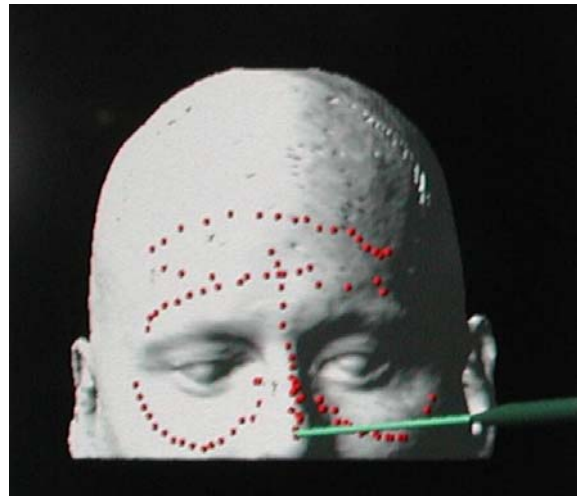


Image Courtesy BrainLab AG Feldkirchen

ICP-based registration of a point cloud

# Augmented Reality and Intraoperative Visualization

Tracking surgical instruments:

Instruments attached with reflective spheres

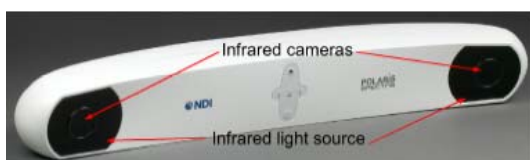
Optical tracking:

The instruments are seen by two cameras.

→ requires direct line of sight

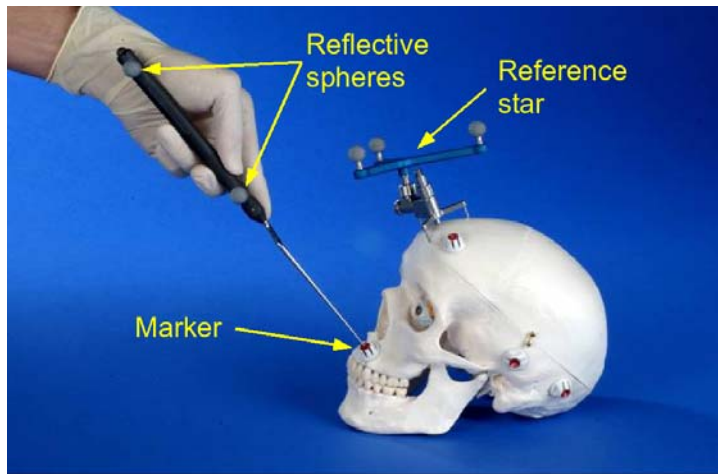
Electromagnetic tracking

No direct line of sight required. Lower accuracy compared to optical tracking. Magnetic field must not be disturbed.



Optical tracking with the Polaris Spectra  
Image Courtesy NDI

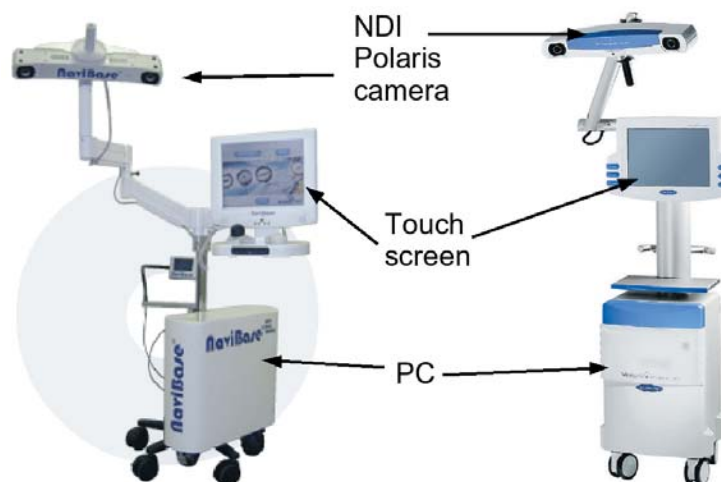
# Augmented Reality and Intraoperative Visualization



Images Courtesy Jürgen Hoffmann, Univ. Tübingen

Tracked pointer tool to identify fiducial positions. A reference star is connected to the forehead.

# Augmented Reality and Intraoperative Visualization



Optical tracking.

