Local and Remote Visualization Techniques for Interactive Direct Volume Rendering in Neuroradiology[1]

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The increasing capabilities of magnetic resonance (MR) imaging and multisection spiral computed tomography (CT) to acquire volumetric data with near-isotropic voxels make three-dimensional (3D) postprocessing a necessity, especially in studies of complex structures like intracranial vessels. Since most modern CT and MR imagers provide limited postprocessing capabilities, 3D visualization with interactive direct volume rendering requires expensive graphics workstations that are not available at many institutions. An approach has been developed that combines fast visualization on a low-cost PC system with high-quality visualization on a high-end graphics workstation that is directly accessed and remotely controlled from the PC environment via the Internet by using a Java client. For comparison of quality, both techniques were applied to several neuroradiologic studies: visualization of structures related to the inner ear, intracranial aneurysms, and the brainstem and surrounding neurovascular structures. The results of pure PC-based visualization were comparable with those of many commercially available volume-rendering systems. In addition, the high-end graphics workstation with 3D texture-mapping capabilities provides visualization results of the highest quality. Combining local and remote 3D visualization allows even small radiologic institutions to achieve low-cost but high-quality 3D visualization of volumetric data.

Abbreviations: DICOM = Digital Imaging and Communications in Medicine, MCA = middle cerebral artery, MIP = maximum-intensity projection, SSD = shaded-surface display, 2D = two-dimensional, 3D = three-dimensional

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Introduction

Interactive three-dimensional (3D) visualization is a prerequisite for comprehensive analysis and understanding of volumetric data from computed tomography (CT) and magnetic resonance (MR) imaging. When one is dealing with a large number of high-resolution images, interactive multiplanar reformation is mandatory for a first inspection of the data (1,2). Investigation of complex 3D structures like the intracranial vasculature requires 3D visualization, which enables the investigator to follow the vessels and to simulate the display of digital subtraction angiography. These methods are called CT angiography and MR angiography and are widely used for investigation of intra- and extracranial vessels (3). In addition, 3D visualization is often helpful for surgical planning (4). However, there are no defined standards for application of 3D visualization tools, and the same data will give completely different information when presented with several visualization algorithms like maximum-intensity projection (MIP), shaded-surface display (SSD), and direct volume rendering (5,6). MIP and SSD have been widely used for visualization of medical data because these methods provide fast "volume rendering" by using only about 10% of the image data (7).

Owing to the rapid improvements in computer power and memory size in recent years, MIP and SSD are being replaced by direct volume rendering (8–10), which is now available on commercial workstations, allowing fast and direct 3D visualization of the complete information within volumetric data. There are enormous differences in the quality of images created with direct volume rendering, which depend on both hardware and software. Low-end, low-cost systems often provide inferior image quality in comparison with high-end systems. Since the technical development of computer hardware and software is incredibly fast, a visualization system should provide the user with good image quality and be inexpensive and thus easy to replace. New technical developments like the VolumePro board (Mitsubishi Electric, Tokyo, Japan) (11) or GeForce graphics boards (nVidia, Santa Clara, Calif) will soon enable real-time volume rendering with high quality even on personal computers.

In this article, two approaches to direct volume rendering are presented, which consist of a low-cost, PC-based direct volume-rendering system and a high-end graphics computer with hardware-accelerated sophisticated visualization software, remotely controlled from the PC system. These systems are combined into a low-cost, high-end 3D visualization tool. This method was applied to several neuroradiologic investigations, which are presented in this article.

Visualization Methods

General Considerations

The images provided by sectional imaging techniques (CT, MR imaging, ultrasonography) show the originally 3D objects in two-dimensional (2D) sections. It is up to the viewer to mentally reconstruct the structures (eg, bones, vessels, cranial nerves) from the section images. For a 3D display, the data have to be transferred to a workstation, where a volume is created out of the sections. Multiplanar reformation is an excellent tool for getting a better idea about the relations of 3D objects within a volume, especially when used interactively (12). Although multiplanar reformation is still a 2D method, it has the advantage that no information is lost. When an isotropic volume is used, axial, coronal, sagittal, and all kinds of curved planes can be reconstructed with the same quality as the source images (2).

There are several techniques for extracting the information of interest from a volume. In all of these methods, an imaginary ray from a defined viewing position is traced through the volume to a screen behind it, where the extracted object is displayed. The most commonly used methods for 3D visualization are MIP, SSD, and direct volume rendering. In the remainder of this section, we present the typical features of these methods, with a focus on the different ways of applying direct volume rendering.

