Stereoscopic Vascular Models of the Head and Neck: A Computed Tomography Angiography Visualization

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Computer-assisted 3D models are used in some medical and allied health science schools; however, they are often limited to online use and 2D flat screen-based imaging. Few schools take advantage of 3D stereoscopic learning tools in anatomy education and clinically relevant anatomical variations when teaching anatomy. A new approach to teaching anatomy includes use of computed tomography angiography (CTA) images of the head and neck to create clinically relevant 3D stereoscopic virtual models. These high resolution images of the arteries can be used in unique and innovative ways to create 3D virtual models of the vasculature as a tool for teaching anatomy. Blood vessel 3D models are presented stereoscopically in a virtual reality environment, can be rotated 360° in all axes, and magnified according to need. In addition, flexible views of internal structures are possible. Images are displayed in a stereoscopic mode, and students view images in a small theater-like classroom while wearing polarized 3D glasses. Reconstructed 3D models enable students to visualize vascular structures with clinically relevant anatomical variations in the head and neck and appreciate spatial relationships among the blood vessels, the skull and the skin. Anat Sci Educ 9: 179–185. © 2015 American Association of Anatomists.

Key words: gross anatomy education; medical education; radiology education; 3D stereoscopic models; 3D virtual models; vasculature of the head and neck; CT angiography; CTA; anatomy imaging

INTRODUCTION

Three-dimensional (3D) information plays an important role in understanding the complex structure of human anatomy in medical education. This is especially true when 3D models are created by combining two-dimensional (2D) computed tomography slice data (Luursema et al., 2008; Tam et al., 2009; Yeung et al., 2011). Use of 3D image displays can potentially decrease the learning curve of students and increase the understanding of spatial relationships as it provides a whole representation of the patient's anatomy. The use of 3D tools can potentially be helpful for students with lower innate spatial ability (Luursema et al., 2008; Brewer, 2012; Foo et al., 2013). In recent years, new interface technologies and 3D virtual models have become possible due to advanced computer technology and software (Trelease, 1996; Nguyen and Wilson, 2009). These virtual anatomical models enable visualization, manipulation, and interaction on the computer, as well as stereoscopic 3D presentation in a virtual environment.

There are currently a number of 3D software creation programs available, including: Amira®, version 5.6 (FEI Visualization Sciences Group, Burlington, MA); Vitrea, version 6.7 (Vital Images, Minnetonka, MN); OsiriX, version 3.6

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Received 5 February 2015; Revised 10 April 2015; Accepted 12 April 2015.

(Pixmeo Geneva, Bernex, Switzerland); Minics, version 14.11 (Materialize, Leuven, Belgium), (Foo et al., 2013; Martin et al., 2013). One of these, Amira® software has been very successful in providing the medical community with a vast array of tools to examine, analyze, and interact with 3D representations of medical patient imaging data obtained from computed tomography (CT) and magnetic resonance imaging (MRI) scans (Sergovich et al., 2010; Adams and Wilson, 2011; Foo et al., 2013). Although 3D models, as a part of computer assisted learning (CAL), are increasingly used in anatomy education (Garg et al., 1999; Aziz et al., 2002; McLachlan et al., 2004.; Nicholson et al., 2006; Petersson et al., 2009; Martin et al., 2013), the images are often limited to online use and flat screen-based 3D computer imaging (Temkin et al., 2006; Hilbelink, 2009; Petersson et al., 2009; Tam et al., 2009; Sergovich et al., 2010). Only a few medical schools currently use stereoscopic 3D anatomical images in a virtual reality environment to teach anatomy (Nguyen and Wilson, 2009; Adams and Wilson, 2011; Yeung et al., 2011; Brown et al., 2012; Anderson et al., 2013). Even fewer schools are taking advantage of 3D stereoscopic projection when studying clinically relevant anatomical variations (Hilbelink, 2009; Brewer et al., 2012).

