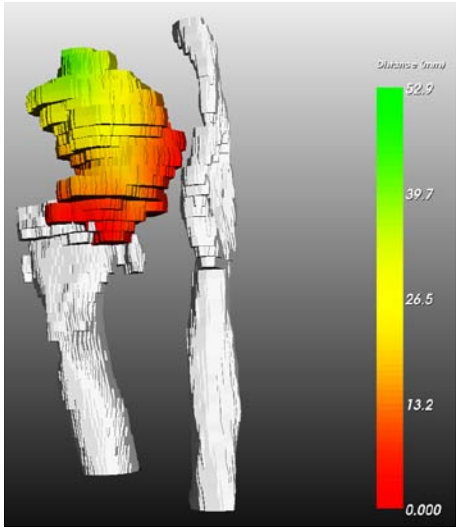
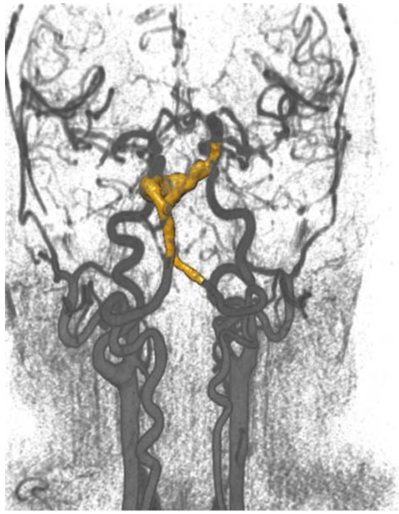
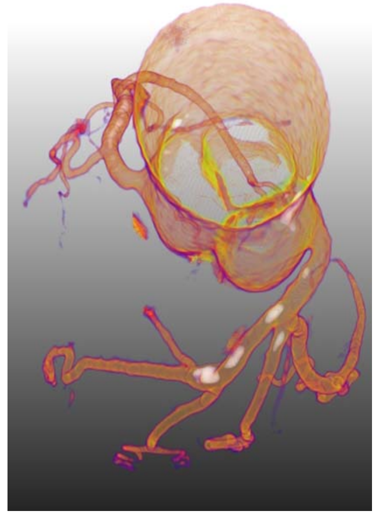
Tutorial Syllabus

Surface Visualization - Marching Cubes and its improvements - Smoothing of surface visualizations	(30 min.)
Direct Volume Visualization - Ray casting and texture-based approaches - Projection methods	(30 min.)
3D Vessel Visualization	(30 min.)
Virtual Endoscopy	(30 min.)
Augmented Reality and Intraoperative Visualization	(20 min.)
Medical Training and Surgical Planning	(20 min.)

Virtual Reality and Visualization

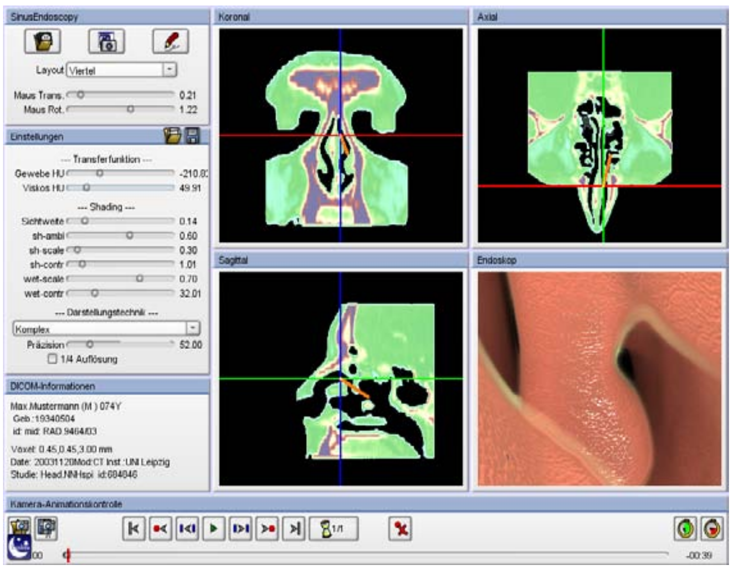






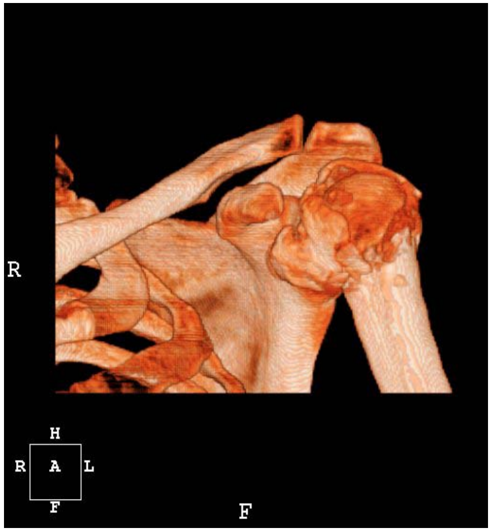
Surface visualization

Volume visualization

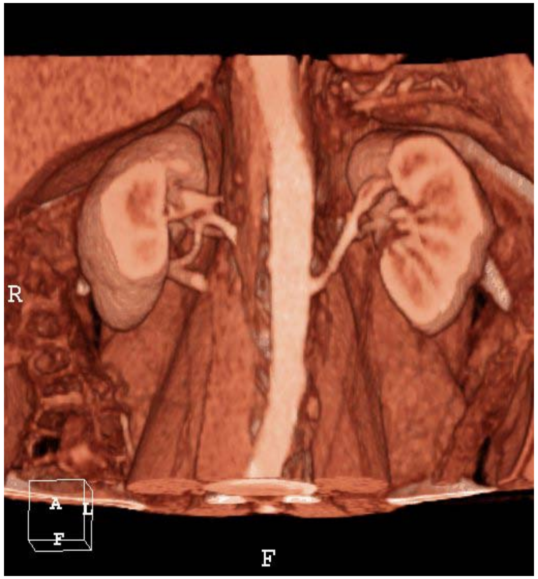


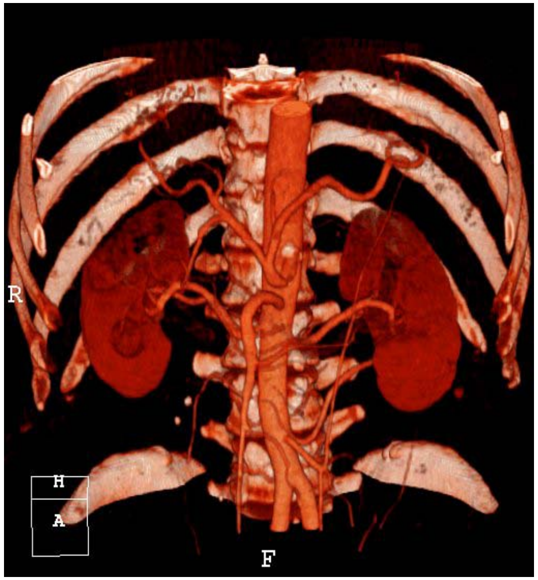
Virtual Endoscopy

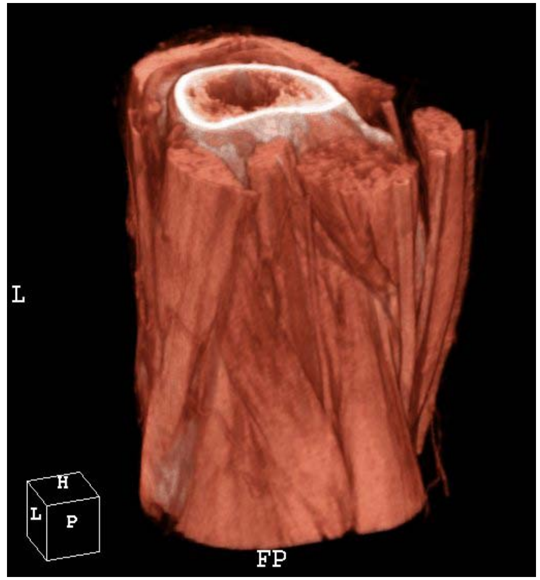
Direct Volume Visualization



- Left, Middle: complex fracture of the shoulder
- Right: visualization of abdominal vasculature







- Left: rare vascular supply of the kidney
- Middle: cystic kidney
- Right: muscles in the knee region

Direct Volume Visualization: Outline

Direct Volume Visualization

- Introduction
- Image-based Volume Visualization
- Texture-based Volume Visualization
- Projection Methods
- Lightning
- Tagged Volume Rendering

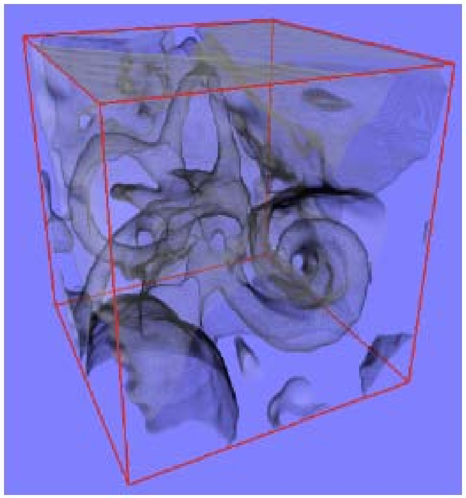
Requirements:

- 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)