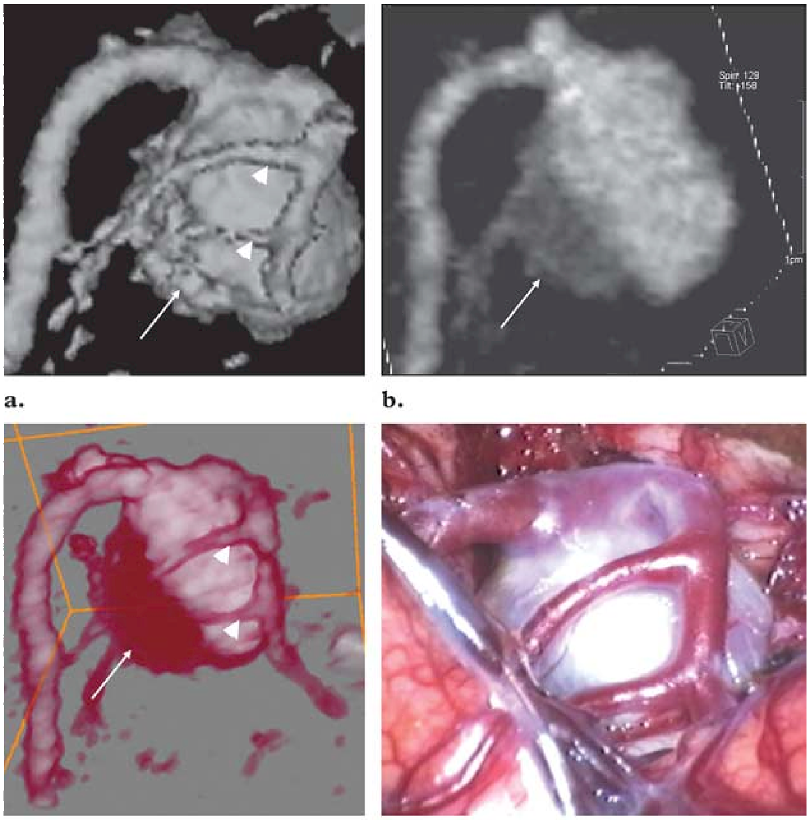
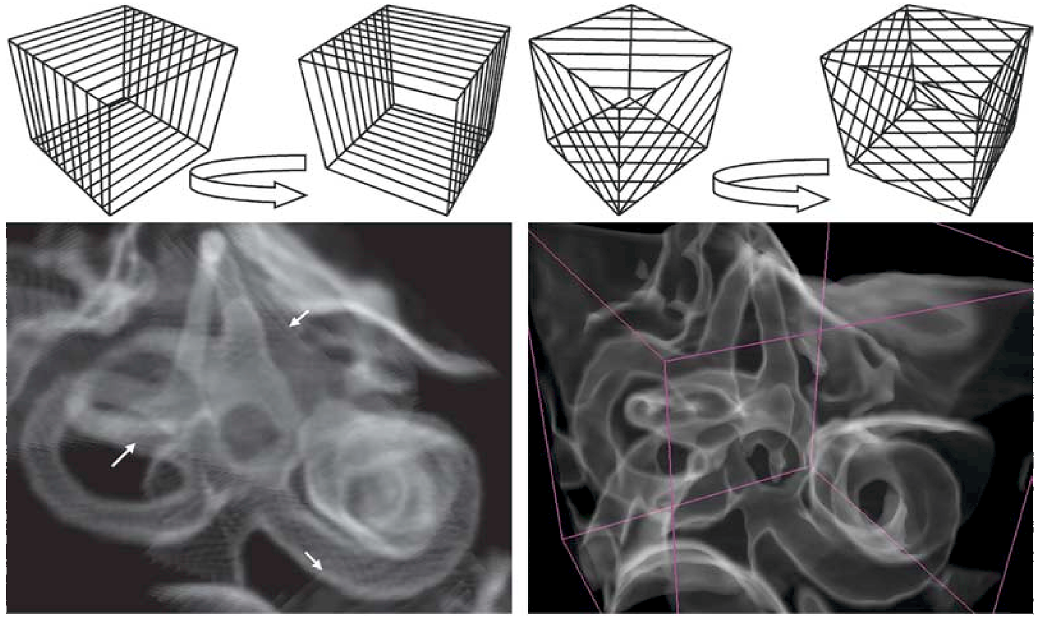


Figure 1. Demonstration of different results depending on the applied visualization technique. Detailed analysis of an intracranial aneurysm with partial thrombosis of the left middle cerebral artery (MCA) was performed, and the results were compared with intraoperative findings. SSD, MIP, and direct volume rendering were used to produce an anterolateral view (skull base on top). **(a)** SSD image shows the aneurysm and small MCA branches (arrowheads), thus providing good information about the shape of the aneurysm and related vessels (depth information). It is not possible to differentiate the thrombus (arrow) from the blood-filled part of the aneurysm (loss of brightness information). **(b)** MIP image shows the thrombus (arrow), thus providing some brightness information. The MCA branches are not visualized (loss of depth information). **(c)** High-resolution image created with direct volume rendering shows both the MCA branches (arrowheads) and the thrombus (arrow), thus providing brightness and depth information. **(d)** Photograph shows intraoperative findings. (Fig 1d courtesy of Michael Buchfelder, MD, University of Erlangen-Nuremberg, Germany.)

M P and SSD

MIP and SSD are still widely used for 3D visualization of volumetric data (Fig 1a, 1b). A feature they have in common is that only one layer of voxels within the volume is used for visualization (2,9), leading to loss of information. With MIP, only one layer of the brightest voxels parallel to the viewing ray is used for display. All other information is ignored. Thus, from a given viewing direction, it is possible to get some information about the brightness of an object (eg, differentiation of calcification and a contrast material–filled blood vessel), but the depth information is lost (we cannot say what is in front or behind) (Fig 1b).



a. b.

