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Virtual Cerebral Ventricular System: An MR-Based Three-Dimensional Computer Model

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The inherent spatial complexity of the human cerebral ventricular system, coupled with its deep position within the brain, poses a problem for conceptualizing its anatomy. Cadaveric dissection, while considered the gold standard of anatomical learning, may be inadequate for learning the anatomy of the cerebral ventricular system; even with intricate dissection, ventricular structures remain difficult to observe. Three-dimensional (3D) computer reconstruction of the ventricular system offers a solution to this problem. This study aims to create an accurate 3D computer reconstruction of the ventricular system with surrounding structures, including the brain and cerebellum, using commercially available 3D rendering software. Magnetic resonance imaging (MRI) scans of a male cadaver were segmented using both semiautomatic and manual tools. Segmentation involves separating voxels of different grayscale values to highlight specific neural structures. User controls enable adding or removing of structures, altering their opacity, and making cross-sectional slices through the model to highlight inner structures. Complex physiologic concepts, such as the flow of cerebrospinal fluid, are also shown using the 3D model of the ventricular system through a video animation. The model can be projected stereoscopically, to increase depth perception and to emphasize spatial relationships between anatomical structures. This model is suited for both self-directed learning and classroom teaching of the 3D anatomical structure and spatial orientation of the ventricles, their connections, and their relation to adjacent neural and skeletal structures. Anat Sci Educ 00: 000-000. © 2011 American Association of Anatomists.

Key words: gross anatomy; neuroanatomy education; three-dimensional models; stereoscopy; anatomical reconstruction; segmentation; cerebral ventricles; medical education; virtual model

INTRODUCTION

The human cerebrum is one of the most complex organs of the body and one of the least accessible through surgical or dissection approaches (Pitiot et al., 2004). The complexity of the cerebrum presents a challenge when it comes to understanding the spatial relations, orientations, and configurations of its anatomical structures (Kikinis et al., 1996).

Cadaveric dissection, while normally considered the gold standard of anatomical education, may be inadequate for learning the anatomy and relationships of the cerebral ventricular system. Even with intricate dissection, ventricular structures remain difficult to observe and conceptualize, as they constitute spaces rather than physical structures (Smith et al., 2007a).

A commonly used alternative to cadaveric dissection is anatomical models. Plastic models and ventricular casts, while useful for showing the three-dimensional (3D) anatomical structure of the ventricular system, allow neither for the student to conceptualize the ventricles as a part of the brain or surrounding cerebral structures to be visualized along with the ventricular system. Estevez et al. (2010) found that

students utilizing modeling clay to create periventricular structures on a ventricular cast had a better understanding of 3D neuroanatomy than students using traditional 2D methods. This indicates that while traditional methods of teaching neuroanatomy (cross-sectional images, textbook diagrams, models) are adequate for a general understanding of human neuroanatomy, interactive 3D learning modalities, clay modeling and by extension, virtual models may be better suited for teaching the complex spatial relationships of neuroanatomy.

Two-dimensional (2D) diagrams of the cerebral ventricles with surrounding structures are also teaching tools used in the anatomical sciences. These tools, however, are inherently limited by the fact they are 2D images attempting to depict 3D anatomical structures and orientations (Smith et al., 2007a). In addition, many conceptual diagrams do not provide the accurate spatial and physical characteristics of an actual brain and ventricular system or a composite of an average brain, but rather an artist's vision of an ideal brain (Toga et al., 2006). Raw magnetic resonance (MR) or computed tomography (CT) data, while accurately representing the ventricular system, can be difficult for students to understand and visualize the actual 3D structure of the ventricular system.

The aim of this project was to create an anatomically accurate 3D reconstruction of the human cerebral ventricular system with surrounding neural structures for the eventual use in a digital atlas for anatomical education. The model will be created using Amira®, version 5.0 (Mercury Computer Systems/TGS, San Diego, CA), a software program that has been successfully used to develop educational models of the head and neck regions from computed tomography imaging and the female pelvis from the visible human project (Nguyen and Wilson, 2009; Sergovich et al., 2010). In addition to a stand-alone digital model, an animation depicting the flow of cerebrospinal fluid (CSF) through the ventricular system, around the central nervous system, and back into the venous system was created.

MATERIALS AND METHODS

Magnetic resonance imaging (MRI) data were retrospectively sampled from an image set of the head and neck region of an unembalmed male cadaver obtained from the Body Bequeathal Program at the University of Western Ontario in accordance with the Ethical Review Board. The unembalmed male cadaver, aged 83 with cause of death listed as myocardial infarction, was scanned using a GE Discovery™ MR750 3.0-T whole body scanner (General Electric Company, Fairfield, CT) operating at 3.0-T field strength (inversion recovery prepared 3D flash, TE = 5 ms, TR = 9 ms, inversion time = 250 ms). The field of view was $25.6 \times 25.6 \times 19.2$ cm^3 ($1 \times 1 \times 1$ mm^3 resolution), and the images were T_2 weighted. This resulted in 512 axial images in the digital imaging and communications in medicine (DICOM) format. These DICOM images were then converted to tagged image file format (TIFF) images.