Creating 3D virtual models usually requires the acquisition of voxel-based radiologic data and the conversion of this data into 3D models. Most 3D virtual models in education are created using MRI and CT scans of deidentified patients or volunteers, using images derived from the Visible Human Dataset (Spitzer et al., 1996; Ackerman, 1998; Tam, 2010; Yeung et al., 2011) or from cadaveric material (Nguyen and Wilson, 2009). Computed tomography angiography (CTA) of the head and neck is used in a variety of clinical settings, including patients presenting with signs and symptoms related to acute hemorrhagic or ischemic stroke. CTA in these cases is used for assessment of vessel anatomy, detection of intracranial aneurysms and subsequent planning of therapeutic interventions (Tomandl et al., 2004). The CTA image acquisition requires administration of intravenous iodinated contrast at a rapid rate, and the imaging is timed to optimize contrast in the arteries, thereby making the arteries easier to identify and evaluate. The raw 2D images are frequently postprocessed into volume rendered 3D models and other reconstructions for viewing by the radiologist on flat panel monitors (without stereoscopic or true 3D modeling). Stereoscopic 3D rendered vasculature models of the head and neck derived from CTA images are not routinely used in clinical medicine or anatomy education.

The purpose of this article is to describe the innovative methodology used to create and display clinically relevant 3D models of the vasculature, based on CTA images, with the goal of teaching anatomy in a classroom setting. Specifically, a combination of volume and surface rendering methods were used to create 3D stereoscopic models of vasculature of the head and neck.

METHODS

The virtual models of the major arteries of the head and neck described in this article were developed using deidentified CTA data provided by the Department of Radiology, University of Mississippi Medical Center (UMMC). The CTA images were acquired with a Siemens SOMATOM Definition CT scanner (Siemens, Erlangen, Germany) with voxel dimensions of 0.35 × 0.35 mm in axial dimension and 0.75 mm in craniocaudal dimension, using routine CT angiography (CTA) techniques that included intravenous iodinated contrast administration and bolus timing for an optimal arterial phase. Raw data were saved as DICOM (Digital Imaging and Communications in Medicine) format files. Three-dimensional virtual models were created using Amira® software, version 5.6.

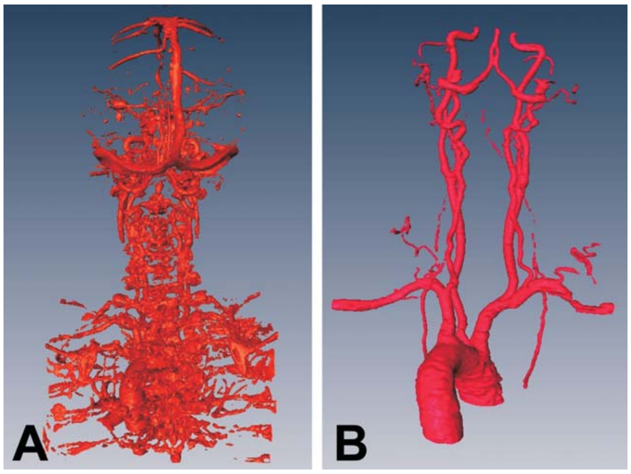

Figure 1.

Example of two models of blood vessels in head and neck. Model on the left (**A**) was created using the volume rendering method; model on the right (**B**) was using the surface rendering technique for segmentation. Of note, vasculatures in Panel A are hidden by the voxels occupied by equally dense tissues, in this case, bone marrow.

There are two general approaches to the construction of a virtual 3D model from a DICOM file (Martin et al., 2013). One technique that is termed "volume rendering", where the relative intensity of a structure is used as the selection criterion during the segmentation. An upper and lower intensity threshold (intensity window) is specified, and all areas in each slice that fit into the specified intensity range are displayed. The volume rendering technique has the advantage of being very fast, but has the serious disadvantage of not being able to discriminate between structures that have similar intensities in the slices. This technique works well, for example, for selecting compact bones in a nonenhanced CT image data set, as bone density (and corresponding pixel intensity) is significantly different from all other structures present in the slices. However, when thresholding is used to display the vessels from a CTA data set, the intensity of the blood vessels is variable, depending upon vessel patency, the amount of injected contrast, and the CTA technique. With CTA imaging, the intensity of contrast in the arteries is often similar to that of bone marrow within the cancellous bone, making it impossible to select only the blood vessels using any threshold values (Fig. 1A). Furthermore, volume rendering cannot discriminate between arteries and veins, leading to possible confusion if they have similar intensity values. The reconstruction of the head and neck shown in Figure 2 was made with volume rendering. It includes a combination of blood vessels and some bone marrow.