Figure 2. Effect on image quality of different algorithms for direct volume rendering. **(a)** Top: Diagram shows an approach based on bilinear (2D) interpolation, which requires three copies of the original volume consisting of sections in three orthogonal directions (object aligned). The volume with sections most parallel to the viewing plane (the view port) is chosen, depending on the viewing direction. Bottom: Anteromedial view of the inner ear created from spiral CT data with this approach clearly shows line artifacts (arrows). The best image quality is achieved when the viewing direction is parallel to one of the planes. **(b)** Top: Diagram shows trilinear (3D) interpolation, which allows rendering of sections parallel to the viewing plane, independent of the viewing direction ("view port aligned"). Bottom: Corresponding anteromedial view shows the structures of the inner ear without artifacts.

The opposite is true for SSD. This technique uses the first layer of voxels lying within defined threshold values for display (2,9). Thus, the brightness information is lost. For example, differentiation of calcification or thrombosis within a blood vessel is not possible (Fig 1a). However, the depth information is preserved. When an artificial light source is used (shading), SSD gives a good impression of the shape of a 3D object.

Owing to these limitations, image analysis should not be based on MIP or SSD images alone. Since the information provided by MIP and that provided by SSD complement each other, the methods can be combined if direct volume rendering is not available. Within the medical community, there is still some confusion about the nomenclature of "volume-rendering" techniques. From the point of view of a computer scientist, MIP and SSD are types of volume rendering in which only one layer of voxels is used for visualization. In the medical literature, the term *volume rendering* is reserved for the technique described next, in which all voxels of a volume are considered for visualization.

Direct Volume Rendering

Direct volume rendering uses all of the information contained in a volume; thus, there is theoretically no unwanted loss of information (9). By assigning a specific color and opacity value to every attenuation or signal intensity value of the CT or MR imaging data, groups of voxels are selected for display. The information from all of these voxels is collected along the viewing ray, and the information from every voxel is integrated into the resulting image on the screen. Meaningful 3D representations of even overlying structures like intracranial vessels within the skull are possible, depending on the selected opacity (high opacity produces low transparency and vice versa). Both brightness information and depth information are presented (Fig 1c).

There are various rendering algorithms for both the PC and the high-end workstation. The popular "shear-warp" approach (13) is often used in commercially available workstations. In this approach, the sections of a volume are set parallel to the coordinate axes of the rectilinear volume data grid ("object-aligned" sections) (Fig 2a). A 2D texture-based variant of the shear-warp algorithm was used for our local PC-based direct vol-

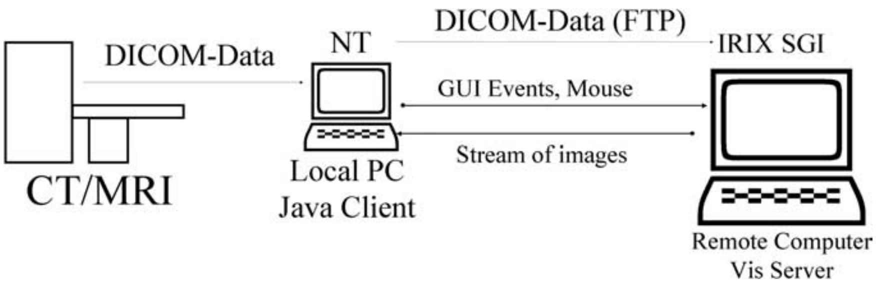


Figure 3. Diagram of the data stream in a local network. The DICOM images obtained with a CT scanner and MR imager are transferred to the local PC. Then, the image data are transferred to the visualization (*Vis*) server, which is remotely controlled from the PC environment via the Java client. *FTP* = file transfer protocol, *GUI* = graphical user interface, *IRIX SGI* = IRIX operating system (Silicon Graphics, Mountain View, Calif), *NT* = Windows NT (Microsoft, Redmond, Wash).

ume-rendering system. This approach requires us to keep three copies of the data set in the main memory, one set of sections for each section direction. Despite the high memory requirements, the major drawback of the 2D texture-based implementation is the missing spatial interpolation. As a result, the images contain visual artifacts, especially when small objects are visualized and zoomed closely (Fig 2a). The image appearance can be improved by using 2D multitexture interpolation, in which additional sections are calculated (14).

If 3D textures are supported by hardware, it is possible to render sections parallel to the image plane with respect to the current viewing direction (Fig 2b). However, if the viewing matrix changes, these view port–aligned sections must be recomputed. Since trilinear texture interpolation is supported by the hardware of the remote workstation, it can be performed at interactive frame rates without distracting artifacts (15).

Materials and Methods

Local Volume Rendering

For local rendering, a desktop PC (Pentium III processor [Intel, Santa Clara, Calif], 500 MHz, 128 Mbytes of random-access memory) equipped with a GeForce256 graphics adapter (nVidia) with 32 Mbytes of double-data random-access memory was used as the local client. The client application was implemented with Java and Java3D. Java, a programming language for the Internet (16), allows one to use the same application from any kind of machine: a PC, a Macintosh (Apple Computer, Cupertino, Calif), a network computer, or even new technologies like personal digital assistants (PDAs) or Internet screen phones (17). This platform independence allows visualization of volume data with any device with minimal graphics capabilities, anywhere in the world. Local rendering makes use of Java3D, the 3D extension of the Java programming language. An approach similar to the shear-warp approach that makes use of locally available, low-cost 2D texture-mapping hardware was realized. First, the data from CT and MR imaging were electronically retrieved from the imagers via a local-area network and a Digital Imaging and Communications in Medicine (DICOM) interface (Fig 3). The personal data of the patients were removed from the image headers for data protection and privacy.