The cerebral ventricular model was created on a Mac Pro desktop computer (Apple Inc., Cupertino, CA; 2×3.20 GHz Quad-Core Intel Xenon, 32-GB, 800-MHz, DDR2 FB-DIMM NVIDIA GeForce 8800 GT Graphics Card) using Amira software, version 5.0. Amira is a commercially available tool designed for visualizing and manipulating volumetric or
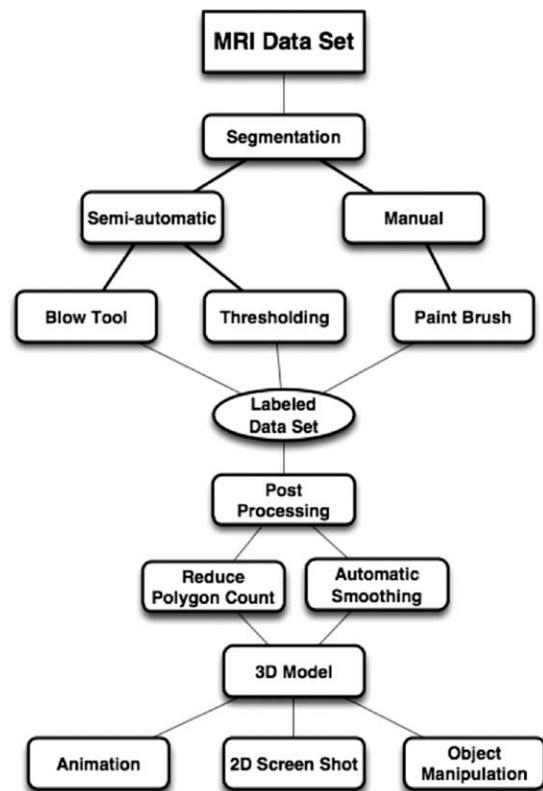

Figure 1.

Overview of procedural steps taken from raw data to finished digital model.

sequentially sliced data files through segmentation, 3D modeling, and surface generation.

The procedural overview of the steps taken for the development of the ventricular model is presented in Figure 1. Segmentation of anatomically relevant structures involved separating structures of interest on the basis of grayscale value (voxel value) and knowledge of anatomical structure and location. A voxel is the 3D equivalent of a 2D pixel (John, 2007). Once a structure has been segmented from the surrounding structures using either manual or semiautomatic techniques, the specific voxels are assigned a label and color (a different label and color was used for each discrete structure that is segmented).

The manual segmentation of structures involved the outlining of specific anatomical structures with a paint–brush tool on a slice-by-slice basis in any anatomical plane (Tam et al., 2009). The semiautomatic segmentation tools used in this project use the principles of voxel grayscale value to separate structures with different densities, as defined by the original MRI dataset. The two semiautomatic techniques used were thresholding (where all user defined grayscale values are selected) and the blow tool (which selected similar adjacent voxels from a central user defined "seed voxel"). The use of semiautomatic segmentation tools allowed for the definition of structures to be completed in a more time efficient manner. Semiautomatic segmentation was used when struc-

tures of interest had well-defined boundaries; however, where partial volume artifacts (multiple tissue types or anatomical structures contributing to one voxel) resulted in blurry lines of delineation between structures, a manual segmentation approach was used to ensure accuracy (Pham et al., 2000, Pitiot et al., 2004). Partial volume artifacts made the segmentation of structures difficult, as boundaries between adjacent structures were not clear. In order to overcome partial volume artifacts, anatomical atlases and textbook images were consulted to help determine the approximate shape and spatial orientation of each structure (Nolte, 2002; Netter, 2006). Segmentation was accomplished in each slice of the dataset where a structure of interest was present. The axial view of the MR dataset was used for the initial segmentation of structures. At times, coronal and sagittal views of the same dataset were used to more clearly and accurately define structures of interest after the initial segmentation in the axial plane was complete.

Once the structures of interest were segmented, Amira was used to create a 3D polygon mesh of each discrete structure by connecting all voxels of a specific structure between adjacent image slices. This mesh frame consists of upward of a million polygons, which places a large burden on the processing capacity of the desktop computer, resulting in slow object manipulation in 3D space (Smith et al., 2007a). For this reason, the segmented structures underwent postprocessing using Amira before the final rendering of structures.

Postprocessing is accomplished by decreasing the polygon count of each reconstructed structure enabling for a fluid motion of the completed model, as well as smoothing any rough edges or "steps" in the finished model that are the result of human error in segmentation or artifacts in the dataset. Polygon count was reduced in each discrete anatomical structure separately on the basis of trial and error. Each structure underwent polygon reduction to the point that they were smooth but without sacrificing structure detail.

In addition to polygon reduction, the software's automatic smoothing of structures was used. This type of smoothing works by shifting the vertices of the polygons in each discrete segmented structure. Each vertex is shifted toward the average position of the vertices around it. When a vertex is on an edge or the boundary of a structure, only those vertices that are also in the specific area are averaged in order to preserve the original detail of the model without the angularity of the polygons.

After each discrete structure was postprocessed, the segmented structures were rendered using Amira. The rendering process converts 3D models into 2D images or frames of an animation. Rendering requires the computer to process the position of the 3D structure in relation to the virtual camera, the lighting of the model within the virtual space, and the surface characteristics of the structure (Vernon and Peckham, 2002; Tam, 2010).

The cerebral ventricular model animation illustrates CSF flow through the ventricles and into the subarachnoid space was created using the DemoMaker module in Amira after all structures were segmented and postprocessed (reduction of polygon count). Actions such as rotation, camera path, and toggling anatomical structures as "on" or "off" (either shown or hidden in the viewer window) were created in a specific user defined sequence to produce an animation of the completed model. This type of key frame animation requires the definition of specific start and stop points for each action, with the computer filling in the frames needed to complete

the operation (Vernon and Peckham, 2002). The video was exported from Amira as an .mp4 file for playback on a computer without Amira software in a similar fashion to those presented in the interactive brain atlas (Sundsten, 1994).

RESULTS

A 3D model of the human cerebral ventricular system with surrounding structures was created using MR images of a male unembalmed cadaver. The reconstruction of the ventricular system consists of: paired lateral ventricles, third ventricle, cerebral aqueduct, and fourth ventricle. In addition, structures surrounding the ventricular system that were reconstructed included: the cerebrum, brainstem, diencephalon, cerebellum, dural venous sinuses, cisterns, and CSF surrounding the brain (reconstructed as a solid structure).

