AJNR

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AJNR Am J Neuroradiol 1997, 18 (3) 417-420
http://www.ajnr.org/content/18/3/417

Methods for Displaying Intracerebral Vascular Anatomy

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Summary: We are developing three-dimensional imaging methods to portray vascular anatomy better, including noise-free display of vessels extracted from 3-D data sets, tree-based display, and reconstruction of angiographic data (preliminary work has resulted in the successful reconstruction of aneurysms from angiographic data). Fast, interactive display permits real-time manipulation of viewing orientation.

Index terms: Computers; Images; Magnetic resonance angiography

It is essential for the vascular neurosurgeon to be able to see intracranial vessels in three dimensions. Unfortunately, no ideal imaging method exists for this purpose. Magnetic resonance (MR) angiography and computed tomographic (CT) angiography are noisy and may omit critical data, including small but surgically important vessels; up to 15% of aneurysms; and portions of arteriovenous malformations (1–4). Projection angiography provides more surgically relevant information, but overlapping vessel projections are difficult to see in 3-D. We are therefore developing new methods by which to display complex vascular anatomy. Features of this new technique include display of vessels extracted from MR angiographic or CT angiographic data sets to provide noise-free projection images, tree-based display methods to permit the highlighting or exclusion of subtrees, and 3-D reconstruction of angiographic data to add vascular information missing from MR or CT angiograms. Preliminary work on these methods has enabled reconstruction of aneurysms from angiographic data, with insertion of the aneurysm into a set of extracted MR angiographic vessels.

Methods

Time-of-flight 3-D MR angiography was performed with a 1.5-T unit with imaging parameters of 38/7/1 (repetition time/echo time/excitations). Voxel size was $0.06 \times 0.06 \times 0.1$ cm. Anteroposterior, lateral, and oblique angiograms were also obtained. Images were digitized by laser scanner.

Segmentation of MR Angiographic Data

MR angiographic segmentation was performed by means of a core-based method (5, 6). Given a user-supplied seed point and an estimate of object width, core analysis automatically extracts an object from even noisy 2-D or 3-D images. MR angiographic data sets are displayed in sections. The user identifies a point within a vessel by mouse click, and the 3-D vessel is then automatically extracted at subvoxel resolution. Vessels often contain hundreds of points and course through multiple sections. It takes approximately 25 minutes to extract 110 vessels on a DEC 5000/200 unit. No precomputation is required (S. Aylward, S. Pizer, E. Bullitt, D. Eberly, "Intensity Ridge and Widths for Tubular Object Segmentation and Description," presented at the IEEE Workshop Mathematical Methods in Biomedical Image Analysis, June 1996).

Segmentation accuracy was tested by simultaneously displaying the original MR angiogram with the set of segmented vessels using a program that displays two fused images in different colors and from any interactively selected angle. Spurious or missing vessels could thus be identified.

Tree Creation from Segmented MR Angiographic Vessels

Tree creation is performed by means of a postprocessing program that takes segmented vessels as input. Vessels are displayed in three windows as anteroposterior, lateral, and axial projections and can be viewed from any user-selected angle in a fourth window. The user can pick any number of vessel roots. The program then generates

Received February 21, 1996; accepted after revision July 8.

Supported in part by grant 1P01 CA47982, "Medical Image Presentation" from the National Cancer Institute, National Institutes of Health.

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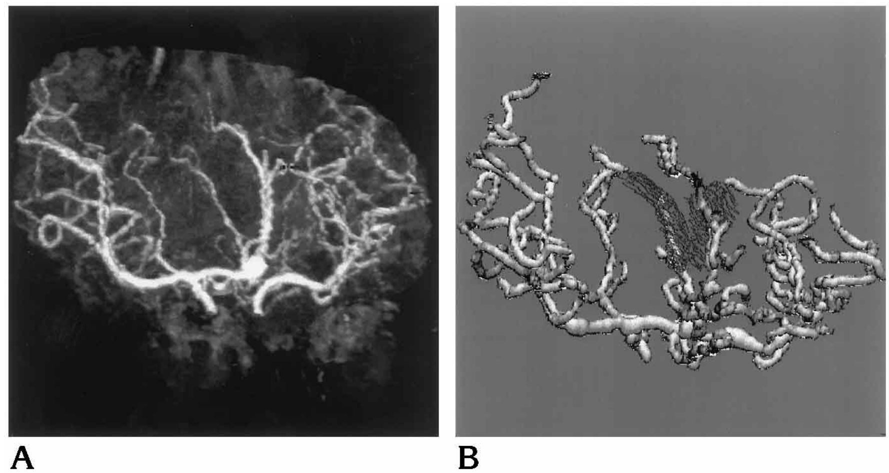