The Java client displays the data in a sectioning tool, which allows inspection of the section images. A subregion of the data can be selected and visualized in 3D with the Java3D renderer. A frame rate of three to eight frames per second is possible with this setup, depending on the data size.

Since Java3D is a platform-independent graphics programming interface, it does not allow use of the special features of modern low-cost graphics adapters. The advances of these graphics adapters, which were mainly developed for computer games, are enormous. To make use of the newest rendering features, like multitextures, we also developed a client based on the C++ programming language and the OpenGL standard that allows us to access the graphics hardware directly, without the additional abstraction layer introduced by Java3D. This client provides even better image quality and rendering speed due to the use of multitexturing hardware for trilinear interpolation (14).

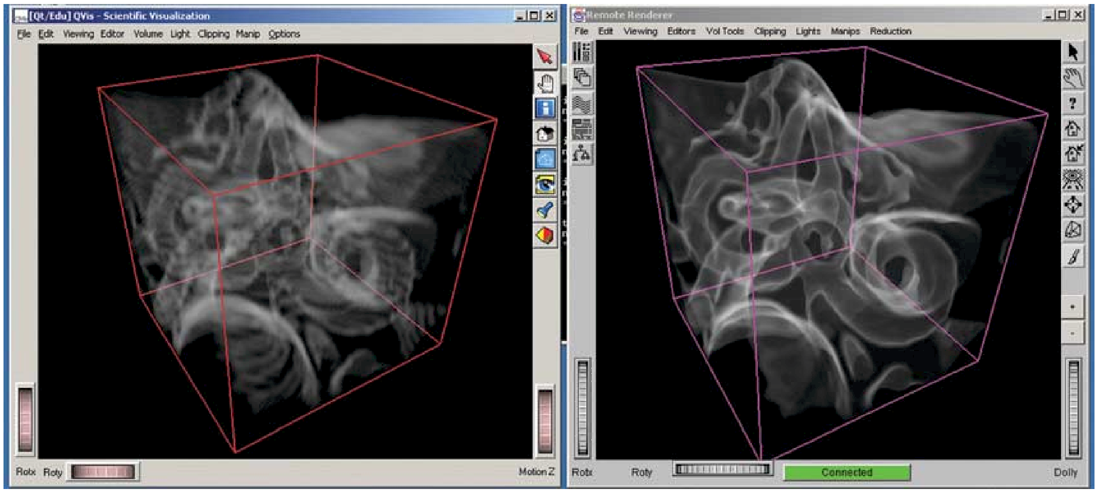


Figure 4. Anterolateral view of the inner ear created from CT data with direct volume rendering. Computer screen shows the results of local (left) and remote (right) rendering within a Microsoft Windows environment. The difference in image quality is obvious. Although the local renderer offers real-time interactivity, the performance of the remote renderer depends on the Internet connection. In our experimental setup, frame rates of three frames per second could be achieved.

This approach allows use of a low-cost PC connected to the MR imager and CT scanner and provides the user with good interaction capabilities due to small latencies. However, it yields reduced image quality when compared with special-purpose high-end graphics hardware.

To enable the user to access remotely available high-end graphics hardware, the Java client also allows one to display and interact with remotely generated images (Fig 4). For this purpose, the volume data have to be transferred from the local machine to the remote visualization server.

Remote Volume Rendering

The remote 3D visualization was performed on an Octane workstation (R10000 processor, 250 MHz) with MXE graphics hardware (Silicon Graphics), which provides 4 Mbytes of texture memory. Rendering was performed with the 3D texture-mapping hardware of the graphics workstation, which allows high image quality and high interaction rates. These results are possible due to the trilinear interpolation of the original data provided by the 3D texture hardware and the high-resolution shading provided by postinterpolation lookup tables.

The local PC uploads the data to the remote graphics workstation via the Internet. In our setup, we used a fast Internet connection (155 Mbits/sec) provided by the German research network. For a CT angiography data set of 150 images, about 3 minutes of upload time was necessary. Once the data are loaded into the graphics server, the visualization process is interactively controlled from the local PC via the Java-based client (18) (Fig 3). Mouse interactions and keyboard input are sent from the local PC to the workstation, which immediately renders new images and sends a stream of resulting images back to the PC (19). The images are compressed for the network transfer to allow remote visualization on low-bandwidth network connections. We tested a number of different connections, ranging from high-speed research networks down to Integrated Services Digital Network (ISDN) connections.

The data size and image size of this setup allow frame rates of up to 10 frames per second, depending on the data exchange rate. In our experimental setup, with the local PC in Erlangen, Germany, and the workstation located in Stuttgart, 200 km away, we achieved an average frame rate of three frames per second using standard Internet access via the German research network. When this approach was presented at the RSNA meeting in Chicago, Ill, in November 2000, a frame rate of about one frame per second was achieved between the PC located in Chicago and the workstation in Stuttgart.