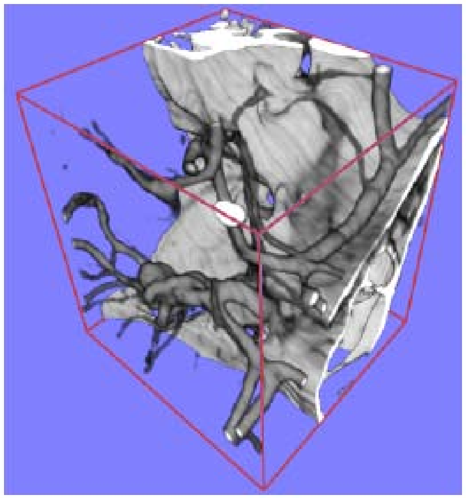
DVR procedure for medical visualization:

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

- 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

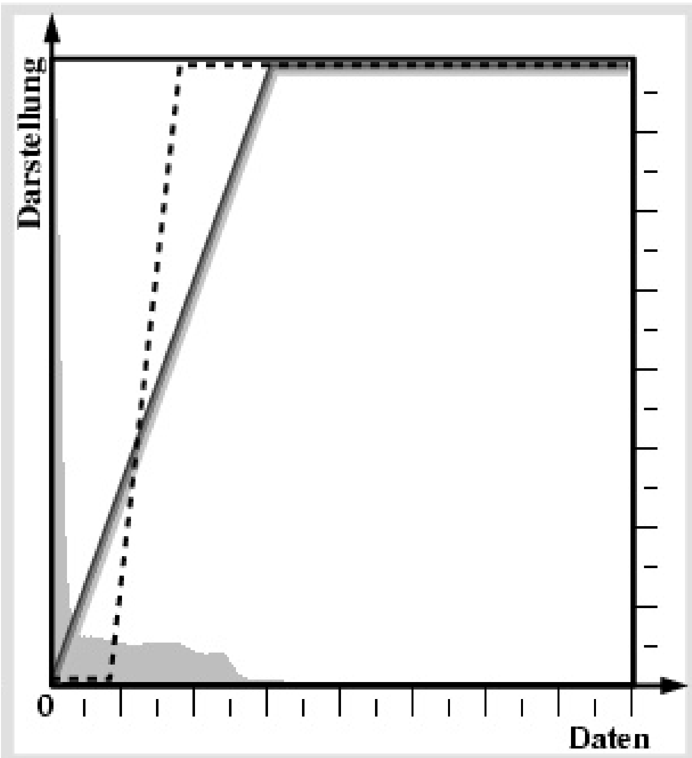
How is this specified?

Through an appropriate transfer function

Source: Rezk-Salama, 2002

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

Histogram displayed as context in a graphic editor.



Source: Hastreiter, 1999

- Volume rendering equation (without shadow and scattering):

$$I_\lambda(x,r) = \int_0^L c_\lambda(s)\, e^{-\int_0^s \alpha(t)\,dt}\, ds$$

$$I_\lambda(x,r) = \int_0^L c_\lambda(s) e^{-\int_0^s \alpha(t)dt} ds$$

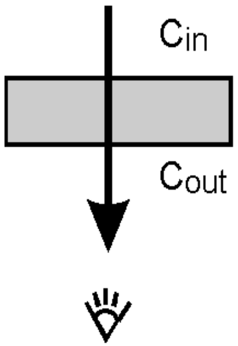
- Numerical approximation:

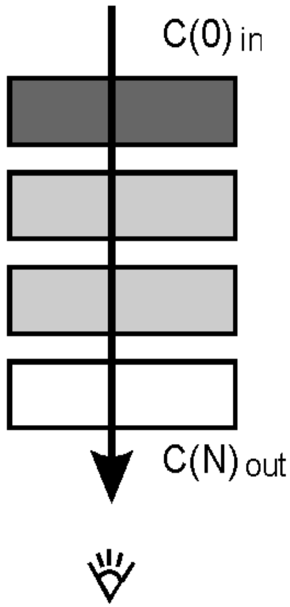
$$I_\lambda(x,r) = \sum_{i=0}^{L/\Delta s} c_\lambda(s_i) * \prod_{j=0}^{i-1} (1-\alpha(s_j))$$

- Cλ(si) local color at position si
- α (si) transparency at position si
- Cλ(si) and α are transfer functions
- Product describes remaining visibility after one pass of a ray

Accuracy strongly depends on the step size.

Set: I (0) = C(0), α(0)

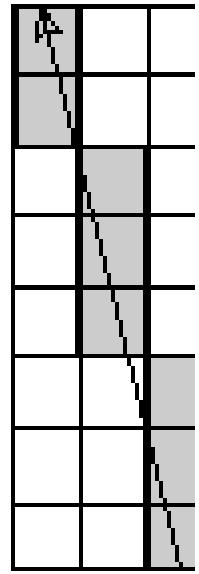


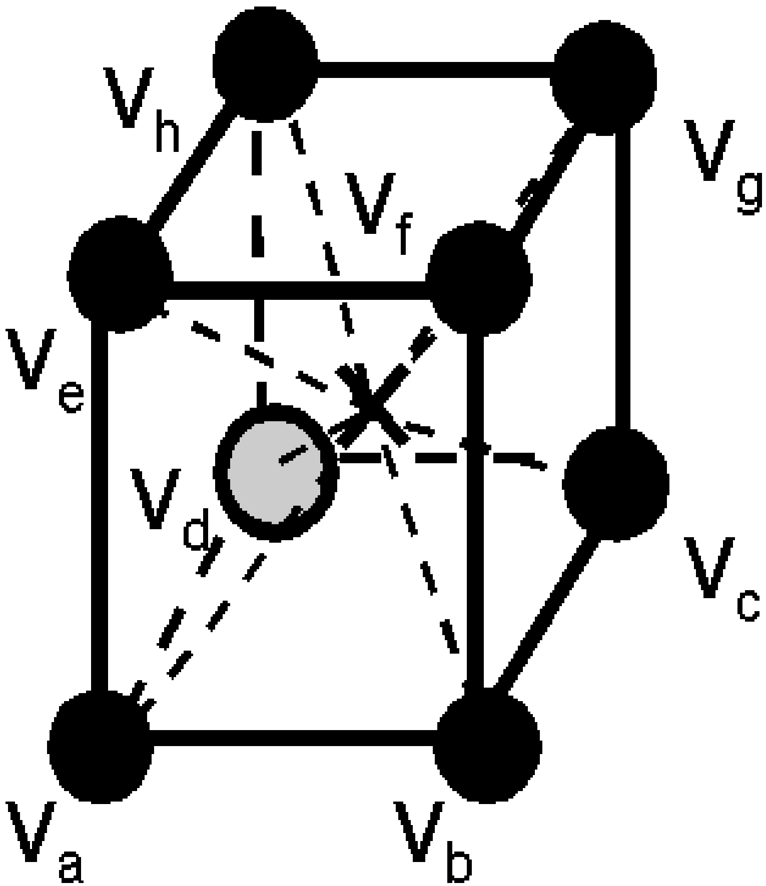


- Color and opacity of a pixel are derived by overlay of semitransparenter voxels (compositing)

$C_i := C_{i-1} * (1-\alpha_i) + \alpha_i C_i$ (color)
$\alpha_i := \alpha_{i-1} * (1-\alpha_i) + \alpha_i$ (opacity)
If $1-\alpha_i$ is very low, the process may be terminated.

- 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





- Trilinear interpolation

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

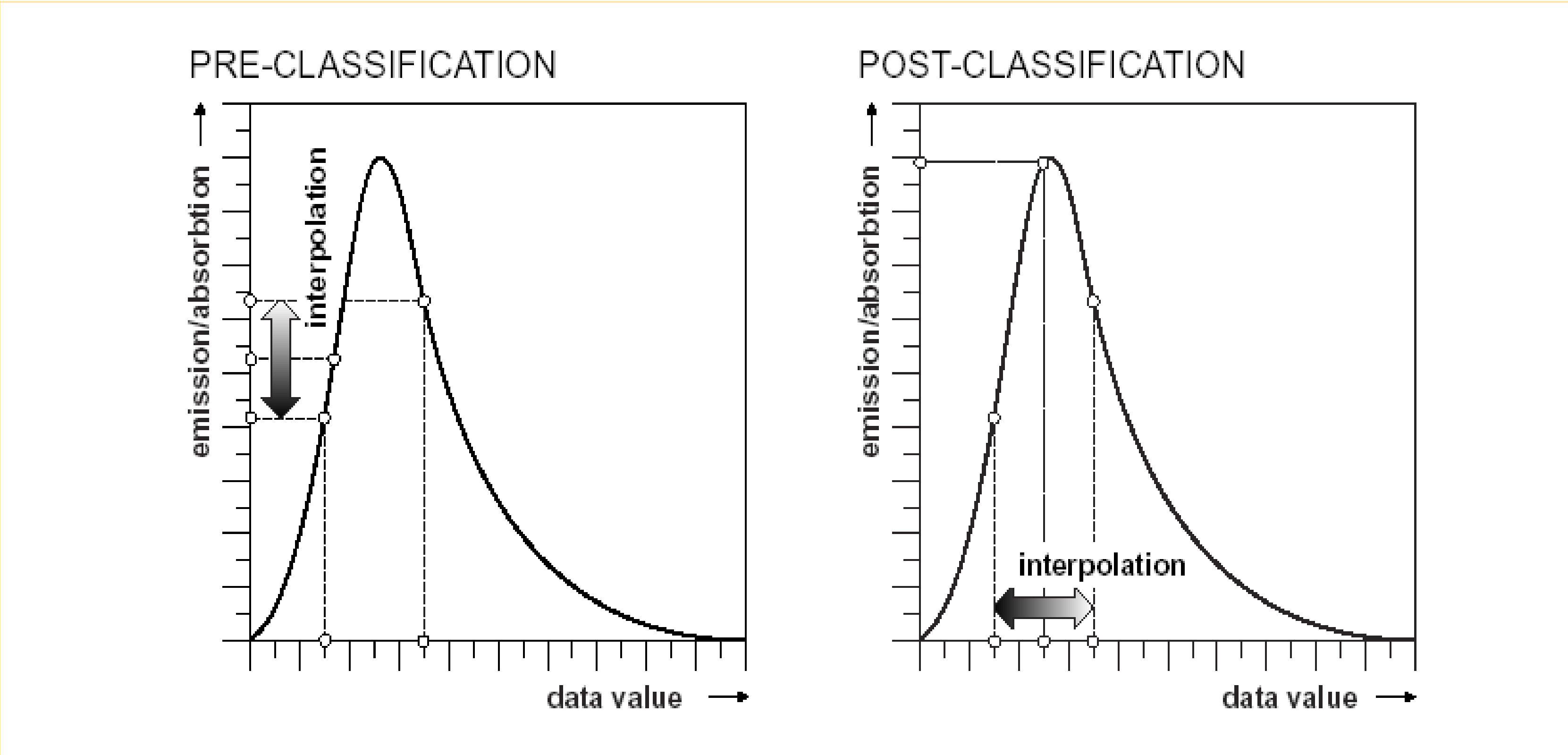
  $$
  \begin{aligned}
  I(Vp) = & I(V_a)(1-x_p)(1-y_p)(1-z_p) \\
  & + I(V_e)(1-x_p)(1-y_p)\, z_p \\
  & + I(V_b)(x_p)(1-y_p)(1-z_p) \\
  & + I(V_f)\, x_p (1-y_p)\, z_p \\
  & + I(V_c)\, x_p\, y_p (1-z_p) \\
  & + I(V_g)\, x_p\, y_p\, z_p \\
  & + I(V_d)(1-x_p)\, y_p (1-z_p) \\
  & + I(V_h)(1-x_p)\, y_p\,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