The second approach to the construction of a 3D virtual model is called "surface rendering" with manual image

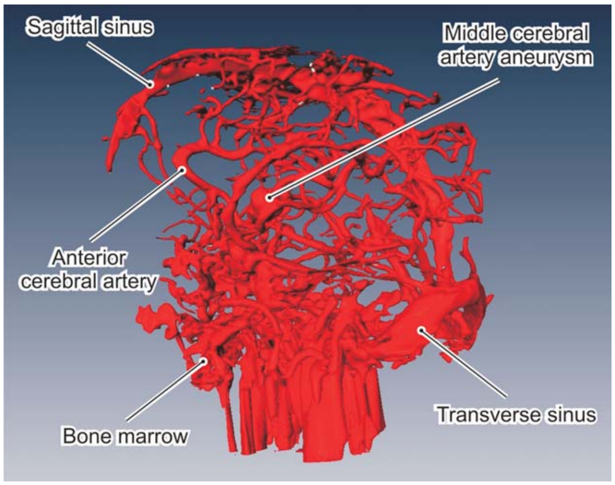

Figure 2.

Volume rendering models of cerebral vasculature in head. This snapshot of the model depicts the cerebral vasculature and a pathological condition, a middle cerebral artery aneurysm. These images show lateral view of the blood vessel model created using the volume rendering method. Using volume rendering techniques with the Computed tomography angiography approach, the model demonstrates visual "noise" in the form of bone marrow visualization at the skull base and venous labeling in the sinuses of the cranium.

segmentation. In this technique, the desired structure is manually identified and digitally selected in each image slice by a user who is familiar with the anatomy of the region in question. In this way, areas in the slice that belong to the desired structure can be discriminated from nearby areas that have similar image intensities but do not belong to the desired structure. Once the structure is fully segmented, through several hundred slices depending on the size of the structures and slice thickness, the software assembles the individual selections into a 3D structure through surface generation. The resulting anatomical model can be viewed on the computer screen or projected stereoscopically. The surface rendering and manual image segmentation technique is time-consuming, but has the important advantage of being very selective. The surface rendering technique with manual image segmentation was used to construct the vascular model shown in Figure 1B, using the same raw data as in Figure 1A. In latter reconstruction, the software included the bone marrow within cancellous bone, with its abundant blood cells in addition to blood vessels because of the similar intensity values of each.

To prepare a virtual 3D model, the DICOM file data set (505 axial images) that contained the head and neck region was loaded into a Dell Precision T7600 computer workstation (Dell Incorporated, Round Rock, TX) with an NVIDIA Quadro K6000 video card (NVIDIA Corporation, Santa Clara, CA). The files in the data subset were imported into a 3D visualization and modeling program, Amira®, version 5.6. For surface rendered models, the desired anatomical structures were selected in each slice using the Amira® "blow" tool. These steps were repeated until each desired structure was selected throughout the set of slices (198 axial slices in CTA) for cerebral vascular structures in the head, and a set of slices (505 axial images in CTA) for the vascular structures in the head and neck region. For volume rendered models, all slices were selected and the intensity threshold was adjusted for the bone or blood vessels using a semiautomated technique (Adams and Wilson, 2011). In the case of CTA, the mean intensity of arteries was about 350 Hounsfield units, and the threshold value for bone marrow was also about 350 Hounsfield units. For reference, the Hounsfield Unit is a linear attenuation coefficient measurement for a substance and corresponds to the density of most normal biologic substances and is related to the amount of iodinated contrast present in other substances (e.g., the arteries in a CTA study). For example, air, water, muscle, and bone have attenuation values of -1000, 0–20, 25–40, and 100–1000 Hounsfield Units, respectively. After selecting the desired anatomical structure using either method, surface generation was used to generate a polygonal surface of the model. Then "surface view" was used to view the newly created models in the display window. "Stereo Preferences" was used in the software to project the models 3D stereoscopically, using dual projection. This required a virtual reality configuration to project the model using a passive stereo display (dual high-definition projector system: InFocus IN3128HD; InFocus, Portland, OR). The models can be displayed as a 3D virtual model on a large silver screen in a dimly lit ambient environment. Students wear linear polarized 3D glasses and sit in a small theater-like classroom. The vascular stereoscopic virtual model can be rotated 360° in all axes, and can be made larger or smaller with manipulation possible with a computer mouse interface.

