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ORIGINAL COMMUNICATION

Visible Korean Human: Its Techniques and Applications

JIN SEO PARK,[1] MIN SUK CHUNG,[1*] SUNG BAE HWANG,[2] BYEONG-SEOK SHIN,[3] AND HYUNG SEON PARK[4]

[1]*Department of Anatomy, Ajou University School of Medicine, Suwon, Republic of Korea*
[2]*Department of Physical Therapy, Kyungbuk College, Yeongju, Republic of Korea*
[3]*Department of Computer Science and Information Engineering, Inha University, Inchon, Republic of Korea*
[4]*Center for Computational Biology and Bioinformatics, Korea Institute of Science and Technology Information, Daejeon, Republic of Korea*

Three recent studies have offered an unprecedented view of the human body. The Visible Human Project, the Visible Korean Human (VKH), and the Chinese Visible Human have featured the serial sectioning of whole cadavers, producing cross-sectional images that methodically catalogue gross human anatomy. By volumetric reconstruction, these cross-sectional images can be transformed into three-dimensional (3D) images of anatomic structures. Compiling these 3D images would create an invaluable library for medical education and research. The goal of this report is to promote the expansion of such a library of 3D anatomic images and to help users fully understand and utilize the serially sectioned images. To do this, we will discuss the fundamental techniques and equipment used in the VKH and its preliminary experiments. We will also address new applications of the VKH, including virtual brain surgery, virtual endoscopy, and virtual cardiopulmonary resuscitation via the development of virtual dissection software. Clin. Anat. 19:216–224, 2006.

Key words: serially sectioned images; three-dimensional images; anatomic image library

INTRODUCTION

The Visible Human Project (VHP) (Colorado University, Denver, Colorado) was the first experiment that compiled data from magnetic resonance (MR), computed tomography (CT), and anatomic images of male (1994) and female (1995) cadavers. The VHP was an original experiment with revolutionary data acquisition methods (Spitzer et al., 1996; Spitzer and Whitlock, 1998; Ackerman, 1999). In 2001, the Visible Korean Human (VKH) experiment began at Ajou University, Suwon, Republic of Korea, which produced data that supplemented the VHP. In addition to producing MR and CT images, the VKH generated comprehensive anatomic images of a male cadaver (interval, 0.2 mm; pixel size, 0.2 mm) with realistic color. The study also produced segmented images of eleven structures derived from the anatomic images (Park et al., 2005a,b). Subsequently, the Chinese Visible Human (CVH) experiment created serially sectioned images of male and female cadavers (Zhang et al., 2003, 2004).

Essential techniques and potential applications of the VKH are discussed in this report so as to encourage further research in generating new serially sectioned images to complement the existing data.

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*Correspondence to: Dr. Min Suk Chung, Department of Anatomy, Ajou University School of Medicine, Suwon 443-749, Republic of Korea. E-mail: dissect@ajou.ac.kr

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MATERIALS AND METHODS

Preliminary Experiments

For five years (March 1996 to February 2001), preliminary experiments were performed to prepare, select, and optimize the equipment and techniques used for the VKH. Tissue specimens included a brain, heart, lung, and a foot, as well as two entire cadavers. MR imaging was also performed on a living subject.

In the first experiment, anatomic, segmented, and three-dimensional (3D) images of a brain, heart, and lung were obtained (Chung et al., 2000; Chung and Kim, 2000). A meat slicer (HFS-330L, FUJEE) was used to generate anatomic slices (thickness, 1.4 mm). A scanner (HP Scanjet 4C, Hewlett Packard; resolution, 600 dpi) was then used to convert the anatomic slices into computerized anatomic images. Some anatomic structures in the images were manually drawn using Corel DRAW (version 8.0). After stacking the images, 3D images were produced by volumetric reconstruction. Virtual dissection software was then created, allowing the 3D images to be virtually sectioned and rotated (Figs. 1 and 2) (Chung and Kim, 2000).

Another experiment was conducted on an embalmed foot from a cadaver perfused with a formaldehyde fixative. The amputated foot was placed in an embedding box and serially sectioned at 10 mm intervals using a bone slicer (HBS-400S, FUJEE). These were photographed with a digital camera (DX3700, Kodak; resolution, 2,160 × 1,440) and downloaded onto a computer to produce anatomic images.

Cross-sectional MR imaging (body coil; slice thickness, 3 mm; interslice gap, 0 mm; field of view, 480 mm × 480 mm; resolution, 512 × 512, T1 weighted) of a living young adult male subject was also performed, generating 613 MR images. The MR images were then semiautomatically segmented using Adobe Photoshop (version 7.0). After stacking the segmented images, 3D images of 47 anatomic structures were made by the polygon surface reconstruction method (3ds max, version 5.0), which could then be displayed and rotated (Fig. 3) (Park et al., 2005b).