-

Interpolation and application of the transfer function

- 1st 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)
- 2nd variant: Interpolation of the intensity values from the data (e.g., Hounsfield Units) and afterwards application of the transfer function to the interpoled result (post-classification)

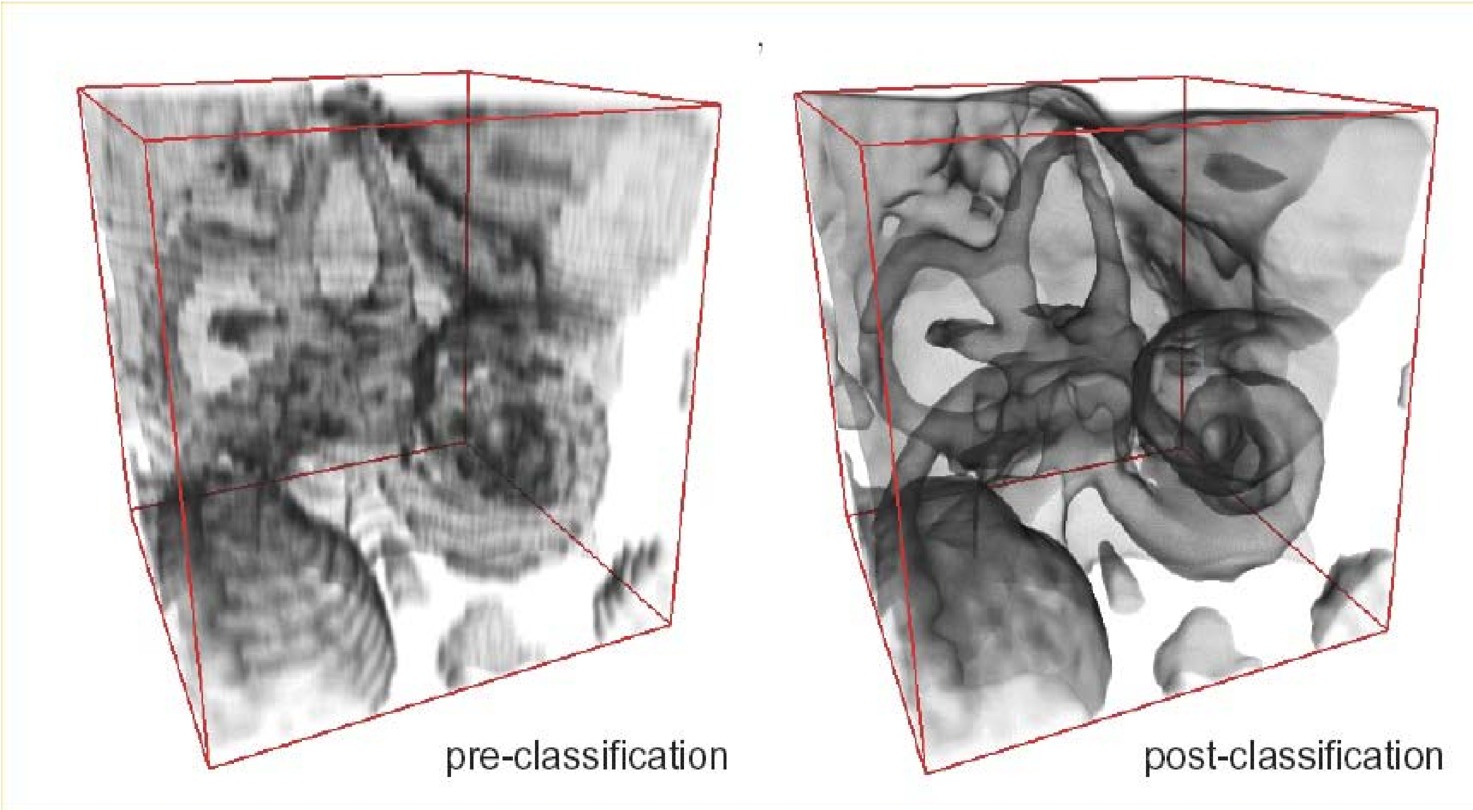
Problem of the first variant: Color perception is non-linear in RGB and interpolation for up to 4 channels. But this variant is often supported through hardware lookup tables.



A late application of the TF is more precise!

Source: Rezk-Salama, Phd thesis, 2002

Interpolation and application of the transfer function



Source: Rezk-Salama, 2002

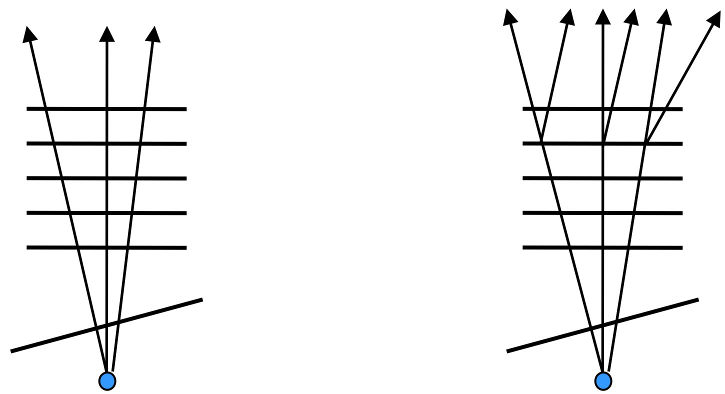
Basic algorithm ray casting:

```
for yi = 1 to ImageHeight
    for xi = 1 to ImageWidth
      for zi = 1 to RayLength
           foreach x0 in ResamplingFilter (xi, yi, zi)
             foreach y0 in ResamplingFilter (xi, yi, zi)
               foreach z0 in ResamplingFilter (xi, yi, zi)
                  add contribution of Voxel [x0, y0, z0] to ImagePixel [xi, yi]
```