RESULTS

Several three-dimensional (3D) stereoscopic models of blood vessels in the head and neck were created. One set of models of the vascular system in the head and neck structure were created using the volume rendering technique, based on tissue density, using CTA data (505 axial slices) and selecting density thresholds of arteries for volume segmentation (Fig. 1A). Another model was created using the surface rendering technique, in which desired structures were manually selected based on anatomic knowledge for surface segmentation (Fig. 1B). These structures included the aortic arch, brachiocephalic trunk, subclavian arteries, common carotid arteries, vertebral arteries, internal carotid arteries, external carotid arteries, basilar artery, anterior cerebral arteries (ACA), middle cerebral arteries (MCA), and posterior cerebral arteries (PCA). The comparison of the volume rendering and surface rendering techniques included the time needed for completing the models, storage requirements, smoothness of rotation, selection of desired structures, and stereoscopic presentation are all listed in Table 1.

Figure 2 shows a model of the cerebral vasculature of the head. During the model segmentation, a middle cerebral artery aneurysm was detected. The MCA aneurysm is in one of the common sites for aneurysms (Haines, 2006). This model was created using the volume rendering technique in order to give a better view of the position of the middle cerebral artery aneurysm, and its relationship to the cerebral vasculature.

After models are created, internal structures can be projected and visualized using a "Translate" tool to zoom in and go right through the surface of the skull, to visualize internal cranial features including foramina and prominences. Using this technique the viewer can "zoom" into the cranium at the location of the arrow in Figure 3A. Upon entering the cranial

Table 1.

Comparison of the Volume Rendering and Surface Rendering Models of Blood Vessels in Head and Neck Using Two Different Techniques

Comparative criteria/features	Volume rendering models of blood vessels in head and neck	Surface rendering models of blood vessels in head and neck
Time needs for completing the models	5–10 min	About 160 h
Storage requirements	Soft tissue 257,666 kb Skull 99,340 kb Volume arteries 4,910 kb	Surface arteries 2,122 kb
Smoothness	Smooth	Smooth, but has slight edge
Selection of desired structures	Poor/minimum	Excellent
Stereoscopic presentation	Slow and jerky (shaking)	Fast and smooth

vault, the left middle cerebral artery (MCA) and left MCA aneurysm are exposed (Fig. 3B).

Because of the nature of the contrast scans, arteries, and bone are easily segmented with the volume rendering techniques thus, volume rendered versions of the head and neck models were created with a solid bone rendition and a transparent bone rendition, both with the vascular systems intact (Figs. 4A and 4B). These models of the skull with highlighted vasculature are intended to aid student understanding of the spatial relationships between the blood vessels and their orientation to the bone. For example, students can see clearly that the vertebral artery ascends the transverse foramina, turning posteriorly along the inferior skull, and entering the cranium at the foramen magnum (Figs. 4A and 4B). The actual model can be rotated 360° at any angle and any magnification for learners. In addition, an internal view, using a 3D stereoscopic presentation demonstrated the path of the vertebral artery as it passes through the foramina of the vertebrae. A model that included soft tissues and skin was created from the same CTA radiographic data using the volume rendering technique (Fig. 4C). Figure 5 demonstrates the vascular structure of the head and neck that was created using the surface rendering method. Blood vessel models were created by manually identifying the main arteries using the surface segmentation. For Figure 5A and 5B, images of raw slice data were inserted that were captured to illustrate the interaction of CT angiography in combination with a surface rendered artery model. This slice data can be dynamically manipulated by users to demonstrate cross-sectional data simultaneously with the resultant 3D models. The alignment is nearly perfect because the CTA slice data were the same data used for the 3D model creation. In the CTA slice shown in Figure 5C, blood vessels and bone are shown bright white, while soft tissue, such as muscle, appears dark gray; skin and