Fig 1. Projection of an MR angiographic data set (*A*) and of a set of segmented vessels (*B*) from similar viewing angles. The MR angiogram has been intensity-windowed so as best to show the vessels. There is considerable background noise. Although different settings can reduce noise, holes will appear in some vessels and other vessels will disappear. Segmented vessels were tiled with triangles and surface-rendered with Gouraud shading. The display is noiseless and contains over 90% of the MR angiographic vessels.

vessel trees automatically from these roots by iteratively selecting the orphan with an end point that is the shortest 3-D distance from any vessel already part of a tree. The orphan connects to this closest available point, becoming part of the tree. The process terminates when no orphans remain or when a preset maximum jump distance exceeds that required by all remaining orphans. Each vessel keeps a list of its offspring. A subtree from a given vessel is determined recursively so that, during display, a user-selected vessel and all its descendants can be painted in a distinctive color or not shown.

Reconstruction of Angiographic Data

Traditional 3-D imaging techniques omit important vessels. It is therefore worthwhile to reconstruct angiographic data into 3-D. We have developed a multistep process for reconstructing angiograms that includes segmentation of MR angiographic and conventional angiographic data, registration (alignment) of an MR angiogram with each of a pair of angiographic images, and reconstruction of uncorrelated angiographic data into 3-D, using the extracted MR angiographic vessels to provide an initial set of parent vessels upon which to build reconstructed angiographic data (7).

MR angiographic segmentation methods were described above. The 2-D images are segmented by a similar point-and-click method (8). We Have also developed a core-based 3-D/2-D registration method that uses vessels as a registration basis. Hundreds of vessel points at subvoxel and subpixel resolution are used during registration, making this method more accurate than traditional methods that are based on a small number of fiducial markers.

We have also delineated methods of automatic curve- and pixel-pairing to reconstruct 3-D curves and have reconstructed a middle cerebral tree in phantom data (7). Fast algorithms providing high spatial resolution are available. We have not corrected for MR distortion and so have not attempted wide-volume reconstruction requiring global registration. As aneurysms can be recognized on both views, however, only local registration is required.

For this study, we extracted MR angiographic vessels adjacent to but not including the aneurysm. Vessels were registered with all three angiographic views, providing local registration in the region of the aneurysm. The aneurysm was extracted from each 2-D image and reconstructed three times, using all three image pairs. If the aneurysmal neck can be seen on two views it can be reconstructed as a separate vessel. In this case, the neck was only visible on one view. However, the reconstruction process includes automatic connection to a 3-D parent vessel, thus providing a reasonable approximation of the neck even if the neck cannot be defined on two views. In this case, the aneurysm was reconstructed from the angiographic data alone; the neck was defined by automatic connection of the aneurysm to its parent vessel. The program automatically calculates the width of a reconstructed vessel from its 3-D spatial location and its width on projection views.

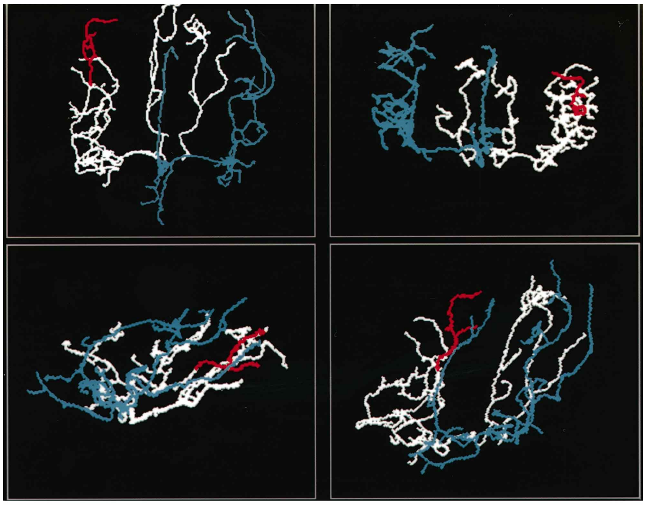
Reconstruction accuracy was tested by comparing the coordinates of the reconstructed and segmented aneurysms. Comparison was also made between projections of the reconstructed aneurysm and aneurysmal neck with the three angiographic images and with projections of MR angiographic data.