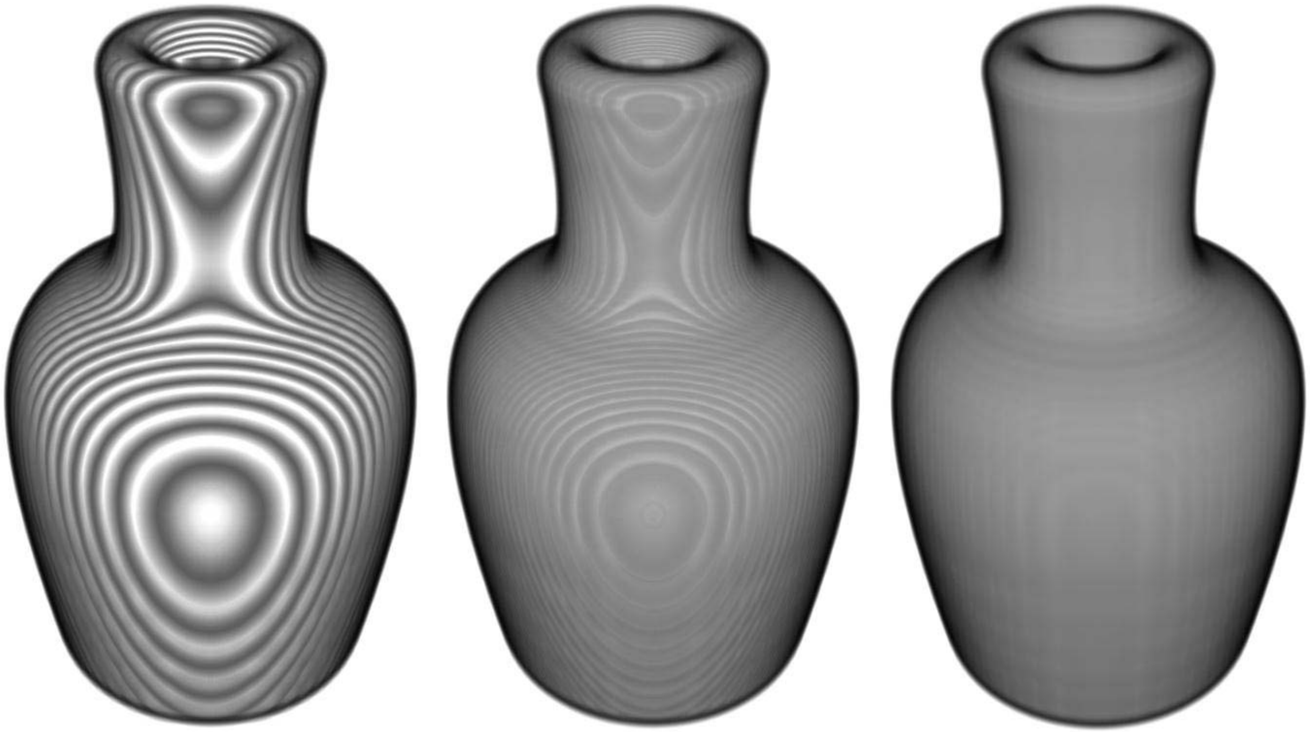
- The resampling filter corresponds to the interpolation (often 2x2x2 values)
- Problem: The volume is not traversed in the order in which it lies in the memory. Often, voxels which are not in the cache or in the central memory, are required.

- 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

Image plane

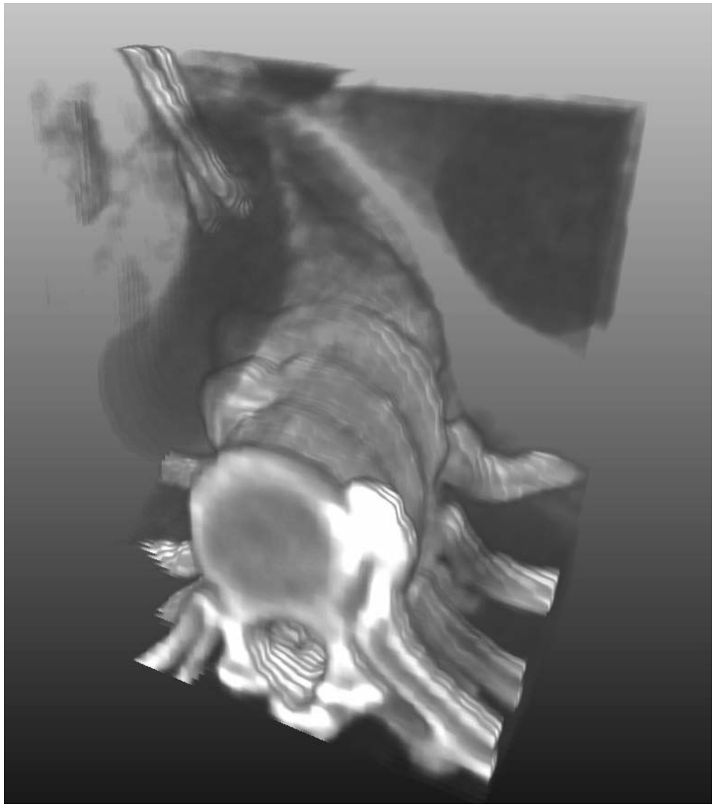


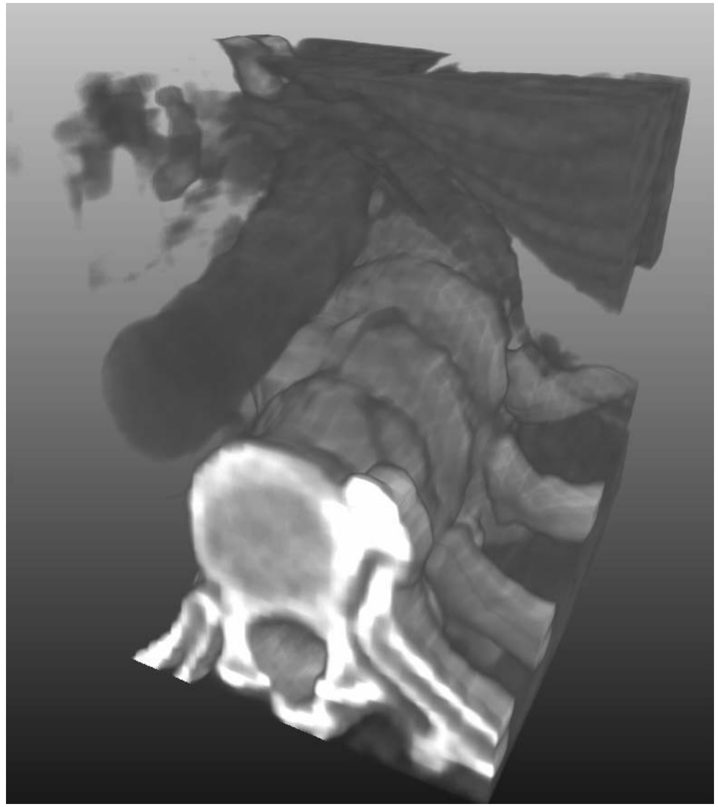
- Influence of the sampling rate on alias effects (increment: 2.0 voxel, 1.0 voxel, 0.1 voxel), (© Schroeder et al. [1998])



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

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



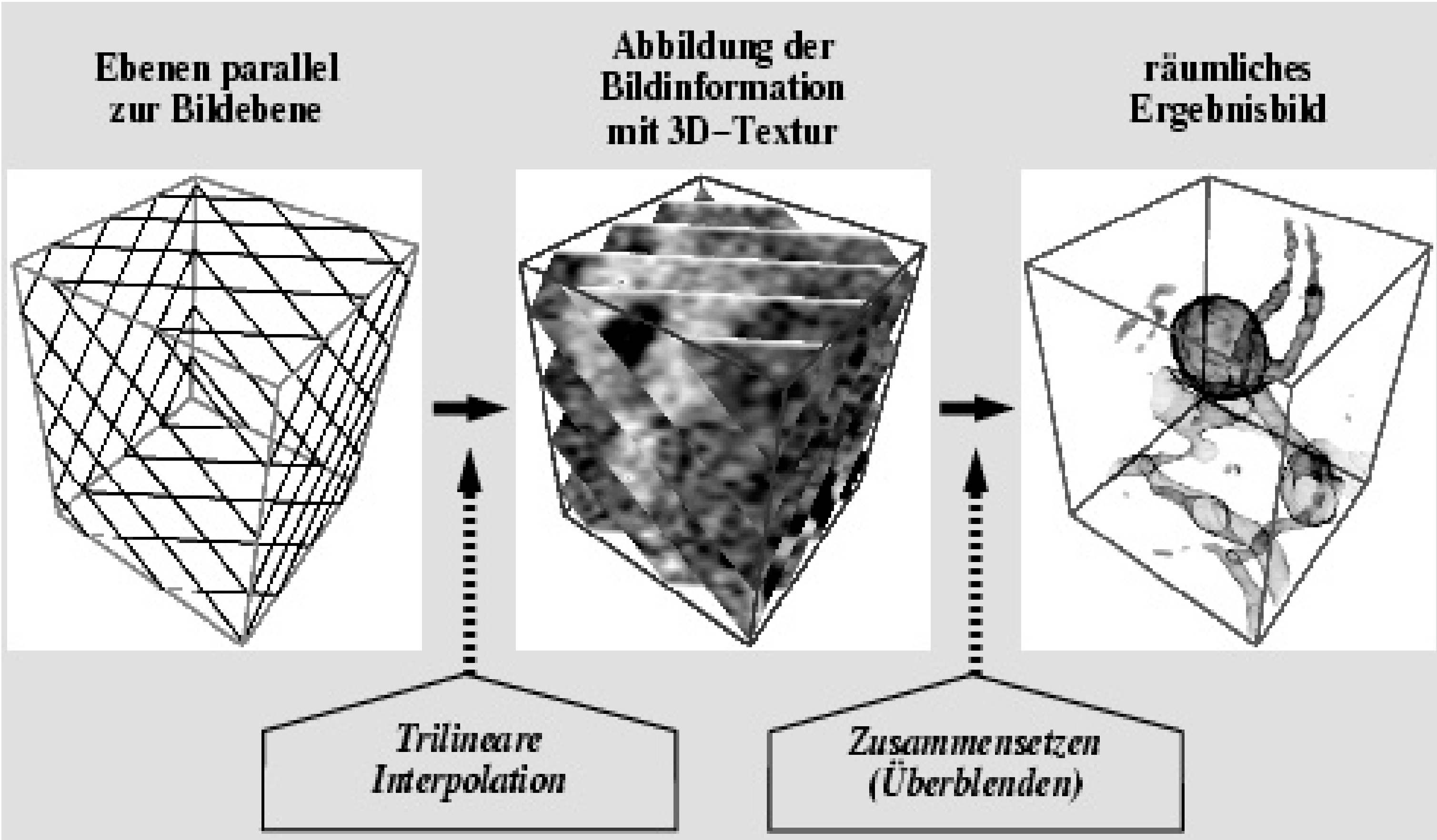


Volume Definition

- 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

Basic Approach:

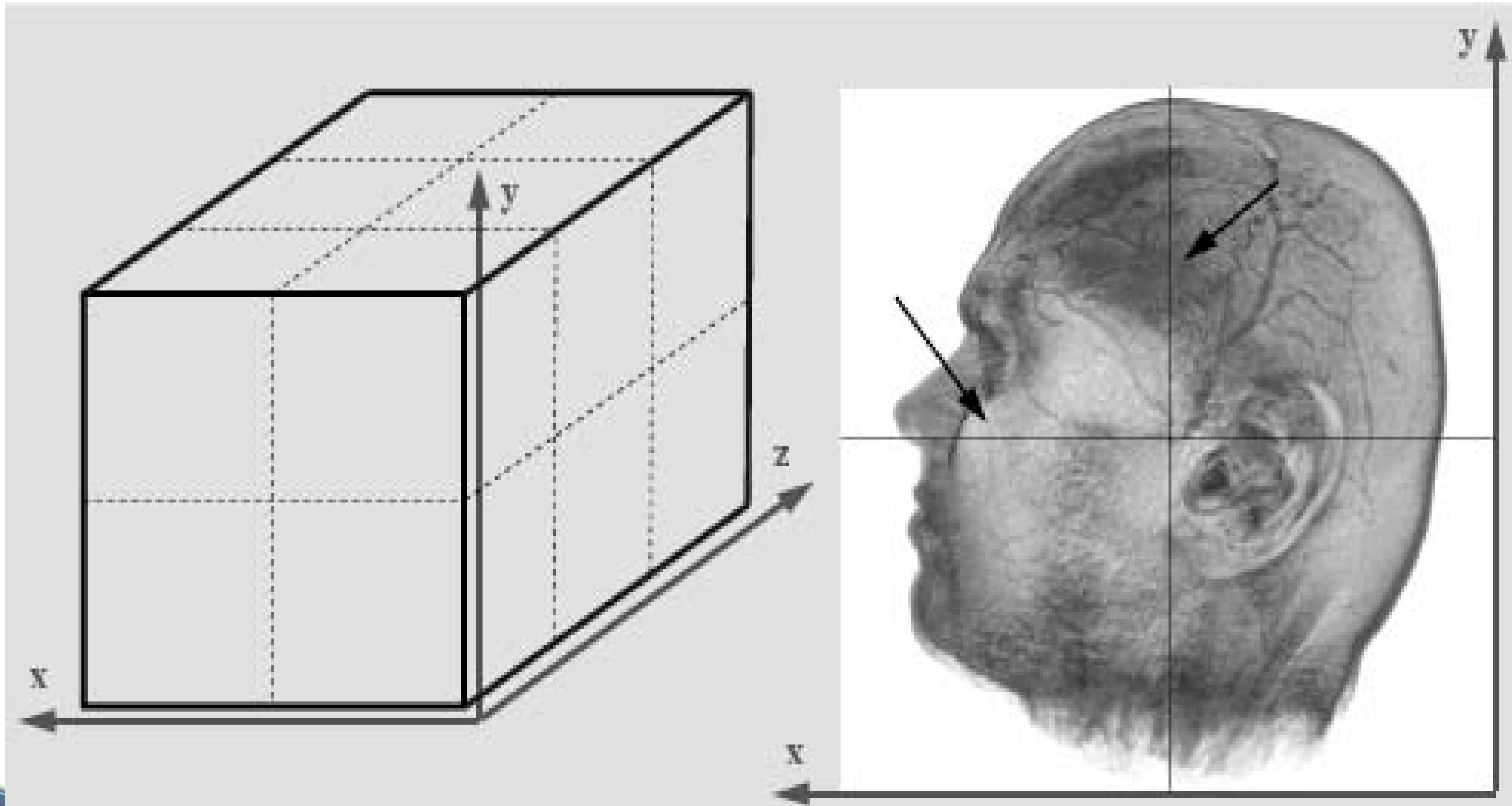
- The volume is cut through equidistant planes
- Textured polygons are generated for each slice plane. They are drawn from back to front and overlaid semi-transparently.
- If volume > texture memory
  - sorting of the blocks according to the distance



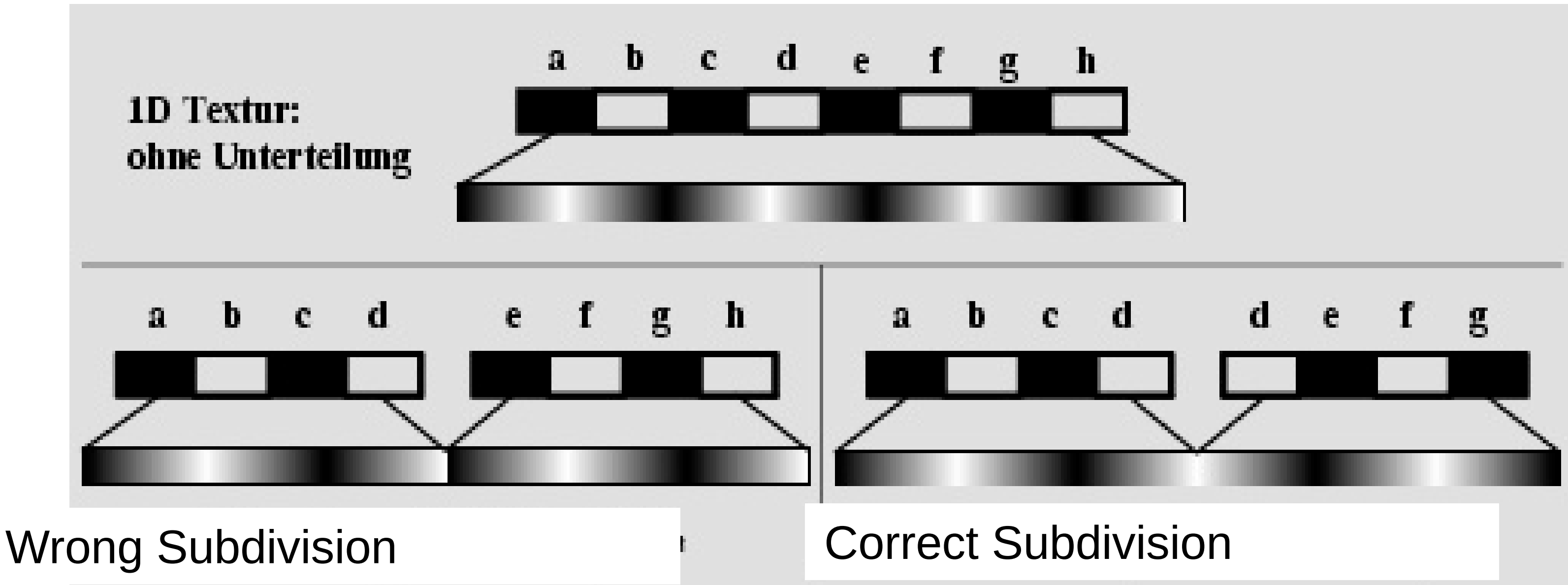
Procedure for the use of 3D textures
(© Peter Hastreiter, University of Erlangen)

- Division of the volume into bricks, artifacts (black stripes) in case of non-observance of the boundaries

  (© Peter Hastreiter, University of Erlangen)