Left: NaviBase-System (RoboDent)

Right: Vector Vision (BrainLab)

# Augmented Reality and Intraoperative Visualization

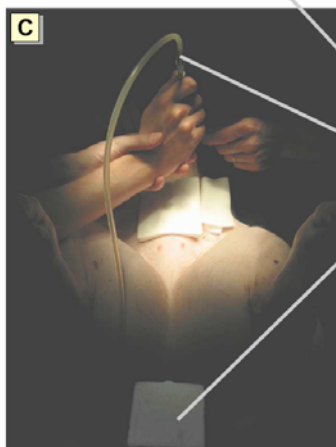
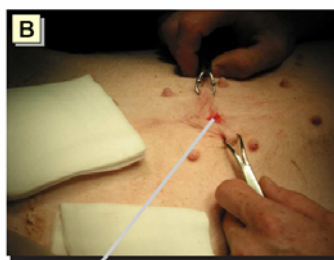
Intraoperative visualization options:

- Data are projected on a special fixed monitor
- Data are projected on a small flexible display in the surgeons hand. Display is tracked.
- Data are included in the endoscope view.
- Data are projected directly onto the patient.



Semi-transparent screen positioned over the OR situs. (Bernd Schwald)

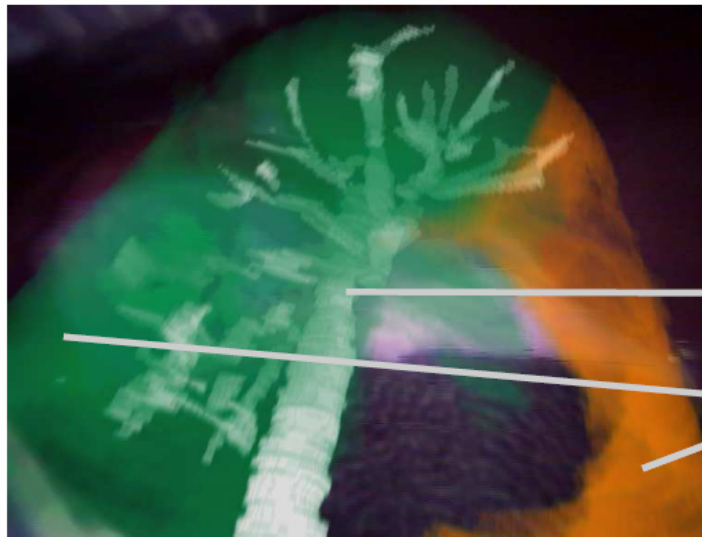
# Augmented Reality and Intraoperative Visualization



- Incision point for Veress needle
- Intra-hepatic vessels
- Veress needle
- Electro-magnetic tracker

- Augmented Reality in Liver Surgery
- Animal Experiment (Scheuering, 2003)

# Augmented Reality and Intraoperative Visualization



Intra-hepatic vessels

Vascular territory

Scheuering, 2003

Video overlay of a laparoscopic liver image with 3D renderings from pre-planning.