Display

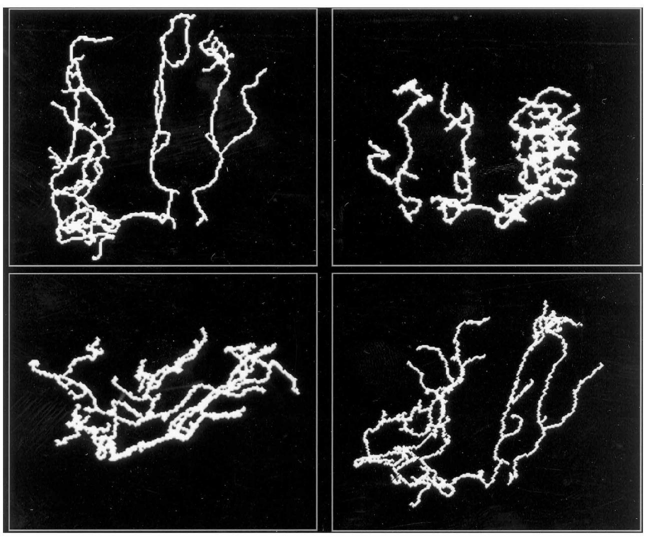
For the surgeon, segmented and reconstructed vessels are displayed using a Silicon Graphics (Mountain View, Calif) Reality Engine, permitting the user to change the point of view in real time. A number of display options are available. A wire frame model of the ventricular system aids orientation.

Results

Figure 1 shows the MR angiographic data set and a full set of segmented vessels from the same projection angle. The segmented data set is noiseless and contains over 90% of the MR angiographic vessels. No spurious creations



A



B

Fig 2. Capabilities of tree-based display. Four views are shown simultaneously. Trees have been created automatically by the use of both M1 segments and both posterior cerebral arteries as roots. In *A*, the user has requested highlighting of the tree associated with one M1 segment (blue) and of a contralateral middle cerebral branch (red). In *B*, the user has requested that the M1 tree be eliminated from display.

were found when the set of extracted vessels was compared with the MR angiogram.

Figure 2 shows the vessels of Figure 1 in a tree-based display. A tree is highlighted in blue and a branch in red in Figure 2A. Highlighted structures are easily recognized from any angle. In Figure 2B, the previously highlighted tree was omitted from display at the operator's request. This feature can be used to remove veins from CT angiographic data or to prevent surrounding anatomy from obscuring relevant details.

When the reconstructed aneurysm was compared with the segmented aneurysm, the center of the reconstructed aneurysm lay in the same voxel in one case and in an adjacent voxel in the other two cases. Superimposition of projections showed excellent agreement of the reconstructed aneurysm with both MR angiographic and conventional angiographic data. The reconstructed neck had the thickness of the parent vessel but was otherwise correct. Figure 3 shows one of the reconstructed aneurysms together with the adjacent, segmented vessels in our surgical display tool. Figure 3D shows these vessels from the most likely angle of surgical approach.

Discussion

Our intent is to create a vascular display program that can be used both for preoperative planning and intraoperative guidance. There are several advantages to our methods. First, segmented and reconstructed vessels can be shown without the noise of MR angiography or the veins and bones shown by CT angiography. Second, tree-based displays enable any vessel or subtree to be highlighted or removed from display. Highlighting is useful for teaching anatomy or for separating arteries from veins in planning treatment for arteriovenous malformations. Omitting subtrees prevents obscuration of areas of interest. Tree creation is not possible without the use of segmented or reconstructed data.