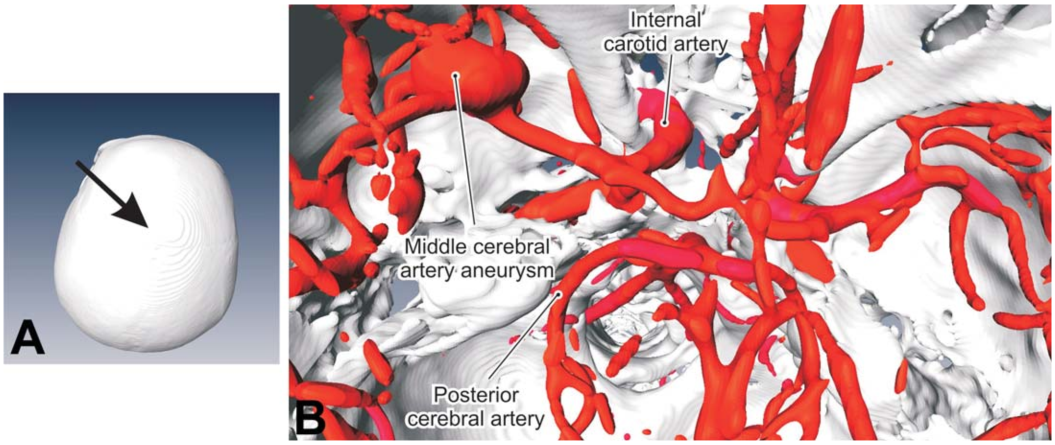

Figure 3.

Intracranial view of the middle cerebral artery aneurysm. It shows the surface of the skull (panel **A**); after using “zoom-in” mode and passing though the skull, the internal structures, cerebral vasculature and middle cerebral artery aneurysm can be viewed in panel **B**.

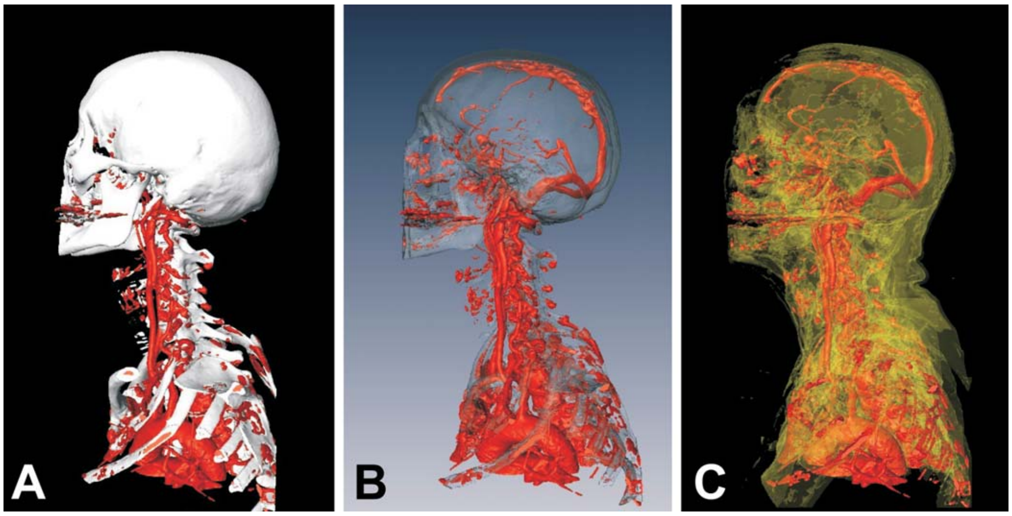

Figure 4.

Vascular structures with solid, transparent bone and soft tissue. The volume rendering models of the vascular structures with solid bone (panel **A**), vascular structure with transparent bone (**B**), and vascular structure with transparent bone, soft tissues, and skin (**C**).

subcutaneous tissue also demonstrate their CT attenuation coefficients visually with varying degrees of gray scale.

