To appear in the IEEE Visualization 1999 conference proceedings

Interactive Exploration of Extra- and Intracranial Blood Vessels

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Abstract

Abstract. We present a system for interactive explorations of extra- and intracranial blood vessels. Starting with a stack of images from 3D angiography, we use virtual clips to limit the segmentation of the vessel tree to the parts the neuroradiologists are interested in. Furthermore, methods of interactive virtual endoscopy are applied in order to provide an interior view of the blood vessels.

CCS Categories: I.3.8 [Application]: Virtual Medicine; I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality;

Keywords: Virtual Environments, 3D Angiography, Virtual Angioscopy, Interventional Neuroradiology, Selective Segmentation, Computer Assisted Diagnosis.

1 Introduction

A common procedure in neuroradiology is the examination of extra- and intracranial blood vessels. After the injection of a contrast agent via an endovascular catheter, X-rays are used to acquire 2D projection images of vessels. These images are of high resolution but lack spatial information due to the projection method. Several other non-invasive techniques are available to visualize vessel trees in 3D, such as CT or MRI-based angiography. Another advanced technique is *rotational angiography*, which provides a volumetric representation of the respective blood vessels and the surrounding tissue. Currently, examinations of the vascular systems are mainly performed using Maximum-Intensity-Projections (MIP) or slicing through the 3D dataset. In contrast, using virtual endovascular methods (virtual endoscopy) enables both quantitative and qualitative analysis of the blood vessels [5].
After a segmentation and classification operation, the blood vessels of the scanned area can be reconstructed from volume data. However, due to reflux of the contrast agent, more blood vessels of the respective area are usually visualized than the vessels of interest. This leads to a situation where the actual important information might be hidden behind less important information. Two techniques are applied to solve this situation. The application of virtual clips limits the segmentation of the vessel tree to the part of the vessels the neuroradiologist is interested in. The second technique applies methods from virtual endoscopy [2, 8] to generate an interactive environment for the vascular examination from a point of view which is inside the vessels.

We present the virtual angioscopy system in Section 3. Specifically, we briefly outline virtual clips in Section 3.1 and the virtual endoscopy system used for virtual angioscopy in Section 3.2. In Section 4, we present our results and we conclude the paper in Section 5.

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2 Related Work

Research on virtual endoscopy is one of the most active areas in virtual medicine. The developed methods were applied to virtual colonoscopy [8, 15], bronchoscopy [6], ventriculoscopy [1, 3], and angioscopy [5, 4, 7].

Different rendering techniques are used to provide sufficient visual quality and/or interactivity. Standard graphics hardware is used to render surface models [16, 11, 8, 2], extracted with the Marching Cubes algorithm [10]. In contrast, volume rendering techniques are used, partially for better visual quality, partially for interactive speed [14, 19, 7, 1]. Unfortunately, interactive speed was always compromising visual quality, general applicability, or flexibility. In [14] and [4], key-framed animations are generated offline, which frequently leads to the time-intense refinement of the key-framed animation. You et al. used a 16 processor SGI Challenge for parallel volume rendering of isosurfaces [19]. In contrast, Gobetti et al. used the texture mapping hardware abilities of high-end graphics systems for volume rendering. However, the lack of shading reduced the visual quality significantly [7][1]. Furthermore, the size of the texture memory limits the size of datasets severely, while swapping techniques like bricking reduce the framerate. The Navigator software of General Electric uses isosurface ray casting with approximately one frame per second. Even if the performance of the 1996 results has significantly improved, it hardly can be viewed as interactive [5].
Considering the pros and cons of these approaches, we adopted a surface rendering approach based on [8].