The final display permits the user to interactively change the point of view in real time. The surgeon can thus inspect an aneurysm and surrounding vessels unimpeded by surrounding structures and from any angle, including that of the surgical approach, so as to assess the relevant anatomy quickly (Fig 3).

Our goal is to provide 3-D reconstruction of vessels that are important to surgical planning but that are seen only by angiography. This article describes progress toward that goal, including segmentation of over 90% of MR angiographic data (Fig 1), tree creation, including even the most peripheral branches (Fig 2), and reconstruction of aneurysms from angiographic studies (Fig 3). This last capability is useful in cases in which aneurysms cannot be seen by traditional 3-D acquisition techniques. The final display program required a high-level workstation; all other modules run well on standard workstations.

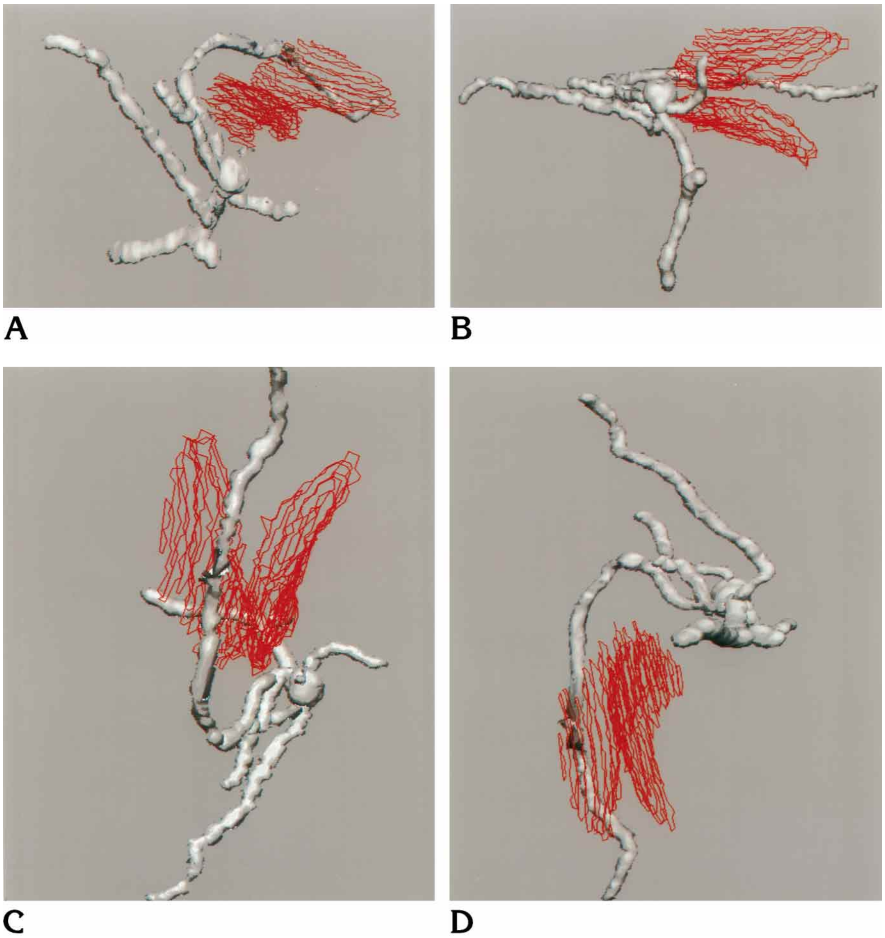


Fig 3. Reconstructed aneurysm added to a set of segmented vessels as seen from several viewing angles. The tree-creation and branch-selection program was used to include only those vessels likely to be seen during a surgical approach. The user can alter the viewing position at will and in real time so as to best study vascular relationships. *D* shows the vasculature from the perspective of a likely surgical approach.

Development is still required in a number of areas, including width determination, stop conditions during object extraction, correction of MR distortions, testing of reconstruction methods, and incorporation of multiple separate programs into a coherent whole. Nevertheless, our current capabilities offer significant advantages over traditional methods of vascular display.

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