The digital ventricular model can easily be manipulated in 3D virtual space using the computer mouse (by intuitively clicking, dragging, and scrolling on the model) in a number of ways; anatomical structures can be rotated in any orientation, magnified or reduced, viewed from within (to observe internal structures), and slices in any plane can be made through the model. In addition, linear measurements between any two points can be made by clicking on different structures to provide a basis for size and anatomical relationships of structures. Three-dimensional labeling of the anatomical structures can also be performed by clicking a label on/off (labels are created during the segmentation process) to help guide students through difficult anatomical areas.

An animation depicting the flow of CSF throughout the 3D ventricular system model from its origin in the choroid plexus through the subarachnoid space and cisterns to its final destination in the venous system has been created (CRIPT, 2010). The CSF animation combines many features of the model into a short video that can be played on any computer, without the use of Amira. The video depicts the brain and spinal cord as they would be seen in digital situ, then proceeds to alter the opacity of structures enabling visualization of the ventricular system. The animation incorporates many different viewing angles, showing the ventricular system with varying surrounding structures added or removed and finally depicts how CSF fills the ventricular system from the choroid plexus and travels around the brain and brainstem before draining into the dural venous sinuses. This 3D animation allows for visualization of a complex physiological process using an anatomically correct model from a number of different angles and orientations.

DISCUSSION

This article describes a method for the creation of a 3D stereoscopic model of the human cerebral ventricular system with surrounding structures using a commercially available image segmentation and reconstruction software package. MR images were chosen for this project, because they afforded higher soft tissue contrast than CT images of the head region (de Crespigny et al., 2008). The completed ventricular system model is intended for use as complimentary component of anatomical education, as current 2D teaching methods describing the human ventricular system may be inadequate for such an undefined area.

The ventricular system is a cerebral space filled with CSF and the process of death and embalming could severely alter

shape and size of these spaces. It has been observed through gross anatomy dissections that the brain shifts and settles after death, altering the original shape of the spaces inside. In addition, embalming of the cadaver, using the arterial and venous system to perfuse the body with embalming fluid, could have an effect on the shape of the ventricular system as fluids are pushed through vessel walls of the choroid plexus into the ventricles (Strub and Frederick, 1989). A comparative MRI study on live human brains and cadaveric brains (both embalmed and unembalmed) by Dashner et al. (2003) showed that unembalmed postmortem brains had higher soft tissue contrast and greater image sharpness than images obtained from embalmed brains. This was because the water content of the recently deceased brain (within 48 h of death) was similar in form to that of the living brain, and MR signal intensities are based on differences in water, specifically the hydrogen concentrations between anatomical structures. The water content of the embalmed brain would be different than the live or unembalmed brain due to the perfusion of tissues with formalin during the embalming process (Strub and Frederick, 1989; Dashner et al., 2003). Had an embalmed brain been used for the present study, less accurate segmentation of structures would have resulted as the lines of delineation between adjacent structures would have been more difficult to discern, as embalming essentially homogenizes tissue ion concentrations.

The 3D model of the cerebral ventricular system created in this study offers a number of advantages over previously created computer models of the ventricular system. Anil et al. (2007) created a 3D model of the head region with the cerebral ventricular system from overlaid MR and CT for use in surgical planning. This model was created using a Dextroscope^{TM}, a commercially available image segmentation and viewing platform (BRACCO AMT, Inc., Princeton, NJ). Segmentation of structures in the study by Anil et al. (2007) was completed using semiautomatic techniques based on the voxel intensities of different tissue types. This type of segmentation, termed volume in contrast to surface segmentation used in the current study, is a limitation of the Dextroscope^{TM}. Volume segmentations cannot separate anatomical structures that have similar tissue characteristics and will be segmented together as one object, preventing them from being visualized separately from surrounding structures.

Nowinski et al. (2009a, b) created a 3D model of the cerebral vasculature that could be viewed with the cerebral hemispheres, diencephalon, subcortical structures, and/or the ventricular system. This model was segmented and labeled from a 3.0-T MRI and a 3.0-T 3D time-of-flight (MRA) by a neuroanatomy expert using a self-developed vascular editor (Nowinski et al., 2009c). The model created by Nowinski et al. provides a highly detailed and fully segmented model of cerebral vasculature, however, inability to view individual ventricles, choroid plexus, and subarachnoid space limits the model's effectiveness in displaying ventricular anatomy for educational purposes.

The Digital Neuroanatomist developed at the University of Washington by Sundsten (1994) is a widely available web-based model of cerebral anatomy. This digital atlas of brain structure contains 2D pictures of brain slices, cadaveric dissections, and MR images, as well as perspective 3D computer reconstructions of various cerebral anatomical structures (including the ventricular system) that can be viewed as 2D images or as short animations (Brinkley et al., 1997). It is unclear how much of the 3D portion of the digital atlas is produced from anatomical scans or author recreation. Further, like the digital movie created here to be used outside Amira, the digital atlas is not interactive per se; anatomical objects cannot be manipulated in 3D space or added/removed from the viewing field. The limited interactivity of digital anatomical objects and limited viewing angles are potential drawbacks of this digital atlas. These aspects of 3D learning environments continue to be a source of rich research in educational psychology research.