In the last of the preliminary experiments, two male cadavers were scanned using MR and CT at 1.0 mm intervals and then serially sectioned at 0.2 mm intervals using a cryomacrotome. Each sectioned surface was photographed with a digital camera (DSC560, Kodak; resolution, 3,040 × 2,008), producing an anatomic image (pixel size, 0.2 mm) (Park et al., 2005a).

Main Experiment

From March 2001 to August 2003, the main experiment was performed to generate MR, CT, anatomic, and segmented images (Park et al., 2005a,b). The specimen was a 33-year-old male cadaver with an average male Korean body habitus (height, 1.64 m; weight, 55 kg). The cause of death was leukemia. Neither fixative nor dye was perfused into the cadaver. The cadaver was placed supine into an immobilization box. The upper extremities were positioned with the palmar aspect of each hand facing medially. A pillow was used as support under the head. The cadaver's position was fixed with an immobilizing agent (Mev-Green).

The entire cadaver was then MR scanned (body coil; slice thickness, 1 mm; interslice gap, 0 mm; field of view, 480 mm × 480 mm; resolution, 512 × 512; TR, 800 ms; TE, 8 ms; two NEX; interleave method). The MR images were downloaded onto a personal computer and saved as tag image file format (TIFF) files (bit depth, 8 bits gray). Two series of MR images (head to knee and knee to toe) were combined and aligned. The entire cadaver was also CT scanned (slice thickness, 1 mm; interslice gap, 0 mm; field of view, 480 mm × 480 mm; resolution, 512 × 512; standard algorithm; voltage, 120 kV; electric current time, 280 mAs). The CT images were also downloaded onto the personal computer (Fig. 4, Table 1).

The cadaver was then transferred from the immobilization box to an embedding box while maintaining its original direction. Four alignment rods were inserted into the embedding box. Small quantities of embedding agent (gelatin with methylene blue) were poured into the embedding box, which was subsequently placed in the freezer. This process was repeated until the embedding box was completely filled. This staged filling prevented the embedding agent from compressing soft regions of the cadaver, e.g., abdomen, as it expanded during freezing. Using a crane, the embedding box was placed on the cryomacrotome parallel to its longitudinal axis. After securing the embedding box on the cryomacrotome, the box was moved (20.8 mm/s) through the rotating cutting blade (628 rpm) to produce serially sectioned (0.2 mm intervals) surfaces. During this process, the frozen state of the embedding box was maintained by using cold laboratory (room temperature less than 5°C), and dry ice; the cutting blade was frequently replaced. After each serial section, the resulting sectioned surfaces were positioned in a consistent reference frame beneath a mounted digital camera (DSC560, Kodak; resolution, 3,040 × 2,008; bit depth, 24 bits color) and digitally captured with both color and gray scale. A total of 8,590 anatomic images (Fig. 4, Table 1) were downloaded onto a computer and saved as TIFF files.