3 Virtual Angioscopy

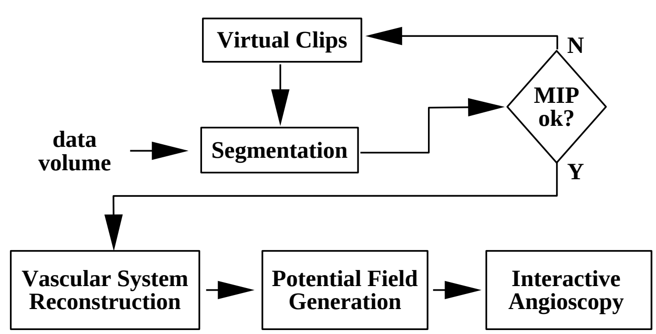


Figure 1: Processing pipeline for virtual angioscopy.

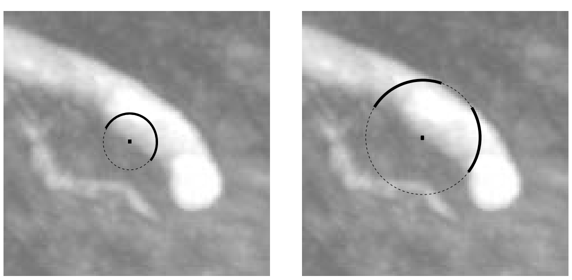
For virtual angioscopy, we follow the standard processing pipeline (Fig. 1 similar to [8] and [2]. The first step after data acquisition

[1]Meanwhile, Westermann and Ertl presented texture mapping-based volume rendering with isosurface shading [18]. However, this approach does not provide sufficient performance for interactive endoscopy applications.

of the volume dataset – based on the image stack from rotational angiography, MRI, or CT –, is the segmentation of the vessel tree. Standard 3D region growing-based segmentation algorithms [2] can be used as well as advanced segmentation methods [17]. However, due to reflux of the contrast agent, arterial and venously blood vessels are usually segmented, thus increasing the visual complexity. To reduce this complexity, we add a selective segmentation refinement step to cut off parts of the vascular tree. Specifically, we apply *virtual clips* to limit the subsequent refined segmentation to parts of the complex vessel tree. Together, virtual clips and segmentation form a segmentation interaction loop.
Once the vessel tree is sufficiently segmented, a hierarchically, Marching Cube-based isosurface algorithm is applied to extract the isosurface representing the inner surface of the segmented vascular system. Finally, distance fields are computed to provide a guided-navigation system for the virtual camera [8].

3.1 Virtual Clips

As mentioned earlier, virtual clips are used to limit the segmentation to the part of the vascular system a neuroradiologist is interested in. Similar to real clips in surgery, virtual clips pinch off blood vessels from the respective vascular system in order to limit the segmentation. To specify the virtual clip, the user interactively picks an area of a Maximum-Intensity-Projection (MIP) of the dataset, which is associated with the vessel surface in the data volume (Fig. 2a). This point is interpreted as the center of a balloon which inflates until the vessel is blocked (Fig. 2b). This process is controlled by a balloon shape constraint volume growing algorithm. During the growing, the surface of the balloon (thick black surface in Fig. 2a and 2b) is either inside the vessel or intersects with the surface of the vessel. Once the surface of the balloon inside of the vessel is partitioned into two disconnected segments, the balloon completely blocks the vessel, thus realizing a virtual clip (Fig. 2b).



(a) (b)

Figure 2: (a) Before the vessel is blocked, there is only one connected area, which is on the surface of the balloon and inside the vessel. (b) If the area on the surface of the balloon inside the vessel is partitioned into two segments, the vessel is blocked.

3.2 Virtual Endoscopy

In this Section, we discuss some of the main features of the virtual endoscopy system, used for virtual angioscopy. Specifically, we focus on the efficient rendering of, and the navigation in reconstructed blood vessel trees. Depending on the image acquisition modality, these trees (or vascular systems) are not connected due to segmentation and contrast problems, or because they are anatomically not connected. However, a visualization and exploration of all parts can provide more insights to the physicians (e.g. arterial or venously systems). In those cases, disconnected parts of the vascular systems can be examined either separately in different sessions, or they can be treated as parts of one unified, but disconnected structure, with individual distance fields for navigation (later in this Section). More details on this system can be found in [2].