Other computer reconstructions of the cerebral ventricular system that have been created focus mainly on developing automatic segmentation techniques for extracting anatomical structures from MR images. Schnack et al. (2001) used region growing and mathematical morphology to segment the lateral and third ventricle from 1.5-T MR images. Similarly, Howden et al. (2008) created a volumetric model of the four ventricles using MR images. A simulation of endoscopic ventricular surgery was created and tested by Burtscher et al. (2002) using 1.5-T MR images from live patients using a ray tracing algorithm. Liu et al. (2010) used a predefined volumetric model to automatically segment the ventricular system from stroke patient CT images. Finally, Pitiot et al. (2004) automatically segmented MR images for the ventricular system and surrounding structures including the basal ganglia and thalamus. These reconstructions have varying degrees of complexity and structures present (from the lateral and third ventricles only, to the entire head region) as well as varying degrees of interactivity. The extent of user interactivity of each of the aforementioned models is not known, however, as the literature focuses mainly on how the models were created, not their utilization. If structures were not segmented as separate materials, which is generally not the case when automatic segmentation is used, discrete structures cannot be easily added or removed from the viewing field.

One of the main benefits in using automatic segmentation is the time required to produce 3D models. Automatic segmentation allows for detailed models to be created in a matter of hours, rather than the hundreds of hours required to create a manually segmented model; however, the interactivity and anatomical subdivision of automatically segmented models is very limited (Giesel et al., 2009; Petersson et al., 2009). Automatic segmentation groups structures with a similar voxel intensity values into one single material; it does not enable single structures to be removed from the viewing field and to be manipulated independently from surrounding structures. In contrast, the surface segmentation used in the current study mainly utilizes manual segmentation of structures to enable user control that surpasses that of volume-based segmentation models.

Virtual models with significant user control and interactivity may have significant benefits for anatomical education. The ventricular system and surrounding structures are particularly well suited for 3D computer modeling; the anatomical structures within the cranium are small with boundaries that are difficult to delineate and dissect in traditional cadaveric dissection (Lemole et al., 2007). In comparison with cadaveric dissection, computer-based 3D models provide unlimited viewing angles and perspectives, portability, and longevity (Spitzer and Scherzinger, 2006).

The purpose of anatomical education is to impart a sound knowledge of anatomical structures and their 3D spatial relationships with surrounding structures and the body as a whole. Computer-aided models will undoubtedly supplement this information in a simplified, yet anatomically accurate
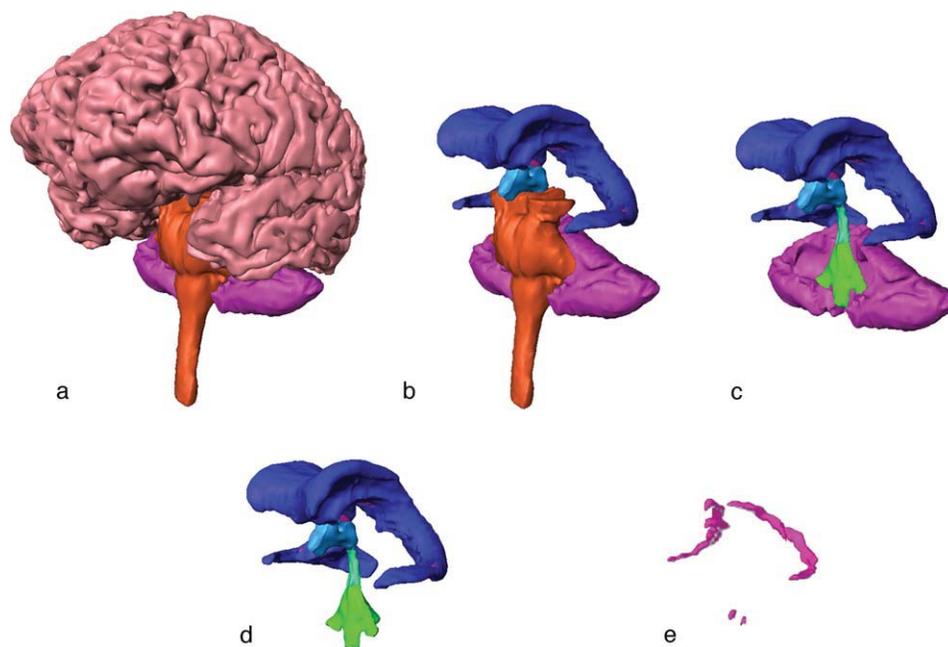
Figure 2.

Virtual ventricular dissection. (a) Complete central nervous system. (b) Removal of cerebrum. (c) Removal of brainstem. (d) Removal of cerebellum. (e) Removal of ventricular system, choroid plexus shown.

manner that enables learners to more easily gain information they need without being overwhelmed by anatomical detail of a particular area (Gorman et al., 1999; Tam et al., 2009). We believe the 3D computer modeling of specific structures (the ventricular system and surrounding structure) simplifies this region into a manageable size and complexity. In addition, previous studies have demonstrated that computerized reconstructions are highly interactive and are useful for increasing student understanding of complex 3D anatomical structures and relationships (Gorman et al., 1999).

This is not to say that computer reconstructions should replace dissection in anatomical education altogether, but for certain anatomical regions, such as the ventricular system, computer models may be an effective supplementation to traditional cadaveric dissection. The ventricular model and animation, although not able to provide all anatomical knowledge and detail, may provide the context and base conditions required for foundational understanding of the ventricular system and increase the long-term retention of information (Gorman et al., 1999; Hallgren et al., 2002). Lessons from surgical training indicate that model fidelity or complexity, at least for the novice user, do not yield better technical skills (Grober et al., 2004).

The completed 3D model can be projected stereoscopically using a system of two parallel projectors and dual polarization in order to offer true 3D viewing of the model (Nguyen and Wilson, 2009). This process can be performed natively using the segmentation software. Stereoscopy allows the viewer to perceive 2D images projected on a screen as 3D structures with a large field of view (structures are not obstructed by surrounding structures) and depth (Balogh et al., 2004; Parikh et al., 2004). The addition of stereoscopy

to the 3D model provides the perception of depth to the viewer; depth perception is a feature of cadaveric dissection and physical models but is not available in virtual models unless stereoscopy is utilized (Balogh et al., 2004; Luursema et al., 2008).