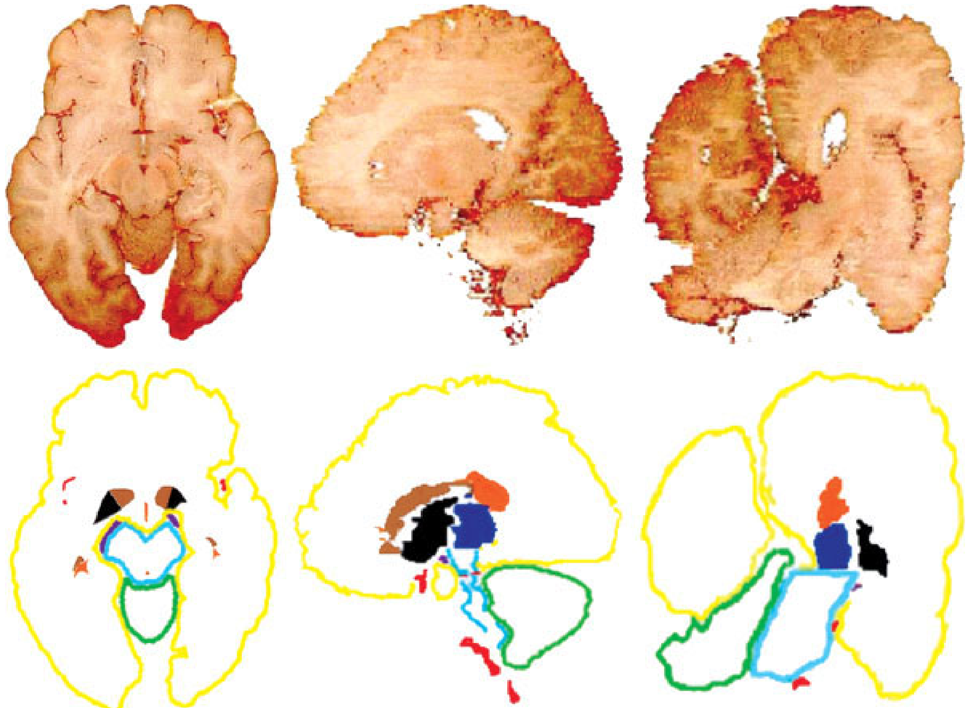

Fig. 1. Anatomic images (top row) and segmented images (bottom row) of a brain in the horizontal plane (left column), sagittal plane (center column), and oblique plane (right column). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

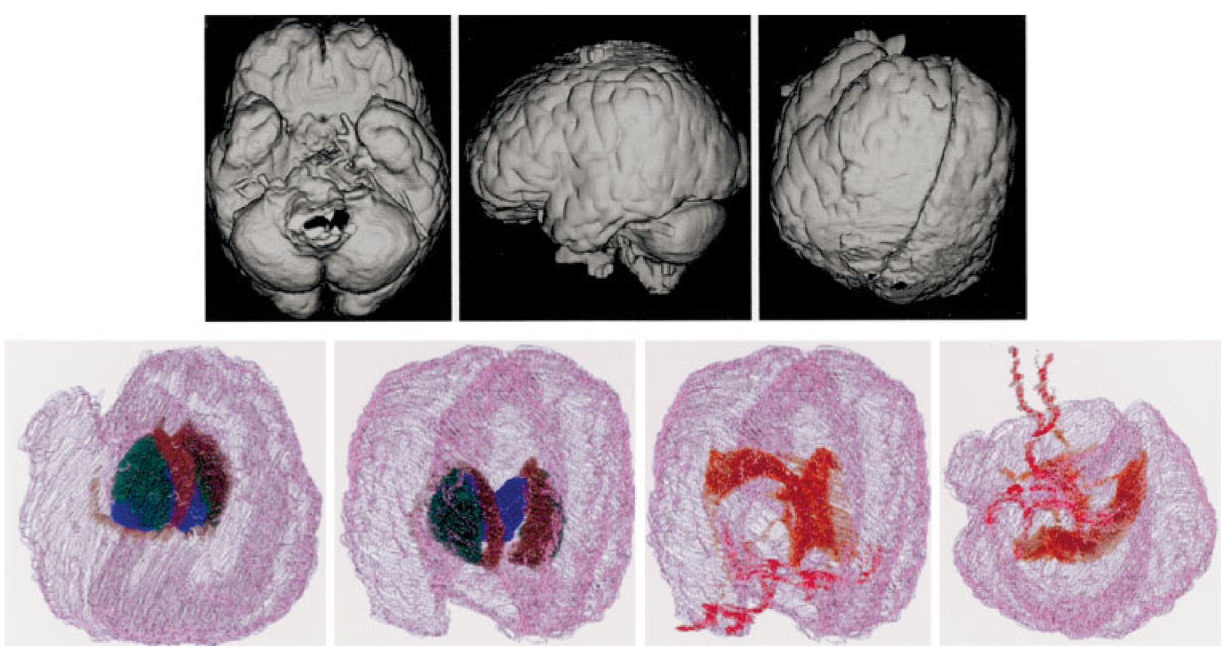

Fig. 2. Arbitrary angle rotation of the 3D image of a brain (top row) and that of selected brain components (lentiform nuclei, caudate nuclei, ventricles, and cerebral arteries) (bottom row). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 3. Three-dimensional images of skin, skeleton, and rotated 3D images of a femur (left to right) made by surface reconstruction. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