All reconstructed 3D models described here can be displayed in true stereoscopic 3D presentation in a virtual environment. To view, students wear polarized 3D glasses and sit in a small theater-like classroom, similar to watching a 3D movie in a theater. Through the use of a mouse, the 3D virtual models can be manipulated by learners to explore. The Translate tool allows flexible viewing of models and allows visualization of internal structures. Names of the structures can be added and viewed by using a labeling tool within the software. Labels were added using the "Annotation" function of Amira® to label each structure after models were created. Snapshot images of the 3D models can also be quickly made from the models and used in PowerPoint lectures and presentations. Each 3D model can be manipulated, magnified and captured as an AVI or MPEG movie and used in presentations both stereoscopically or in a normal presentation mode.

DISCUSSION

In the current project, the use of CTA was explored to create 3D stereoscopic models of blood vessels for anatomy teaching. Our goal was to create 3D virtual models of blood vessels, particularly arterial models with clinical relevance, with the specific aim of enhancing students' ability to visualize

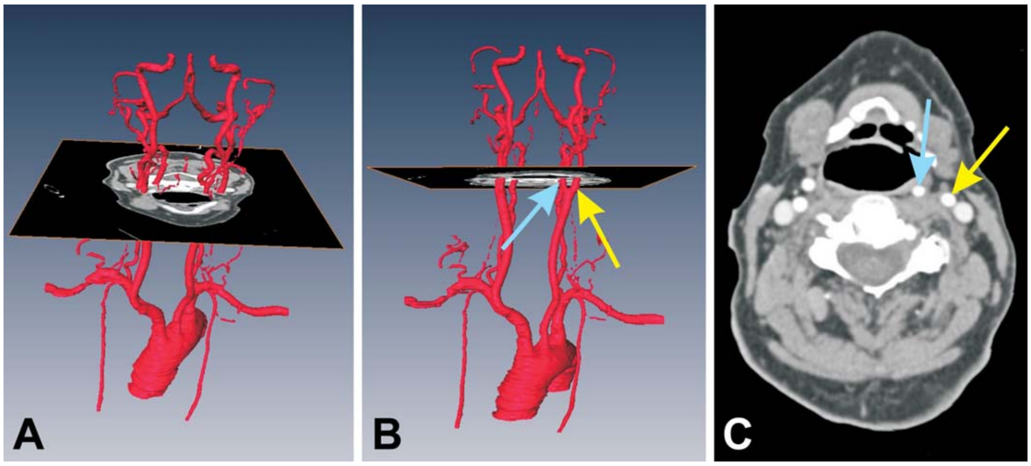

Figure 5.

A surface rendered model of arteries with a superimposed computed tomography angiography slice. Two different views are presented: a raw computed tomography angiography slice overlaid on the model of blood vessel (panel **C**) at the same level of **A** and **B**, external carotid artery pointed by blue arrows, and internal carotid artery indicated by yellow arrows.

and learn three-dimensional spatial relationships. CTA is frequently used for detection of intracranial aneurysms and has been used for detection and diagnosis of abnormal blood vessels in clinic medicine (Tomandl et al., 2004), and thus is well suited for teaching clinical correlations. Also, CTA provides better contrast of blood vessels than conventional CT or MRI. As noted in the Introduction, CT and MRI scans have been recently used as source material for 3D stereoscopic models in anatomy teaching (Nguyen and Wilson, 2009; Adams and Wilson, 2011; Yeung et al., 2011). To our knowledge, CTA material has not been used previously for this purpose.