The model can also be used for individual self-study on a computer workstation. Both the methods of displaying the model allow for complete interactivity. By removing or adding surrounding anatomical structures to the ventricular model (by simply clicking on the names of structures), users can perform "virtual dissections" of the model (Figs. 2a–2e). This "dynamic exploration" is a key feature of cadaveric dissection and the ventricular system model that is not available in 2D diagrams (Luursema et al., 2008). Structures can also be "added" to the base ventricular model using the syncretion approach for anatomical education, illustrating dissection from the opposite direction, by starting within the brain and building up structures (a feature that is not available in standard cadaveric dissection; Miller, 2000).

The transparency of any anatomical structure in the model can also be altered quickly and easily using Amira to enhance the visuospatial relationships between superficial and deep brain structures (Fig. 3; Temkin et al., 2006). Semitransparent visualization allows for observation of structures and spatial relationships to be seen as they exist in the confines of the brain (Henn et al., 2002).

The 3D animation of CSF flow that was created using the ventricular models allows for visualization of a complex physiological process using an anatomically correct model from a number of different angles and orientations. This video, in the authors' opinion, would be an excellent teaching aid as it can be shown in either three dimensions (using dou-
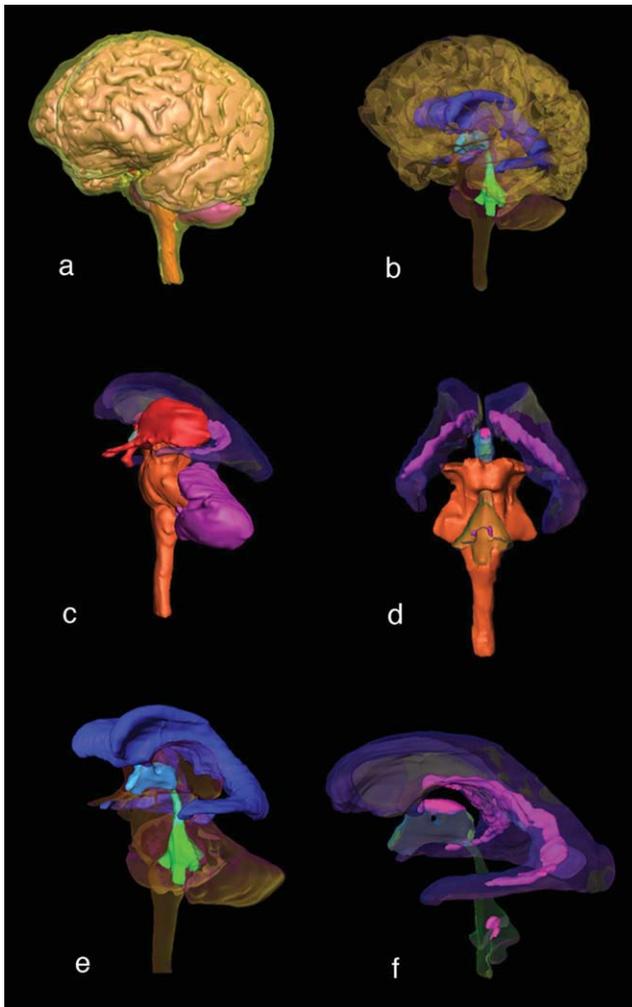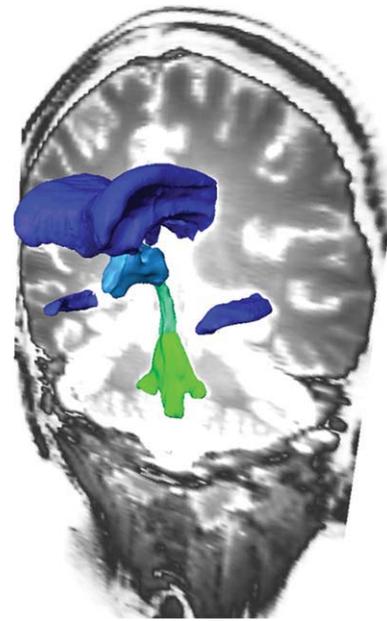
Figure 3.

Structures of the cerebral ventricular system with transparent structures. (a) Oblique view of opaque central nervous system with transparent CSF. (b) Oblique view of transparent central nervous system with opaque ventricular system. (c) Lateral view of transparent ventricular system with opaque choroid plexus, brainstem, cerebellum, and diencephalon. (d) Posterior view of transparent ventricular system with opaque choroid plexus and brainstem. (e) Oblique view of opaque ventricular system with transparent brainstem, cerebellum, and diencephalon. (f) Lateral view of transparent ventricular system with opaque choroid plexus.

Figure 4.

Canonical view of cerebral ventricular system reconstruction overlaid with original MRI scan (coronal slice). This view is useful for spatial orientation for the student user.

ble projectors and Amira software) or two dimensions (using a single projector or screen and a video playing device). Previous educational studies have shown that the use of videos and animations in anatomical teaching increases students' interest and attitudes toward learning as well as retention of information (Vernon and Peckham, 2002; Petersson et al., 2009).

A solid anatomical foundation is a prerequisite for medical education, and today's medical students are becoming increasingly proficient in using computer resources throughout their education (Marks, 2000). Providing these students with the option of using 3D computer models, such as the ventricular system, would allow them to gain insight into this complex anatomical area by interacting with the model on a self-directed basis (Gorman et al., 1999). Self-directed learning using 3D models may allow students to learn information and make specific spatial relationship links at their own pace through active integration of new concepts with previous anatomical understanding (Mantovani et al., 2003; Tam et al., 2009).