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



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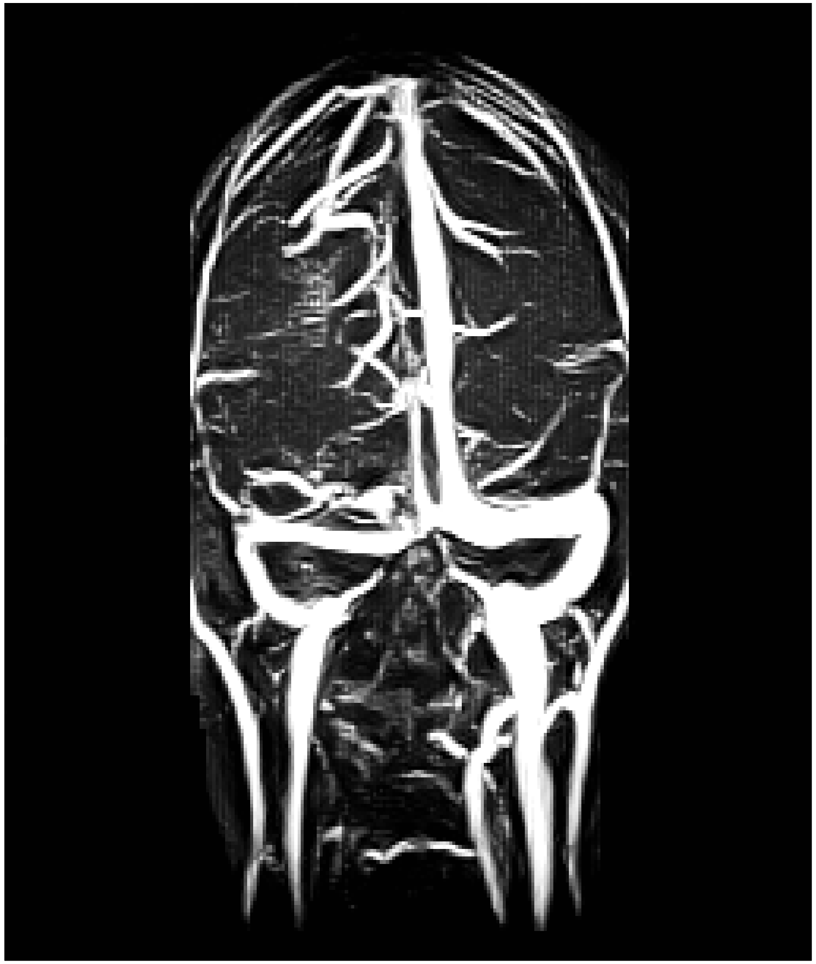
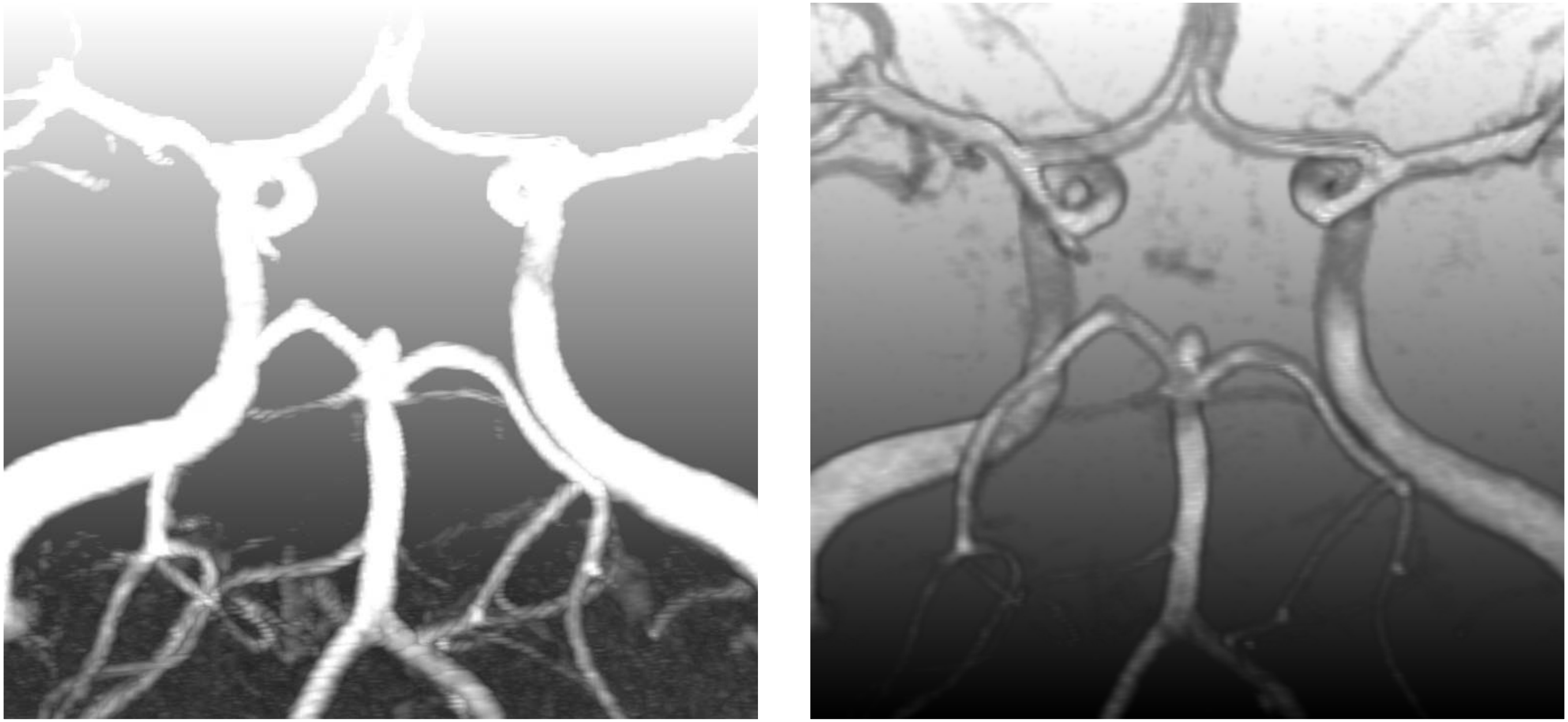
Direct Volume Visualization: Projection Methods

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)



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

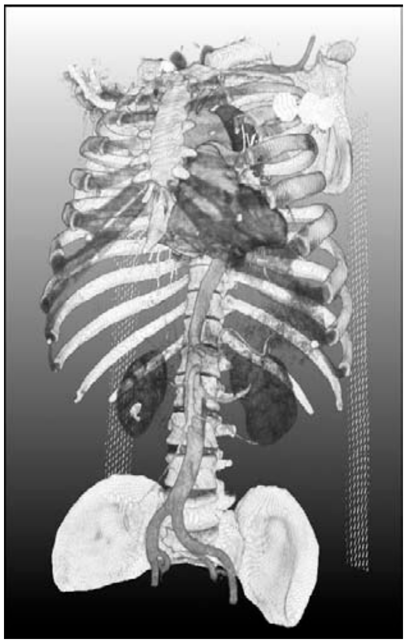
Restriction of the data on which a MIP is applied:

- (1) Remove certain structures which disturb the MIP display.

  Example: Removal of bones (interactively byplacing a seed point and Region Growing).

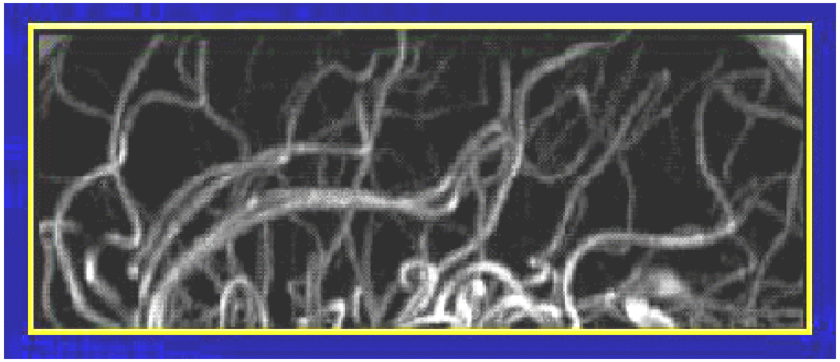
  (2) Apply the MIP to a certain partial volume.

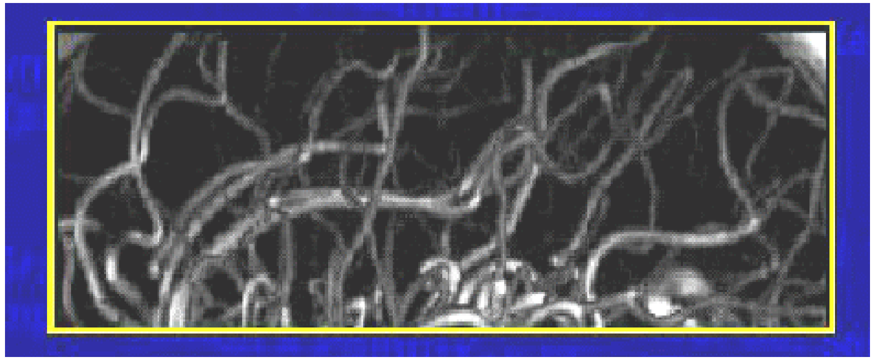
  Example: MIP illustration in a segmented organ for the selective evaluation of this organ



Before and after bone removal,

© Hans Drexl, Fraunhofer MEVIS

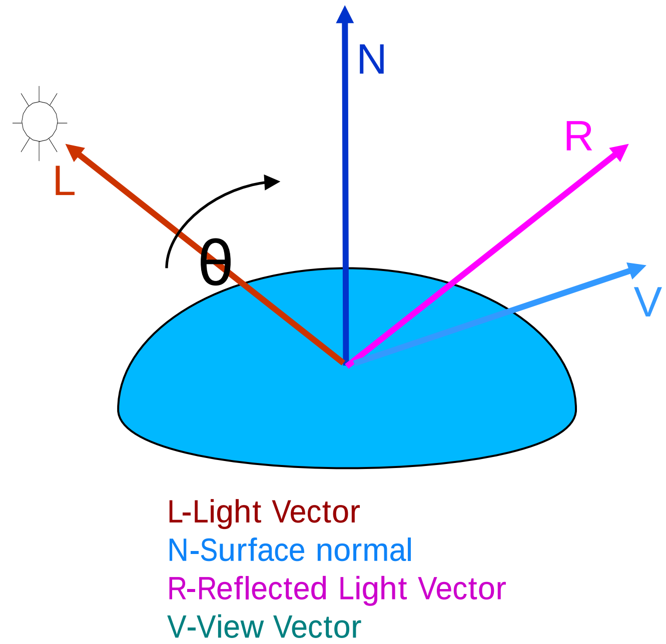


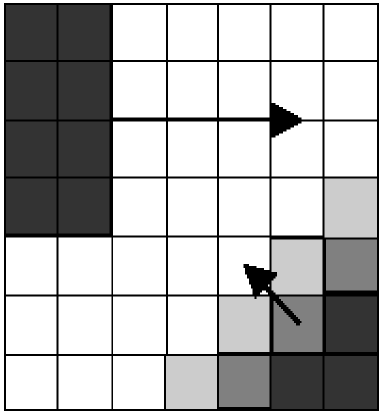


- MIP and CVP of brain vessels (© Karel Zuiderveld)
- To evaluate spatial relations, movies with rotations of MIP and CVP in a central perspective are often used.