Remote volume rendering allows the sharing of expensive remote graphics hardware via the Internet by using a simple client computer. By connecting more clients to the rendering server, the collaboration of many experts from different locations is possible. However, owing to signal propagation delays, latencies are introduced, which are noticeable as a delayed reaction to user input. Especially for the remote visualization setup in Chicago, this was the main drawback. Combining the local and remote visualization approaches can prevent these latencies. During interaction, local graphics hardware is used to provide low latencies and fast rendering. After the user stops interaction, an image with high resolution and high quality is requested from the remote graphics workstation.

Neuroradiologic Studies

For comparison of the local and remote direct volume-rendering systems, we used the CT angiography data of five patients with intracranial aneurysms and the MR imaging data of two patients who had been examined for suspected neurovascular compression syndromes. The CT studies were performed on a multisection spiral CT scanner (Somatom Plus4 VZ; Siemens, Erlangen, Germany) with the following parameters: collimation = 4×1 mm, table feed = 2.7 mm per rotation, section thickness = 1.25 mm, increment = 0.5 mm, field of view = 120 mm^2, 100 mL of contrast medium, flow rate of 4 mL/sec. The MR imaging studies were performed on a 1.5-T system (Magnetom Symphony; Siemens) by using a 3D constructive interference in the steady state (CISS) sequence with 0.7-mm-thick sections.

For the CT angiographic studies, additional reconstruction of the temporal bones was performed (field of view = 60 mm^2, high-resolution kernel) so that these data could be used for visualization of the structures of the inner ear.

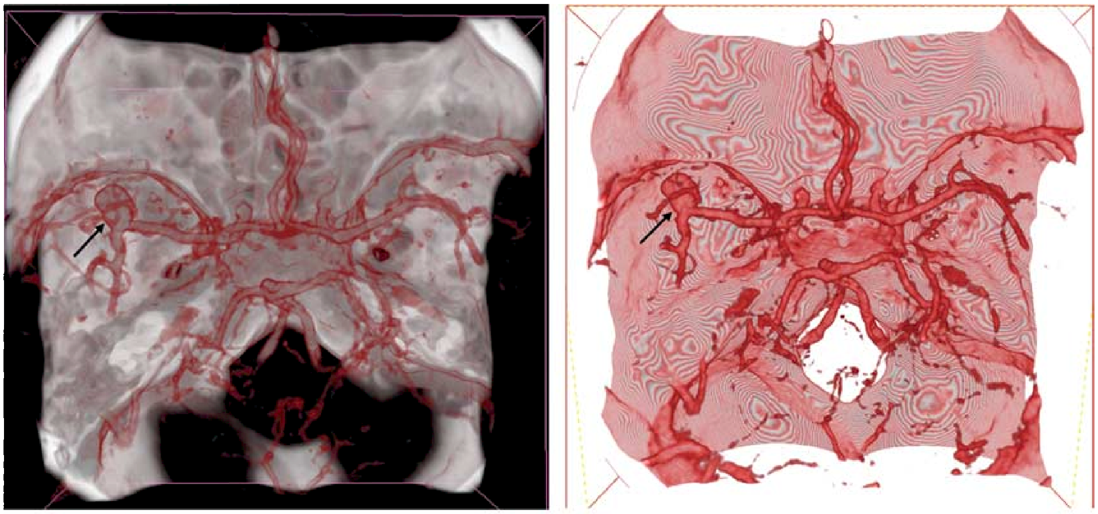
Results

To demonstrate the difference in visualization quality between the two volume-rendering systems, we applied the methods to visualize the structures of the inner ear and intracranial aneurysms from spiral CT data and for 3D display of neurovascular structures surrounding the brainstem from MR imaging data. Three-dimensional visualization of the inner ear from CT data performed with direct volume rendering without explicit segmentation requires optimal quality to obtain clear and meaningful images (20). Thus, this is a suitable application for getting an impression of the visualization capabilities of a direct volume-rendering system. As mentioned earlier, we used spiral CT scans of the normal temporal bone. The small field of view of 60 mm^2 not only leads to better in-plane resolution but also allows preselection of the subvolume containing mainly the required information. Figures 2 and 4 demonstrate the results achieved with both systems. Although the PC-based system provided a coarse display of the inner-ear structures due to interpolation artifacts, these structures can be recognized much more clearly on images created with the high-end graphics system by using trilinear interpolation.

To investigate the use of the two systems under routine conditions, the CT angiography data of the five patients with intracranial aneurysms were transferred to both the local and remote workstations directly after the investigation. The average time for the complete visualization process in our experimental setup, including data transfer, was 15–25 minutes, depending on the complexity of the vascular structures. This is already fast enough for this method to be used in the clinical situation of a patient with subarachnoid hemorrhage under emergency conditions. CT angiography is a well-known tool for therapy planning of intracranial aneurysms. In contrast to the results achieved with digital subtraction angiography, not only the shape of the aneurysms but also the relation to the skull base, thromboses, and calcifications are clearly demonstrated (21–24). An optimal quality of 3D images is mandatory for extracting all available information from the data. As demonstrated in Figure 1, MIP and SSD can be used in combination to demonstrate both the brightness and depth information of the data. However, only direct volume rendering has the capability of showing the complete information in a single 3D image. For therapy planning, high-quality close-up views are important.