Using the 3D model of the ventricular system prior to, or during, cadaveric dissection may provide a number of educational benefits to the student. Using a combination of 3D reconstructions and 2D image slices, flexible viewpoints previously unobtainable with cadaveric dissection, are now possible (Hisley et al., 2008). Any anatomical structure, segmented from the original scan data can be viewed, either in isolation or with surrounding structures, with or without adding a planar slice (in any orientation) of the original MRI dataset (Fig. 4). In addition, because the model is created from MR images of a cadaver, it represents an accurate anatomical structure. This is in contrast to some textbook, webpages, and atlas diagrams of anatomy, that represent an artist's perception of "normal anatomy" that may or may not represent the spatial and structural characteristics of actual anatomical specimens.

LIMITATIONS

A number of difficulties were encountered when reconstructing the ventricular system and surrounding structures from the MR dataset. The voxel intensity of structures within the central nervous system is very close, and in many cases causing structural overlap. This overlapping makes it difficult to delineate separate anatomical structures in the MRI dataset of a cadaveric specimen. The signal intensities of certain neu-

ral structures, such as cortical gray matter and the thalamus overlap, making segmentation of these structures challenging (Fischl et al., 2002).

The "intensity inhomogeneity artifact" of MR images is also a limitation in the current project. The intensity inhomogeneity artifact as described by Fischl et al. (2002) is where one anatomical structure/tissue class does not have uniform voxel intensity throughout the image. For example, the voxel intensity of the lateral ventricles is between about 15 and 95 units on the arbitrary scale, resulting in a wide range of voxel intensities for one structure (Pham et al., 2000). This wide range of voxel intensity makes automatic segmentation of structures more complex, as a larger number of voxel intensities must be included to segment the entire structure without crossing boundaries into adjacent structures (Liu et al., 2009).

The age of cadaver used for the reconstruction may be considered a limitation. Structural brain changes are associated with normal aging, mainly the increased volume of the ventricular system due to the volumetric shrinkage of the brain (Fjell and Walhovd, 2010). Both Good et al. (2001) and Smith et al. (2007b) found an age related decrease in gray matter volume with a resultant increase in CSF. Ambarki et al. (2010) found the average volume of the ventricles in healthy subjects between the ages of 61–82 to be 37 mL. This increase in ventricular size could lead the user of the finished model to incorrectly infer that the ventricular size of an elderly person is equal to that of a younger individual. In addition, Allen et al. (2002) found that in healthy subjects the lateral ventricles were variable. For these reasons, users of the ventricular model will be informed that the ventricular model was created from the brain of a deceased 83-year-old male and the size and shape of the ventricular system may differ from younger subjects and that normal variation of ventricular size and shape exists. The use of digital anatomical education tools in the literature, like that portrayed in this article, has not generally made use of any anatomical variation during their construction. The digital ventricular segmentation remained fidel to specimen size, shape, and variability further adding to the reality of the final model.

The 3D model of the human cerebral ventricular system could be improved through the use of a better dataset and the inclusion of more anatomical structures. The current project utilized retrospectively sampled 3.0-T MR; image quality might be improved through the use of a higher energy MR scanner, but this is currently not clear using cadaveric materials. The slice thickness of the current dataset was 1 mm; however, a slice thickness of less than this would allow for more anatomical details to be accurately reconstructed. Small structures of the ventricular system, such as the arachnoid granulations, could not be visualized in the current dataset of 1 mm slice thickness, as the average size of an arachnoid granulation cap is 300 μm with a thickness of 150 μm (Upton and Weller, 1985). The CRIPT group, using parallel principles to the Nyquist limit in Doppler ultrasound, suggests slice thickness of any visualization modality be at least twice as small as the materials intended for segmentation (Gill, 1985). By adhering to these principles, the final segmentation accurately represents these materials spatially and to the correct scale. The segmentation and reconstruction of additional anatomical structures would result in a more complex model of the ventricular system and surrounding structures. Adding the dura mater and skull would allow students to better understand the relationships between the three layers of meninges,

the CSF, and the periosteum of the skull. In addition, blood vessels and structures of the basal ganglia were not reconstructed in the current study. The addition of these structures would give the student added information about the relationship and spatial orientation of the ventricular system to these surrounding structures. These structures were not reconstructed in the current project due to limitations in MR image quality and time constraints. The MR images are not well suited for the visualization of bone, and blood vessels were difficult to visualize in the cadaver due to a lack of contrast with surrounding structures. In future studies, this could be overcome by overlaying the MR images with CT scans (which provide a visualization of bone) or angiography images in living persons with contrast agents (to visualize blood vasculature) to allow for complete visualization of structures to be segmented (Jackowski et al., 2008).

Time to complete segmentation could be a limitation in the study. Automatic segmentation of structures was used whenever possible (when structure boundaries were clear and structures had consistent voxel intensities) to reduce the time required to segment individual structures; however, even after automatic segmentation, manual segmentation of structure edges was usually required to ensure anatomical fidelity. For this reason, the time required to accurately segment individual structures was between two hours (for smaller discrete structures such as the fourth ventricle) to upward of twenty or more hours (for large structures with a variety of voxel intensities, such as the cerebrum).

CONCLUSION

The field of digital anatomical creation is advancing rapidly. In some instances, artistic impression outweighs anatomical realism. This article describes a methodology that builds a 3D reconstruction of the human cerebral ventricular system with surrounding structures. In addition, an animation depicting the flow of CSF from the choroid plexus to the dural venous sinuses was created to highlight function of these anatomical substrates. This model and animation are intended for use as a resource in anatomical education, as current methods for teaching cerebral ventricular anatomy, such as cadaveric dissection and atlas diagrams, may be inadequate in some instances. The methods of segmentation, simplification, and model animation provide a basal architecture for future digital modelers for the use in anatomical education.