Visibility-Culling-based Rendering

Extracting a polygonal representation of an isosurface from a volume dataset usually generates a large number of polygons. In order to enable interactivity, we employ a hierarchical polygon culling scheme based on view-frustum and occlusion culling.

The isosurface extraction process is based on an octree decomposition of the pre-segmented volume dataset (Fig. 3). During the interactive virtual exploration, the virtual angiograpy systems hierarchically checks which of the individual octants intersects with the field of view. Only those blocks are considered potentially visible. All other entities are not visible, hence they are not rendered. After this view-frustum culling stage, all potentially visible leaf blocks of the octree – which contain the actual geometry – are depth-sorted (details can be found in [9]) and the associated geometry is sent to the graphics pipeline for rendering. For the measurements, we performed a virtual fly-through of the vascular system of a patient dataset. The vascular system consisted of 419,639 polygons, extracted from a $512 \times 512 \times 258$ rotational angiography dataset.

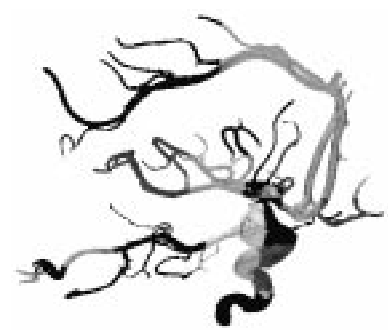


Figure 3: Octree decomposition of reconstructed vessel tree. Different grey-shades mark geometry of different octants.

For view-frustum culling only, we achieved an average culling rate of approximately 62.1 %, and a framerate of 7.5 fps on an HP B180/fx4 graphics workstation, and a framerate of 4.5 fps on an SGI Octane/MXE using an R10000/250 MHz CPU. These framerates compare to 4.9 fps and 3.2 fps without any visibility culling on the HP and SGI respectively.

On the HP fx4/fx6 graphics workstations, hardware support for occlusion culling is available [13]. The HP Occlusion Culling Flag indicates if graphics primitives – rendered in an occlusion render mode – would have a contribution to the framebuffer. Using this flag, we render the bounding boxes of the depth-sorted[2] octants to check for occlusion, resulting in a list of not occluded octants. The associated geometry of all these octants is finally rendered. On an HP B180/fx4 graphics workstation, we achieved a total visibility culling rate of 90.6 %, and a total framerate of 15.7 fps, thus enabling interactive explorations of large angiography datasets.

[2]This occlusion check is performed after the view-frustum culling step, but before the rendering of the actual geometry.

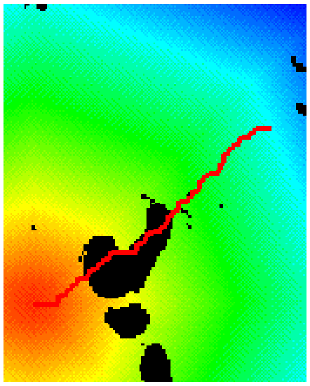


Figure 4: Distance field coding the drift to the target point.

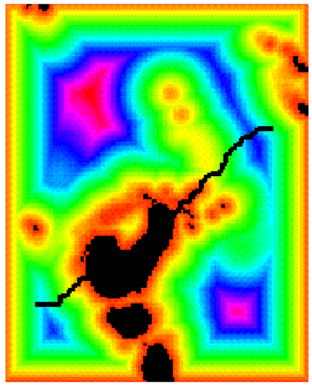


Figure 5: Distance field coding the distance to the outer vascular surface.