# Augmented Reality and Intraoperative Visualization

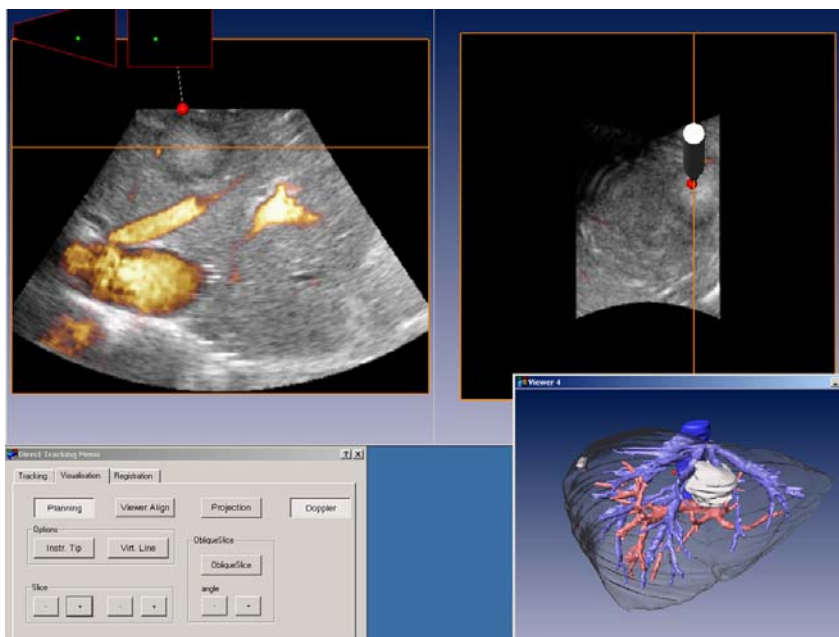
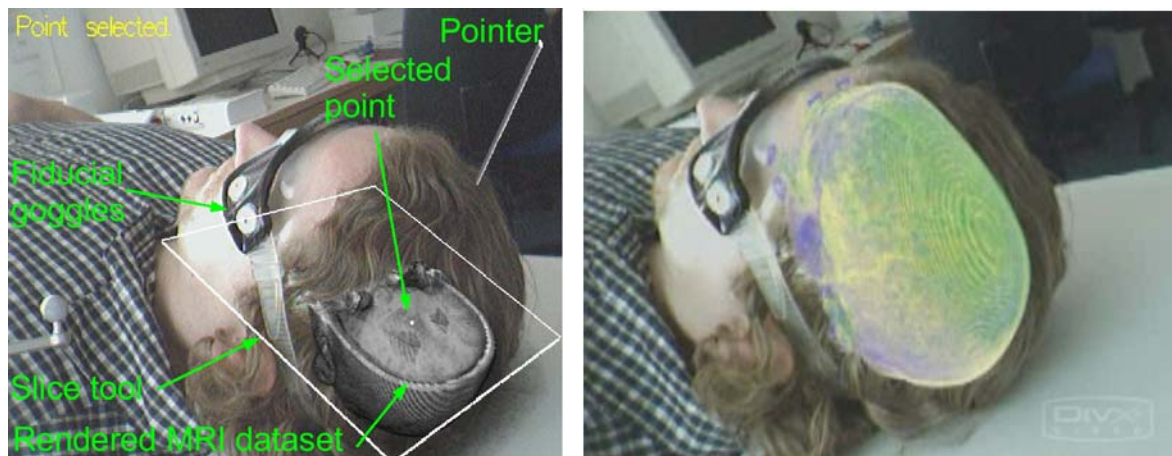


Image Courtesy  
Thomas Lange,  
Charite Berlin

Intraoperative 3D ultrasound in the OR. Preoperative imaging.



# Augmented Reality and Intraoperative Visualization



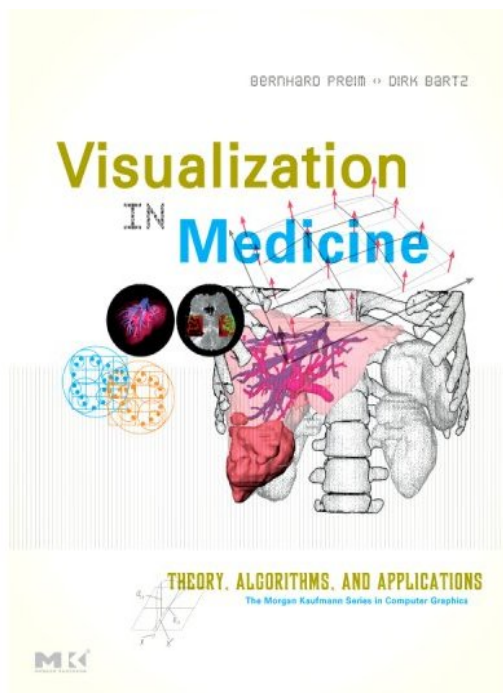
A volume rendered image of an MRI dataset is augmented with a video of the OR-situs. Courtesy of Angel del Rio, Universität Tübingen.

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# More detail on all this



- 1 Introduction
- 2 Medical Image Data and Visual Perception
- 3 Acquisition of Medical Image Data
- 4 Medical Volume Data in Clinical Practice
- 5 Image Analysis for Medical Visualization
- 6 Fundamentals of Volume Visualization
- 7 Indirect Volume Visualization
- 8 Direct Volume Visualization
- 9 Algorithms for Direct Volume Visualization
- 10 Exploration of Dynamic Medical Volume Data
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- 12 Clipping, Cutting, Virtual Resection
- 13 Measurements in Medical Visualization
- 14 Visualization of Vascular Structures
- 15 Virtual Endoscopy

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