NOTES ON CONTRIBUTORS

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LITERATURE CITED

Allen JS, Damasio H, Grabowski TJ. 2002. Normal neuroanatomical variation in the human brain: An MRI-volumetric study. Am J Phys Anthropol 118:341–358.

Ambarki K, Israelsson H, Wåhlin A, Birgander R, Eklund A, Malm J. 2010. Brain ventricular size in healthy elderly: Comparison between Evans index and volume measurement. Neurosurgery 67:94–99.

Anil SM, Kato Y, Hayakawa M, Yoshida K, Nagahisha S, Kanno T. 2007. Virtual 3-dimensional preoperative planning with the dextroscope for excision of a 4th ventricular ependymoma. Minim Invasive Neurosurg 50:65–70.

Balogh A, Preul MC, Schornak M, Hickman M, Spetzler RF. 2004. Intraoperative stereoscopic QuickTime Virtual Reality. J Neurosurg 100:591–596.

Burtscher J, Bale R, Dessl A, Eisner W, Twerdy K, Sweeney RA, Felber S. 2002. Virtual endoscopy for planning neuro-endoscopic intraventricular surgery. Minim Invasive Neurosurg 45:24–31.

Brinkley JF, Bradley SW, Sundsten JW, Rosse C. 1997. The digital anatomist information system and its use in the generation and delivery of Web-based anatomy atlases. Comput Biomed Res 30:472–503.

CRIPT. 2010. Corps for Research of Instructional and Perceptual Technologies. Schulich School of Medicine and Dentistry, University of Western Ontario, London, Ontario, Canada. URL: http://www.anatatorium.com/CRIPT/Ventricles.html [accessed 20 Aug. 2011].

Dashner RA, Chakeres DW, Kangarlu A, Schmalbrock P, Christoforidis GA, DePhilip RM. 2003. MR imaging visualization of the cerebral microvasculature: A comparison of live and postmortem studies at 8 T. AJNR Am J Neuroradiol 24:1881–1884.

de Crespigny A, Bou-Reslan H, Nishimura MC, Phillips H, Carano RA, D'Arceuil HE. 2008. 3D micro-CT imaging of the postmortem brain. J Neurosci Methods 171:207–213.

Estevez M, Lindgren K, Bergethon P. 2010. A novel three-dimensional tool for teaching human neuroanatomy. Anat Sci Educ 3:309–317.

Fischl B, Salat DH, Busa E, Albert M, Dieterich M, Haselgrove C, van der Kouwe A, Killiany R, Kennedy D, Klaveness S, Montillo A, Makris N, Rosen B, Dale AM. 2002. Whole brain segmentation: Automated labeling of neuroanatomical structures in the human brain. Neuron 33:341–355.

Fjell AM, Walhovd KB. 2010. Structural brain changes in aging. Rev Neurosci 21:187–221.

Giesel FL, Hart AR, Hahn HK, Wignall E, Rengier F, Talanow R, Wilkinson ID, Zechmann CM, Weber MA, Kauczor HU, Essig M, Griffiths PD. 2009. 3D reconstructions of the cerebral ventricles and volume quantification in children with brain malformations. Acad Radiol 16:610–617.

Gill RW. 1985. Measurement of blood flow by ultrasound: Accuracy and sources of error. Ultrasound Med Biol 11:625–641.

Good CD, Johnsrude IS, Ashburner J, Henson RN, Friston KJ, Frackowiak RS. 2001. A voxel-based morphometric study of ageing in 465 normal adult human brains. Neuroimage 14:21–36.

Gorman PJ, Meier AH, Krummel TM. 1999. Simulation and virtual reality in surgical education: Real or unreal? Arch Surg 134:1203–1208.

Grober ED, Hamstra SJ, Wanzel KR, Reznick RK, Matsumoto ED, Sidhu RS, Jarvi KA. 2004. The educational impact of bench model fidelity on the acquisition of technical skill: The use of clinically relevant outcome measures. Ann Surg 240:374–381.

Hallgren RC, Parkhurst PE, Monson C L, Crewe NM. 2002. An interactive, web-based tool for learning anatomic landmarks. Acad Med 77:263–265.

Henn JS, Lemole GM Jr, Ferreira MA, Gonzalez LF, Schornak M, Preul MC, Spetzler RF. 2002. Interactive stereoscopic virtual reality: A new tool for neurosurgical education. Technical note. J Neurosurg 96:144–149.

Hisley KC, Anderson LD, Smith SE, Kavic SM, Tracy JK. 2008. Coupled physical and digital cadaver dissection followed by a visual test protocol provides insights into the nature of anatomical knowledge and its evaluation. Anat Sci Educ 1:27–40.

Howden L, Giddings D, Power H, Aroussi A, Vloeberghs M, Garnett M, Walker D. 2008. Three-dimensional cerebrospinal fluid flow within the human ventricular system. Comput Methods Biomech Biomed Eng 11:123–133.

Jackowski C, Persson A, Thali MJ. 2008. Whole body postmortem angiography with high viscosity contrast agent solution using poly ethylene glycol as contrast agent dissolver. J Forensic Sci 53:465–468.

John NW. 2007. The impact of Web3D technologies on medical education and training. Comput Educ 49:19–31.

Kikinis R, Shenton ME, Iosifescu DV, McCarley RW, Saiviroonporn P, Hokama HH, Robatino A, Metcalf D, Wible CG, Portas CM, Donnino RM, Jolesz FA.

1996. A digital brain atlas for surgical planning, model-driven segmentation, and teaching. IEEE Trans Vis Comput Graph 2:232–241.

Lemole GM Jr, Banerjee PP, Luciano C, Neckrysh S, Charbel FT. 2007. Virtual reality in neurosurgical education: Part-task ventriculostomy simulation with dynamic visual and haptic feedback. Neurosurgery 61:142–148.