Interactive Guided-Navigation

Most virtual endoscopy applications either automatically generate an animation of a fly-through of the respective part of the body, or the user can freely navigate through it. The navigation of the first approach is limited to a VCR-like functionality [11, 4, 15, 12]. However, if the structure of interest is not in the focus of the pre-specified path of the camera, it needs to be refined and the animation needs to be re-generated. This is a potentially very time-consuming task with limited flexibility.
The second approach provides full flexibility for navigation [5, 6, 1]. Unfortunately, anatomical structures commonly found in patient datasets are very complex. Even for a specifically trained physician, it can be difficult to navigate to the target. Furthermore, collision avoidance is a costly operation which is frequently not available in these systems.
In our approach, we adopted a guided-navigation paradigm in order to implement full navigation flexibility, combined with user guidance, and an efficient collision avoidance scheme [8]. Specifically, we apply image processing techniques to the pre-segmented volume dataset to calculate three distance fields which are interpreted as potential fields by our virtual camera. Two of these fields represent the drift of the camera from a specified start point to a specified target and vice versa (see Fig. 4[3]). The third distance field codes the distance from any position in the pre-segmented volume to the surface (actually the isosurface) of the respective vessel (see Fig. 5[3]). If the camera approaches the inner vascular surface, repulsion forces circumvent the penetration of this surface. Together with the user interaction, interpreted as a force, a set of kinematic rules calculates the movement of the camera [8].

4 Results

We applied the presented virtual angioscopy system to a variety of angiography-based volume datasets. After a pre-processing of approximately 15 minutes, we examined the interior of the vascular systems using a virtual endoscope.
In this paper, we focus on an isotropic rotational angiography dataset of resolution $512 \times 512 \times 258$ – spacing 0.39mm, 0.39mm, 0.39 mm – of a 41 year old patient with a fusiform aneurysm of the *Middle Cerebral Artery* (A. cerebri media), which is located at the base of the skull, below the anterior horns of the lateral ventricles of the human brain. Figure 6 shows the endoscopic view into the aneurysm, and Figure 7 gives a rotatable 3D overview of the reconstructed vessel tree, including the markers and current position of the virtual camera.

[3] Pre-processing is usually based on the interior of the vascular systems. For didactic purposes, these figures show the pre-processing results of the exterior of the vascular system.

Lessons Learned

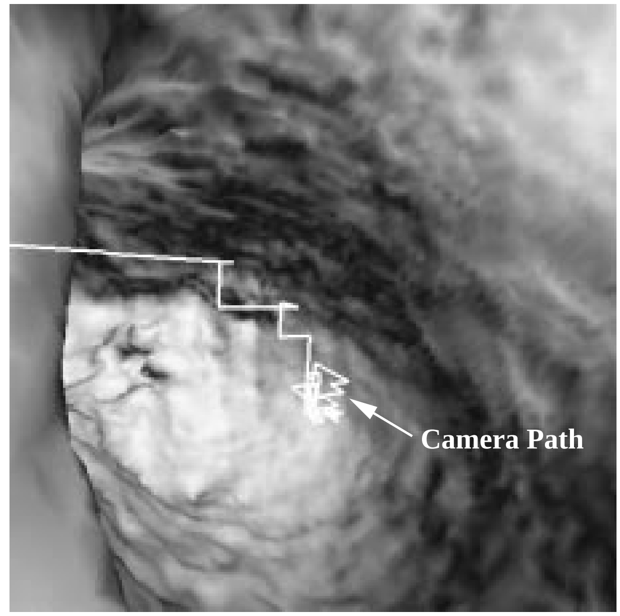


Figure 6: Virtual Angioscopy: View through virtual endoscope into the reconstructed fusiform aneurysm.