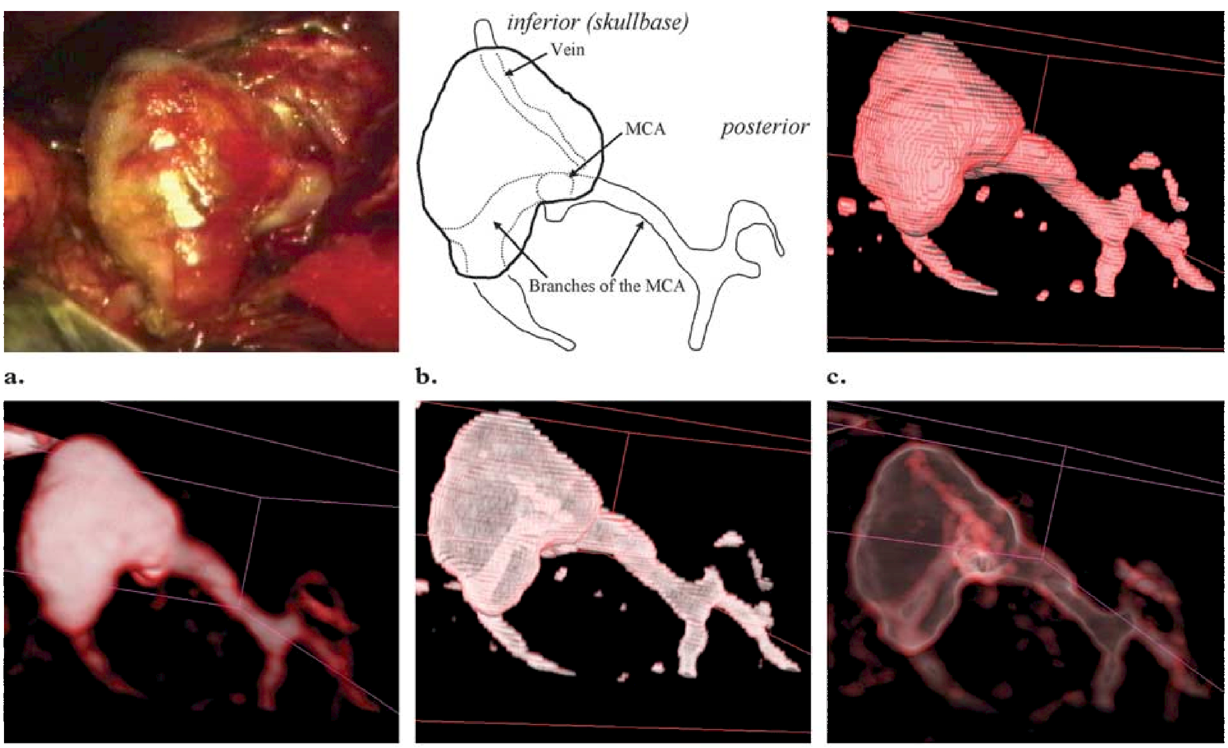
In our setup, the PC-based system was used to get fast information about the shape and location of an aneurysm with real-time interaction. Once the ideal viewing position for therapy planning was found on the PC system, the selected area was remotely evaluated on the high-end system and high-resolution 3D images were created. The performances of both systems in visualization of intracranial aneurysms were compared (Figs 5, 6). Although the PC-based system allowed very fast, real-time visualization of good quality, the close-up views were still disturbed by line artifacts. The high-end workstation produced clearer images that showed more detail information, especially on the semitransparent images. The ability to create semitransparent images that show even structures lying behind the aneurysm without choosing another viewing position is an advantage of the remote rendering system. This capability can be used to demonstrate hidden structures from the viewpoint of the neurosurgeon's surgical microscope. Of course, the ability to interactively move the structures rather than looking at static images like those in Figure 6 supports detail analysis.

Figure 5. Comparison of two different direct volume-rendering systems applied to visualization of an intracranial aneurysm of the left MCA (arrow). **(a)** Superior opaque view created with the remote high-end system shows the vessels and skull base. **(b)** Corresponding view created with the PC-based system shows more artifacts within the skull base. There is no significant difference in quality in the visualization of vascular structures.



a. b.