Thin-Slab-MIP

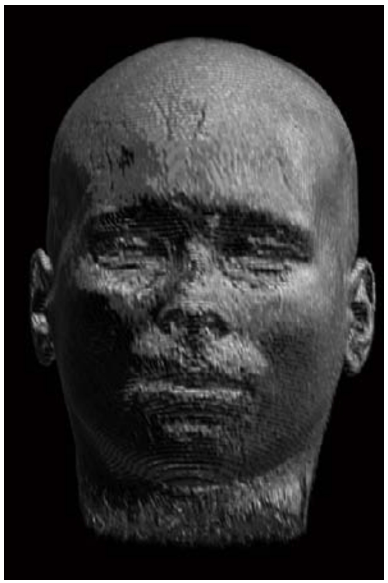
- Angle of incidence θ: angle between L and N (determines the diffuse reflection)
- Reflection angle r: angle between R and N.
- Angle Φ between V and R determines the intensity of the incident light.
- If V = R (respectively Φ =0), the light is reflected maximal to the viewer.





- Approximation of the surface normal by calculating the gradient (grey level gradient shading, [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)

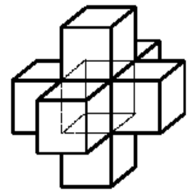
  → Discretization of the normal in a gradient lookup table

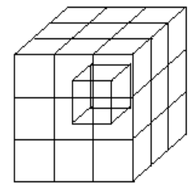


- Illuminated illustration of an MRT data set
  (high sampling rate and trilinear interpolation)

Problems:

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





- Common variants of gradient estimation:
  (1) central differences (6 neighbors):

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

$$\nabla V(xi, yj, zk) = (\tfrac{1}{2}\ (V(xi+1, yj, zk) - (V(xi-1, yj, zk)),$$
$$(\tfrac{1}{2}\ (V(xi, yj+1, zk) - (V(xi, yj-1, zk)),$$
$$(\tfrac{1}{2}\ (V(xi, yj, zk+1) - (V(xi, yj, zk-1))\ )$$

  (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 xi+2, xi-2, yi+2, yi-2, zi+2, zi-2,
- The second variant is more complex than the first one, but qualitatively better.
- Problems: treatment of boundaries, line structures

Direct Volume Visualization: Shadow

- Shadow may further enhance depth perception
- Requires the definition of a light source and the analysis, how the voxels are oriented towards the light source.
- Method:
  - Two-Pass-Rendering: First Pass: illumination per voxel is computed and represented in the shadow-Buffer. Second pass: image generation based on the shadow buffer. (Levoy [1988])
  - Disadvantage: required size of a 3d-Shadow-Buffer
  - Recent refinements reduce memory consumption and increase performance:
    - **Deep Shadow Maps (Kratz [2006]),**
    - **Adaptive Volumetric Shadow Maps (Salvi [2010])**

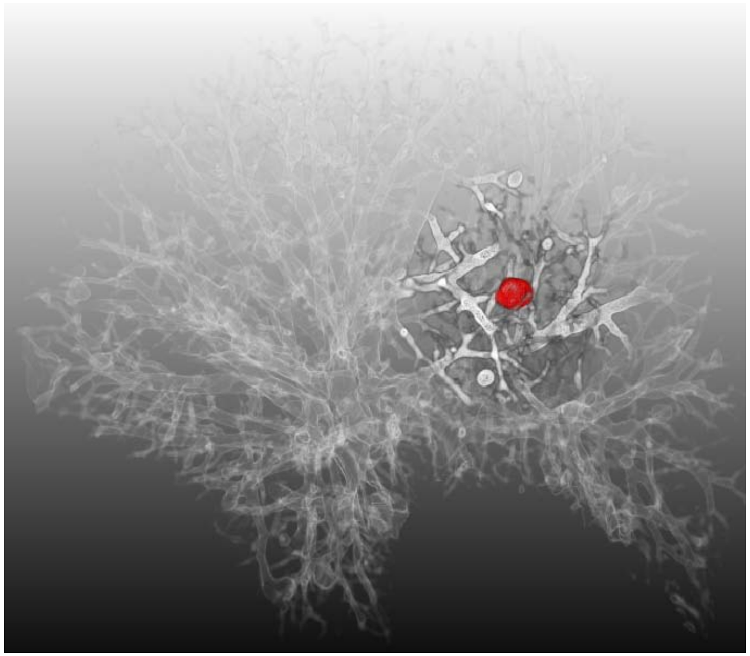
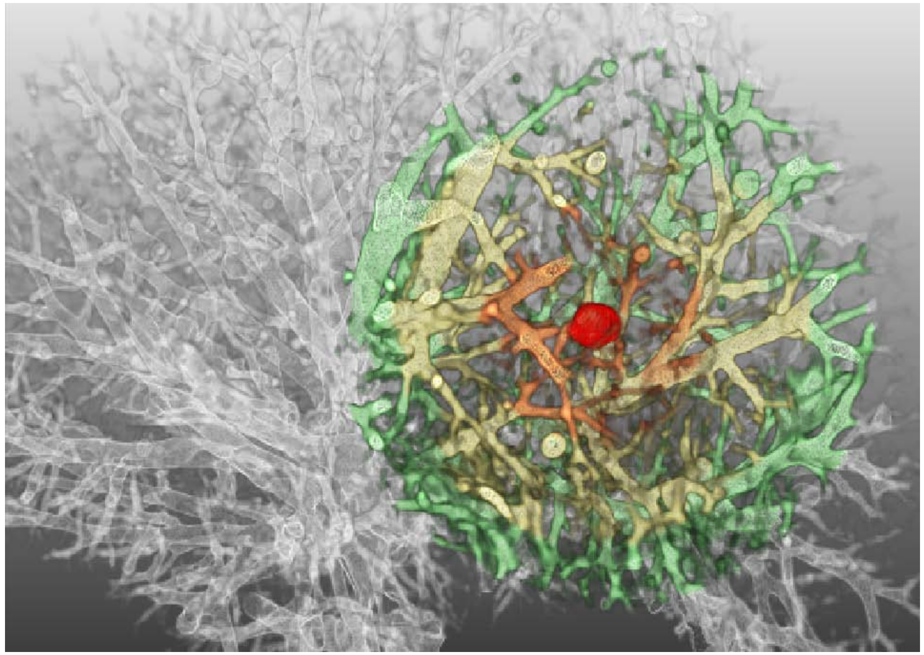
Direct Volume Visualization: Shadow

(a) DVR (b) Shaded DVR (c) DVR with shadows

(a) DVR (b) Shaded DVR (c) DVR with Shadows

[Kratz2006]

Direct Volume Visualization: Tagged VR

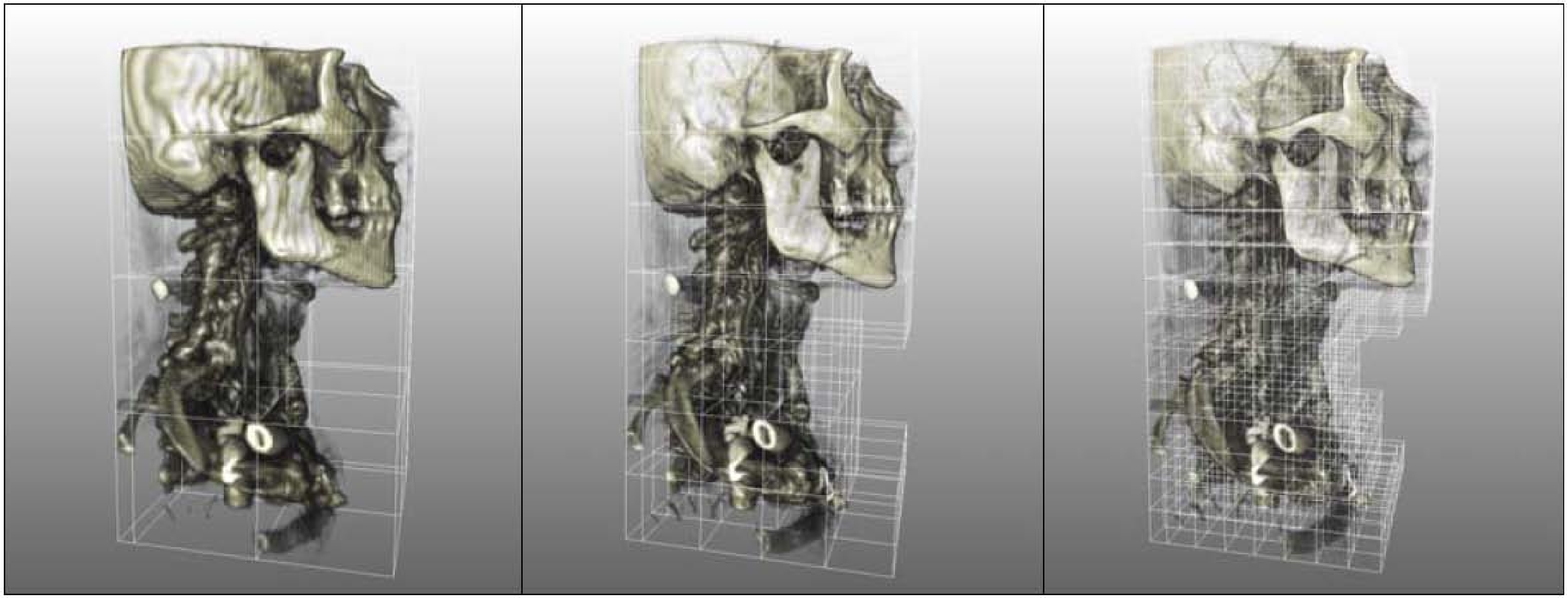
Tappenbeck [2006]