To create these models, two different types of techniques were combined for processing the CTA images. First, volume rendered models were created based on tissue density (Martin et al., 2013). Because many types of tissue have unique densities, this type of technique allowed us to select certain thresholds based on each tissue's density. Contrast enhanced CTA images worked well with the vascular system, and the volume rendered models displayed fine detail textures, a natural and smooth appearance, and could be created relatively rapidly. However, this technique has a considerable storage requirement and required a high-speed computer to run the 3D presentation. Also, tissue such as bone marrow within cancellous bone, which was not intentionally included in our images, ended up being selected due to the fact that its attenuation (pixel intensity) was similar to that of the desired structures. Second, in order to create precise models of arteries, surface rendered models of vasculature in the head and neck were created by using thin slice data and manually selecting desired structures based on their anatomical identification. Using surface rendered models, desired structures can be selected individually and manipulated in a separately. In this case, bone marrow within cancellous bone can be excluded while only arteries were selected for the model (Fig. 1B). As a final step, additional bone and soft tissue were added to the blood vessel models, in order to provide a better appreciation of the spatial relationships between the layers of the skin, skull, and blood vessels than seen in a simple vasculature model. This combination of different types of models shows the depth of structures from multiple angles, as well as the spatial relationship among the blood vessels, bone, and soft tissue in external and internal aspects (Fig. 4).

There are several distinct advantages to the approach using CTA employed here. One advantage is the ability, as noted above, for the CTA data to allow three types of models to be created from the same data. With CTA data, vascular 3D models can be combined with bone and soft tissue models, allowing students to visualize spatial relationships of the precise course and trajectory of blood vessels through bone and soft tissues. For example, using these combined models, students are able to visually trace the path of vertebral arteries as they ascend through the transverse foramina, as well as the course of the internal carotid arteries as they enter the cranium via the carotid canal. Another exciting feature of the model created here is the ability to place 3D vascular anatomy into the context of individual CT slices (Fig. 5). Using this feature, students are able to visualize the initial segment of the external carotid arteries and place that structure medial, and not lateral, to the internal carotid arteries (Fig. 5); this is a point that is often confused by students via traditional learning. Finally, stereoscopic presentation of these models in a virtual environment is impressive and gives students a "wow" experience that may encourage further study time with the anatomical materials. Students have the experience of almost being able to reach out and touch each structure. As noted above, they also see the 3D rendered structures in the context of the original radiographic images, enhancing their spatial appreciation of the complexity of neck and vascular structures.

LIMITATIONS

Notwithstanding these advantages, there are also some limitations to creating 3D models. First, volume rendered models can be created rapidly, but the file size is very large (4,910 kb) about twice as large as the surface rendering models (2,122 kb) thereby requiring a larger storage capacity. In addition, volume rendering models do not allow structures to be selected as precisely as with surface rendered models. One example of this is bone marrow within cancellous bone that was also included during the volume rendering creation of blood vessel models. This is due to the fact that bone marrow has similar attenuation to contrast-enhanced vessels on CTA images, making it very difficult to separate bone marrow from the blood vessels (Fig. 1A). Finally, surface rendering models of the vascular structure in the head and neck were best for our purposes. The relatively small file size accounts for the excellent stereoscopic presentation. However, these models have slight rough edges and are not as smooth as volume rendered models. It also takes considerable time to construct 3D models due to the requirement for selecting the relevant anatomy structure from each slice of the radiographic images (200–500 images) during the creation process.

CONCLUSIONS

Overall, 3D virtual models created from CTA scans hold significant promise as tool in the teaching of anatomical spatial relationships. The models created here, which combine blood vessels, skull and skin, and their display capabilities, should provide students with a new approach with which to visualize and learn the three dimensional relationships of anatomical structures. Ongoing work will test this assumption by analyzing the effectiveness of these 3D models as a teaching supplement in student's knowledge acquisition, as compared with 2D models of the same material.

ACKNOWLEDGMENTS

The authors thank: Drs. Tracy C. Marchant, John T. McCarty, and Anson L. Thaggard (Dept. Radiology, University of Mississippi Medical Center) for providing the deidentified CT angiography images used in this study. The authors also thank Dr. Jian Chen, and Mr. Jerome Allison (University of Mississippi Medical Center) and Mr. Jeremy Roth (University of Western Ontario) for providing technical support. In addition, the authors are grateful for support and encouragement from Drs. Robin W. Rockhold, Duane E. Haines, Marianne L. Conway, Allan R. Sinning, and Mr. David A Juergens at the University of Mississippi Medical Center. The work reported here was supported by a Faculty Scholarship Exchange Award from the University of Mississippi Medical Center. The authors have no conflicts of interest to disclose.

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