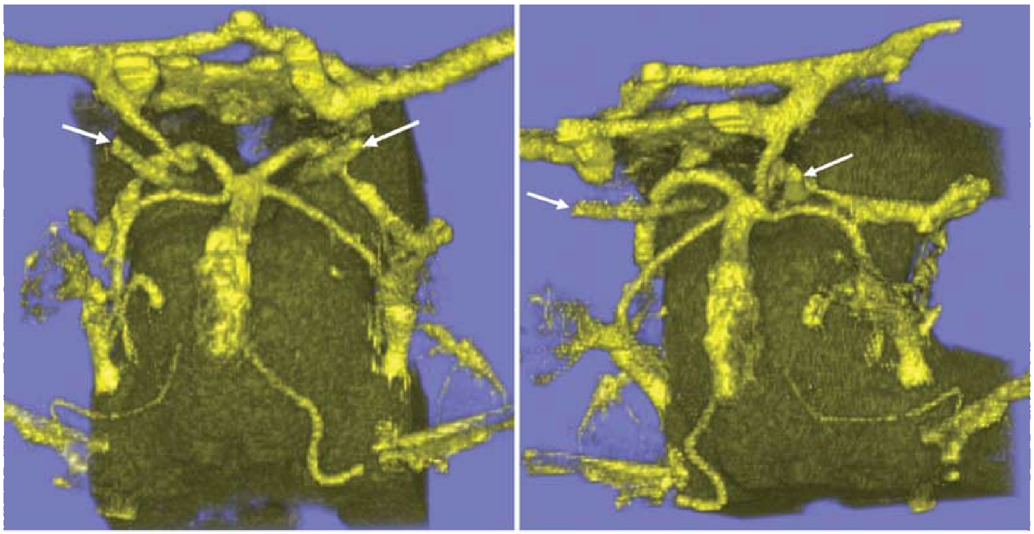
Figure 6. Comparison of two different direct volume-rendering systems applied to detailed analysis of an intracranial aneurysm of the MCA. All images are lateral views. **(a)** Image from the intraoperative video shows the neurosurgeon's view. The large aneurysm hides adjacent vessels, thus necessitating surgical manipulations to obtain more information. (Courtesy of Christian Strauss, MD, University of Erlangen-Nuremberg, Germany.) **(b)** Diagram shows the aneurysm and adjacent vessels. **(c)** Opaque image created with PC-based direct volume rendering clearly shows the shape of the aneurysm. However, the image quality is reduced by line artifacts. **(d)** Opaque image created with the suggested remote direct volume-rendering approach shows the aneurysm without visible artifacts. **(e)** Transparent image created with PC-based direct volume rendering shows only a rough outline of the vasculature behind the aneurysm due to artifacts. **(f)** Transparent image created with remote direct volume rendering shows a view "through" the aneurysm, thus providing additional information about the adjacent vasculature.



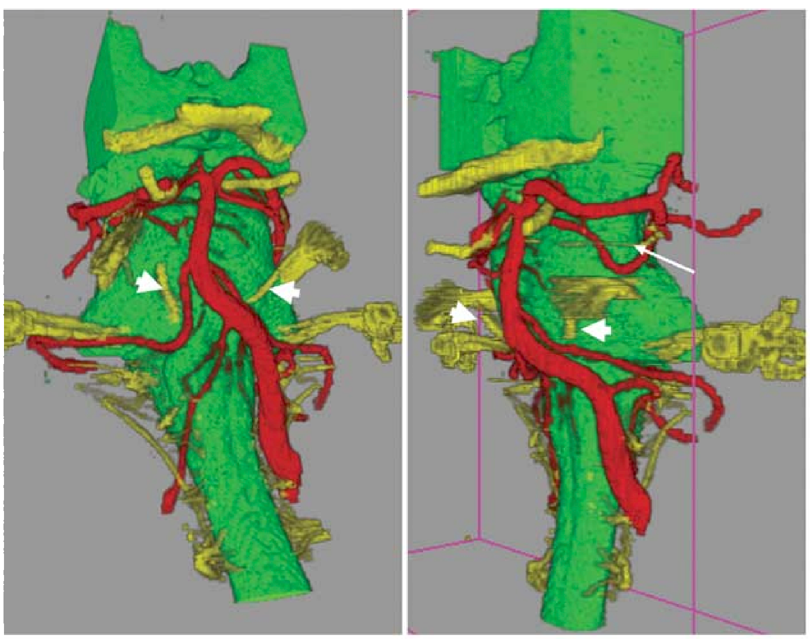
a. b. c.

d. e. f.

Figure 7. Three-dimensional visualization of the cranial nerves from the MR imaging data of two patients. Frontal (left) and frontolateral (right) views were created. Two subvolumes had been created prior to the visualization, which contained the brainstem and the structures within the cerebrospinal fluid space. **(a)** Image created with PC-based direct volume rendering shows the larger structures adjacent to the brainstem, such as the oculomotor nerves (arrows), as well as the space between the posterior cerebral artery and superior cerebellar artery. It is not possible to visualize very small structures like the trochlear nerves. **(b)** High-resolution image created with remote direct volume rendering shows the brainstem and related structures. Even very small structures like the trochlear nerve (thin arrow) and the abducent nerves (thick arrows) are visible. The remote system allows assignment of different colors to differentiate nerves (yellow) and vessels (red).



a.



b.

To evaluate the capabilities of the two visualization systems for MR imaging data, we used the data of the two patients investigated for suspected neurovascular compression syndromes (25). For a better understanding of the 3D relationships of the small neurovascular structures in the area of the brainstem, we used direct volume rendering following semiautomatic segmentation, which created subvolumes of the brainstem and the structures within the cerebrospinal fluid space (26). The PC-based system was able to create meaningful 3D images of sufficient quality that clearly demonstrated the relationships of the neurovascular structures (Fig 7). However, the close-up views demonstrated the typical line artifacts, so that very small structures like the trochlear nerve could not be identified. The images created with the high-end system demonstrated the trochlear nerve in both cases, thus allowing higher-quality visualization.