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

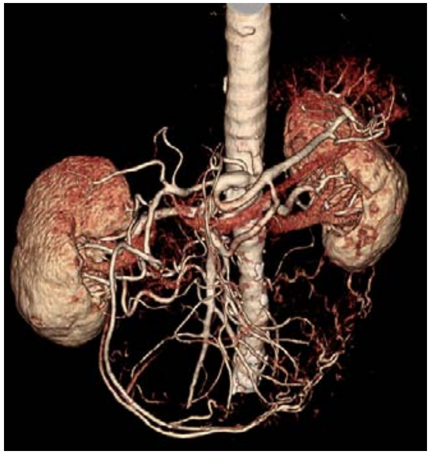
- Goal: restrict rendering to visible portions and/or importance
- Typical data structure: Octree
- Node size, 16x16 …. 64x64
- Requires resampling, e.g. by means of a rank filter
- Overlap of the nodes for correct interpolation (1 voxel)
- Moderate additional memory load

Direct Volume Visualization: Hierarchical Methods

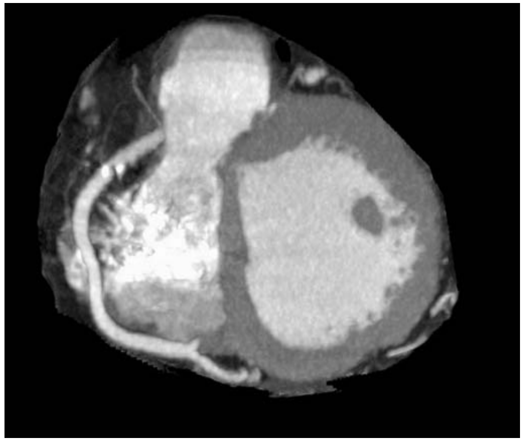
- Octree nodes are rendered back to front
- Order of nodes depends on the viewing direction
- Lower resolution may be used for interactive rendering



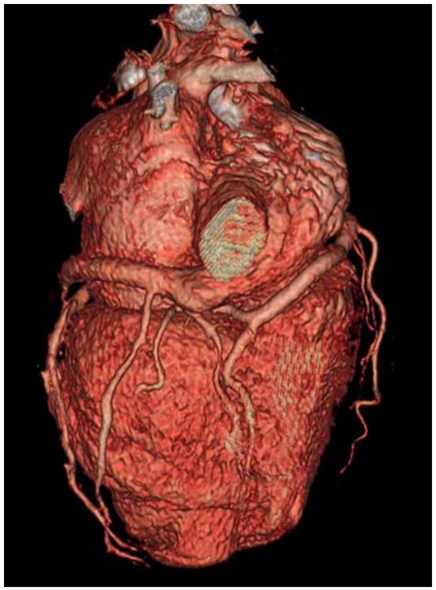
Link [2006]

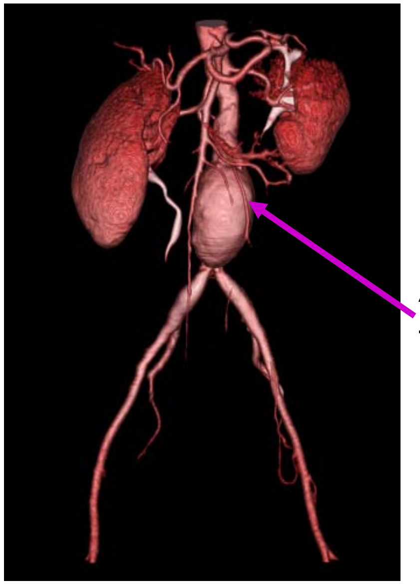


CTA of the abdominal vessels

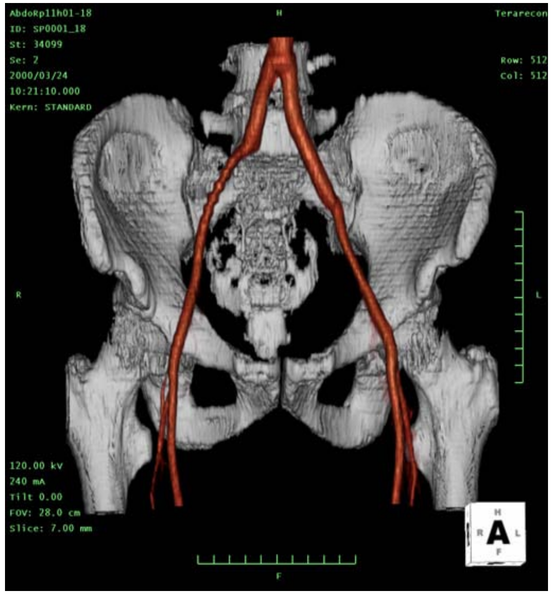


MIP restricted to a subvolume (slab)
Data: Cardiac CTA



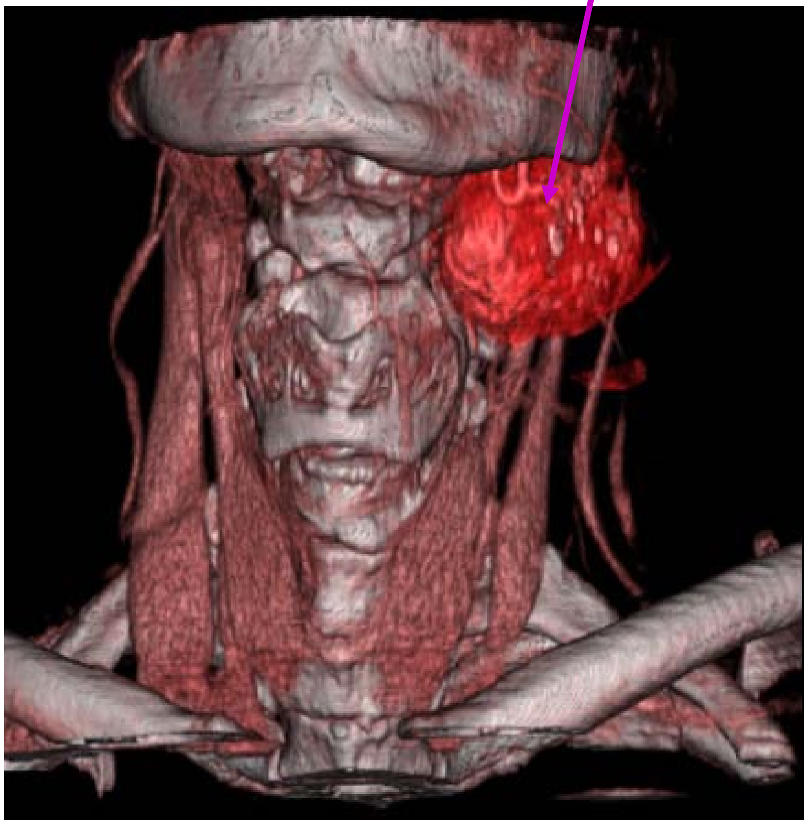


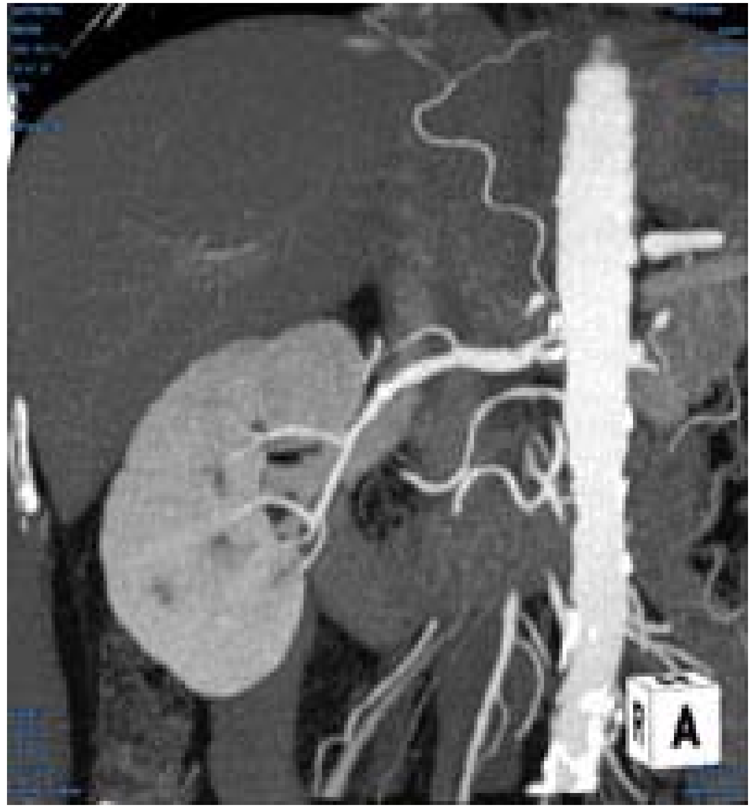
Aneurysm of the abdominal aorta



Tools for Volume Visualization: Volume per 1000 – Image Gallery

tumor in the neck area





MIP illustration of the kidney (vessels)

Literature: Volume Rendering

VE Bramkov, RP Barneva, P Nelig (2000) “Minimally Thin Discrete Triangulation”, In: Chen et al. [2000], p. 52-70

M Chen, AE Kaufman, R. Yagel (Hrsg.) (2000) *Volume Graphics*, Springer

J Danskin and P Hanrahan (1992) “Fast Algorithms for Volume Ray Tracing”, *Proceedings of 1992 Workshop on Volume Visualization*, Boston, MA, p. 91-105

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