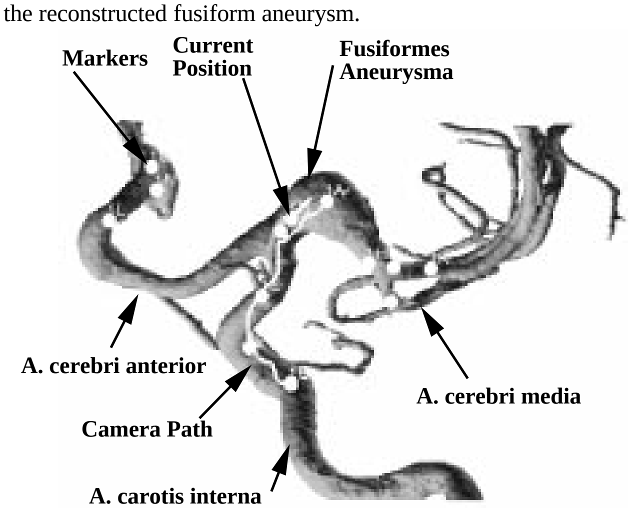


Figure 7: Virtual Angioscopy: Annotated 3D overview of reconstructed vessel tree. The white arrow points to current position. (B/W for print contrast).

A general virtual endoscopy framework [2] was used for virtual angioscopy, the interactive exploration of extra- and intracranial blood vessels. The quality of the visualization of the anatomical structures of real patients depends very much on the scanning modality. The examined datasets were acquired using rotational angioscopy, which provided good contrast to the surrounding tissue. Furthermore, it enables high-resolution data which ensures good reconstruction quality. Unfortunately, a high data resolution leads to

a large polygon complexity of the reconstructed vascular system. One popular way to reduce the rendering complexity is mesh reduction. However, this approach has serious acceptance problems in the medical community, due to quality losses in the course of the reduction. In contrast, we used a hardware-supported occlusion culling approach to guarantee interactive framerates of more than 15 fps. This approach does not inflict any quality losses and is well accepted by the physicians.
While virtual clips are already used in the daily practice of the Department of Neuroradiology, we have only preliminary experience using the virtual angioscopy system. However, guided navigation and interactive rendering was well perceived by our partners in the hospital. A clinical evaluation of the system will give more insights on the usability.

5 Conclusion and Future Work

In this paper, we presented a virtual angioscopy system, based on advanced segmentation using virtual clips and on a virtual endoscopy system. Interactive performance on a graphics workstation and intuitive handling was achieved using a visibility culling scheme and adopting the guided-navigation paradigm.

Hardware support for visibility culling is currently only available on HP fx4/fx6 graphics system and on the new SGI Visual PC. Unfortunately, these are not the systems which are typically found in a radiology department of large hospitals. Consequently, we will focus on using software-based occlusion culling algorithms to enable interactive angiogscopy even on low-end graphics workstations and PCs [9]. Another future focus will be the clinical evaluation of this system for angioscopy. Furthermore, other applications of virtual endoscopy will be explored.

Acknowledgements

This work has been supported by the MedWis program of the German Federal Ministry of Education and Research and by hardware of Hewlett-Packard Workstation System Lab, Ft. Collins, CO. Datasets were provided by the Department of Neuroradiology and the Philips Research Laboratory in Hamburg. Special thanks to Marion Strayle-Batra of the Department of Neuroradiology of the University Hospital in Tübingen for providing diagnostic support. Furthermore, we would like to thank Anders Kugler, Michael Meißner, and Mike Doggett for proof reading.