Liu J, Huang S, Ihar V, Ambrosius W, Lee LC, Nowinski WL. 2010. Automatic model-guided segmentation of the human brain ventricular system from CT images. Acad Radiol 17:718–726.

Liu J, Huang S, Nowinski WL. 2009. Automatic segmentation of the human brain ventricles from MR images by knowledge-based region growing and trimming. Neuroinformatics 7:131–146.

Luursema J-M, Verwey WB, Kommers PA, Annema J-H. 2008. The role of stereopsis in virtual anatomical learning. Interact Comput 20:455–460.

Mantovani F, Castelnuovo G, Gaggioli A, Riva G. 2003. Virtual reality training for health-care professionals. Cyberpsychol Behav 6:389–395.

Marks SC Jr. 2000. The role of three-dimensional information in health care and medical education: The implications for anatomy and dissection. Clin Anat 13:448–452.

Miller R. 2000. Approaches to learning spatial relationships in gross anatomy: Perspective from wider principles of learning. Clin Anat 13:439–443.

Netter FH. 2006. Atlas of Human Anatomy. 4th Ed. Philadelphia, PA: Saunders, Elsevier Inc. 640 p.

Nolte J. 2002. The Human Brain: An Introduction to Its Functional Anatomy. 6th Ed. Philadelphia, PA: Mosby. 736 p.

Nowinski WL, Thirunavuukarasuu A, Ananthasubramaniam A, Chua BC, Qian G, Nowinska NG, Marchenko Y, Volkau I. 2009a. Automatic testing and assessment of neuroanatomy using a digital brain atlas: Method and development of computer- and mobile-based applications. Anat Sci Educ 2:224–252.

Nowinski WL, Thirunavuukarasuu A, Volkau I, Marchenko Y, Aminah B, Gelas A, Huang S, Lee LC, Liu J, Ng TT, Nowinska NG, Qian GY, Puspitasari F, Runge VM. 2009b. A new presentation and exploration of human vasculature correlated with surface and sectional neuroanatomy. Anat Sci Educ 2:24–33.

Nowinski WL, Volkau I, Marchenko Y, Thirunavuukarasuu A, Ng TT, Runge VM. 2009c. A 3D model of human cerebrovasculature derived from 3T magnetic resonance angiography. Neuroinformatics 7:23–36.

Nguyen N, Wilson TD. 2009. A head in virtual reality: Development of a dynamic head and neck model. Anat Sci Educ 2:294–301.

Parikh M, Rasmussen M, Brubaker L, Salomon C, Sakamoto K, Evenhouse R, Ai Z, Damaser MS. 2004. Three dimensional virtual reality model of the normal female pelvic floor. Ann Biomed Eng 32:292–296.

Petersson H, Sinkvist D, Wang C, Smedby O. 2009. Web-based interactive 3D visualization as a tool for improved anatomy learning. Anat Sci Educ 2:61–68.

Pham DL, Xu C, Prince JL. 2000. Current methods in medical image segmentation. Annu Rev Biomed Eng 2:315–337.

Pitiot A, Delingette H, Thompson PM, Ayache N. 2004. Expert knowledge-guided segmentation system for brain MRI. Neuroimage 23:S85–S96.

Schnack HG, Hulshoff Pol HE, Baaré WF, Viergever MA, Kahn RS. 2001. Automatic segmentation of the ventricular system from MR images of the human brain. Neuroimage 14:95–104.

Sergovich A, Johnson M, Wilson TD. 2010. Explorable three-dimensional digital model of the female pelvis, pelvic contents, and perineum for anatomical education. Anat Sci Educ 3:127–133.

Smith DM, Oliker A, Carter CR, Kirov M, McCarthy JG, Cutting CB. 2007a. A virtual reality atlas of craniofacial anatomy. Plast Reconstr Surg 120:1641–1646.

Smith CD, Chebrolu H, Wekstein DR, Schmitt FA, Markesbery WR. 2007b. Age and gender effects on human brain anatomy: A voxel-based morphometric study in healthy elderly. Neurobiol Aging 28:1075–1087.

Spitzer VM, Scherzinger AL. 2006. Virtual anatomy: An anatomist's playground. Clin Anat 19:192–203.

Strub CG, Frederick LG. 1989. The Principles and Practice of Embalming. 5th Ed. Dallas, TX: Professional Training Schools, Inc. 712 p.

Sundsten JW. 1994. Digital Anatomist: Interactive Brain Atlas. University of Washington, Seattle, WA. URL: http://www9.biostr.washington.edu/cgi-bin/DA/PageMaster?atlas:Neuroanatomy+ffpathIndex:Splash^Page+2 [accessed 20 May 2011].

Tam MD. 2010. Building virtual models by postprocessing radiology images: A guide for anatomy faculty. Anat Sci Educ 3:261–266.

Tam MD, Hart AR, Williams S, Heylings D, Leinster S. 2009. Is learning anatomy facilitated by computer-aided learning? A review of the literature. Med Teach 31:e393–e396.

Temkin B, Acosta E, Malvankar A, Vaidyanath S. 2006. An interactive three-dimensional virtual body structures system for anatomical training over the internet. Clin Anat 19:267–274.

Toga AW, Thompson PM, Mori S, Amunts K, Zilles K. 2006. Towards multi-modal atlases of the human brain. Nat Rev Neurosci 7:952–966.

Upton ML, Weller RO. 1985. The morphology of cerebrospinal fluid drainage pathways in human arachnoid granulations. J Neurosurg 63:867–875.

Vernon T, Peckham D. 2002. The benefits of 3D modelling and animation in medical teaching. J Audiov Media Med 25:142–148.