Both systems allowed interactive manipulation of the data, with some latency when the remote system was used. Nevertheless, frame rates of three frames per second could be achieved, which is sufficient for fine-tuning following fast, real-time visualization of the volume on the PC-based system.

Discussion

The quality of 3D visualization depends on multiple factors. Of highest importance is the quality of the source images. Although in-plane resolutions of less than 0.5 mm are easily achieved with modern CT scanners and MR imagers by using a 512^2 matrix and a narrow field of view, the through-plane resolution in most studies will be greater than or equal to 1 mm. Therefore, in clinical practice, real isotropic voxels in a volumetric data set are an exception. When spiral CT is used, this problem can be overcome to some degree by using smaller reconstruction increments (eg, 0.5 mm), leading to higher visualization quality at the cost of a greater number of images; however, at this time, this technique is reasonable only for small volumes to allow interactive manipulation within the renderer. For small volumes, even a collimation of 0.5 mm is technically possible when multisection CT is used (1).

Use of a narrow field of view not only provides higher in-plane resolution but also leads to presegmentation of the volume, reducing it to data of diagnostic interest and thus facilitating 3D visualization. It is often useful to create two data sets, with the first containing the whole examined volume and the second containing mainly the information of interest. When using CT angiography for investigation of intracranial aneurysms, we first reconstruct the raw data from the whole circle of Willis (field of view = 120 mm^2) and then create a data set containing the detected aneurysm within a narrow field of view (eg, 60 mm^2), which facilitates detail analysis. An optimal volume would contain nothing more than the structures to be visualized.

It is often stated that with volume rendering there is no information loss from the volume data and extensive editing and segmentation are not necessary (8,9). In fact, at this time, some of the commercially available products are not able to handle large numbers of high-resolution images; therefore, reduction of the image matrix to 256^2 is often used for faster manipulation of the data and thus less need of memory. Obviously, this technique leads to information loss and reduced quality of the 3D images, which are unfavorable factors when dealing with small objects, as in neuroradiologic studies.

The quality of the 3D images depends strongly on the applied hardware and software. There is a difference between rendering algorithms like the shear-warp algorithm (13), which is based on 2D texture mapping, and the more challenging 3D texture mapping used in our remote workstation, which requires specific hardware acceleration (15). At this time, only 3D texture mapping results in artifact-free visualization of small structures due to the calculation of parallel planes according to the viewing position. The quality of visualization based on 2D texture mapping can be enhanced by the interpolation of intermediate sections, leading to clearer images (14).

When one is dealing with very small objects, like the examples shown in this article, some kind of segmentation will always be necessary (6). In most cases, segmentation can be performed sufficiently by using clip planes, which can be used interactively to eliminate parts of the volume to give a clearer view of deeper-lying structures. For visualization of intracranial arteries from CT angiography data, it is always necessary to eliminate the upper parts of the venous system to give a free view to the basilar artery when one is looking from above. Direct visualization of the cranial nerves from MR imaging data was possible to some degree, but the results were not sufficient to provide enough information about the relationships of the neurovascular structures. By semiautomatically creating two subvolumes of the brainstem and the surrounding cerebrospinal fluid space, the visualization results were of much better quality.

The presented approach offers many advantages. First, it is cost-effective, since expensive specialized workstations are no longer necessary for every institution. Owing to the mass market of computer games and entertainment software, PC graphics accelerator boards have become more flexible and powerful. A low-cost PC system equipped with a high-end graphics adapter (cost about $300) is sufficient to provide satisfactory direct volume-rendering visualization for routine studies. In the near future, even hardware-accelerated 3D texture mapping will be possible on standard PC systems (14). In cases in which the highest quality is essential, the high-end hardware and software can be accessed from the local system via the Java client. Since many users can use the high-end workstation, conferences about case studies are possible. Remote rendering allows access to expensive high-end graphics workstations with any Java-enabled device from anywhere in the world (16,17). Therefore, it is theoretically possible to view and manipulate the images via a mobile phone. The client has to be able only to display remotely generated images and send interaction events. Remote rendering introduces a higher latency due to the transfer of user commands from the client to the server and the transfer of rendered images back to the client. To avoid this latency, we experimented with a combination of local and remote rendering. During interaction with the data, local 3D graphics hardware is used for image generation. After the interaction, a high-quality image from the server is requested and displayed (18).

Remotely controlled visualization also allows the neurosurgeon to obtain a position-controlled view of the surgical situation (22) without the need for expensive high-end hardware. It will also be possible to integrate this information into the surgical microscope of the microsurgeon.

Although interactive use of 3D visualization is often helpful, it has the limitation of being user dependent and thus leading to inaccurate results (9). In the future, standardized visualization tools, with which defined video sequences are produced that can be evaluated for sensitivity and specificity, should replace individual interactive 3D visualization. These standard tools can be provided by remotely accessed workstations. In addition, specialists who could also provide the local institution with a report could evaluate the findings.

Conclusions

The approach of combining a local, low-cost, PC-based volume-rendering system with a remotely accessed high-end graphics workstation makes this fascinating and promising tool for 3D visualization available to all institutions dealing with volume data. In the near future, even high-quality visualization will be possible on standard personal computers equipped with modern graphics adapters. The ability to access these workstations from almost anywhere will help radiologists develop new applications for standardized 3D visualization.

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