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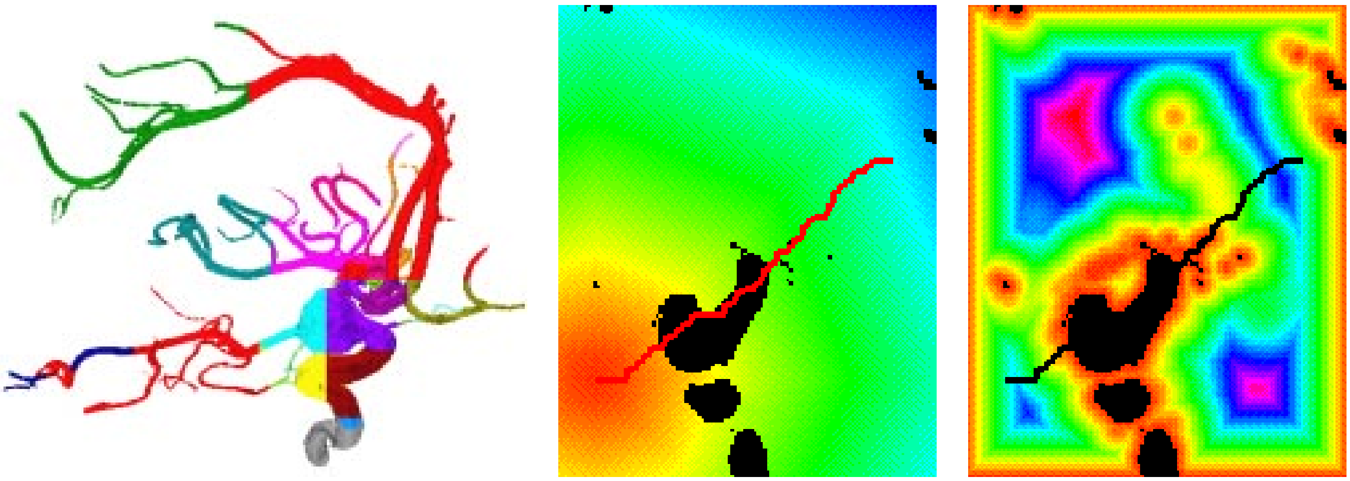
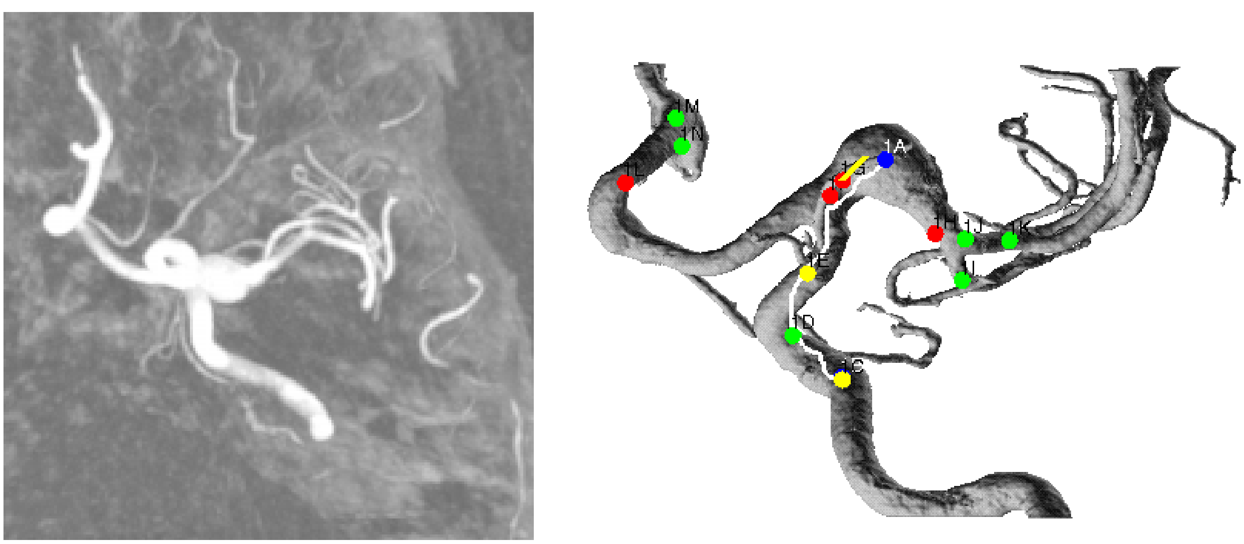


(a) (b) (c)

Figure 8: Preprocessing: (a) Octree decomposition of vasular system – different colors mark geometry of different octants. (b) Drift distance field to target point along camera path (red/black line is a 2D projection of path onto the displayed slice), (c) Surface distance field for collision avoidance.



(a) (b)

Figure 9: (a) Maximum Intensity Projection of rotational angiography dataset, (b) Snapshot from the Scout panel.