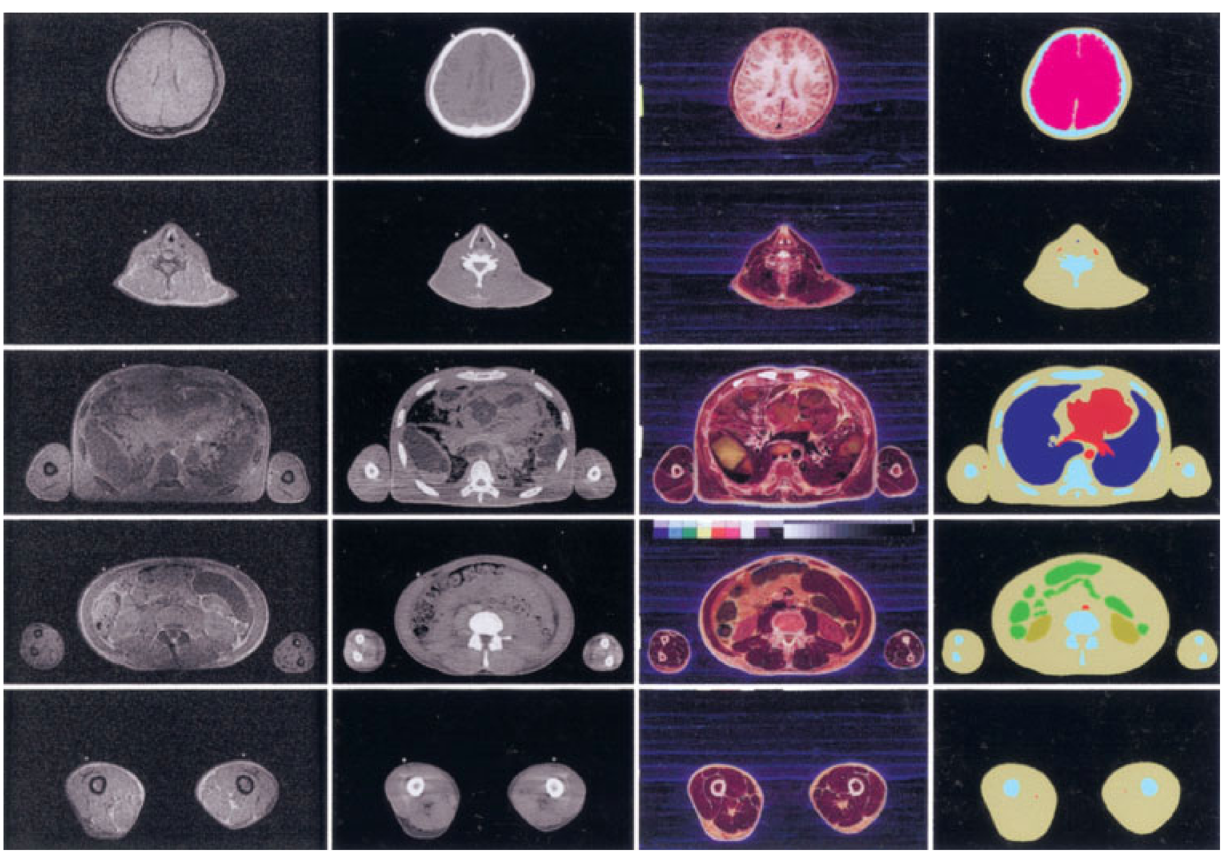

Fig. 4. MR images (1st column), CT images (2nd column), anatomic images (3rd column), and segmented images (4th column) of the head (1st row), neck (2nd row), thorax (3rd row), abdomen (4th row), and lower limbs (5th row). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 1. MR, CT, Anatomic, and Segmented Images Either as Full-Sized Data or as Reduced Data

	Intervals (mm)	Number	Resolution	Bit depth	Single file size (KB)	Total file size (GB)
Full-Sized data						
MR images	1.0	1,718	505 × 276	8 bits gray	147	0.2
CT images	1.0	1,718	505 × 276	8 bits gray	147	0.2
Anatomic images	0.2	8,590	3,040 × 2,008	24 bits color	17,890	146.4
Segmented images	0.2	8,590	3,040 × 2,008	8 bits color	5,900	50.7
Total						197.5
Reduced data						
MR images	1.0	1,718	505 × 276	8 bits gray	147	0.2
CT images	1.0	1,718	505 × 276	8 bits gray	147	0.2
Anatomic images	1.0	1,718	608 × 402	24 bits color	716	1.1
Segmented images	1.0	1,718	608 × 402	8 bits color	238	0.3
Total						1.8

Eleven important structures (skin, bones, liver, lungs, kidneys, urinary bladder, digestive tract, respiratory tract, arteries, brain, and heart) from the anatomic images were selected to be segmented (Table 2). Contours of the anatomic structures were semiautomatically drawn using the magnetic lasso tool of Adobe Photoshop. Each structure was colored to produce 8,590 segmented images (Fig. 4, Table 1) (Park et al., 2005b).

RESULTS

Main Experiment

The length of the cadaver with the feet plantarflexed was 1,718 mm. Intervals of the MR and CT images were 1.0 mm, producing 1,718 pairs of MR and CT images. Each cropped MR and CT image had 505 × 276 resolution (pixel size, 1.0 mm), 8 bits gray, and 147 KB file size. Intervals of the anatomic

TABLE 2. Segmented Anatomic Structures

Anatomic structures	Components
Skin	
Bones	
Liver	
Lungs	
Kidneys	
Urinary bladder	
Digestive tract	Oral cavity,[a] pharynx,[a] esophagus,[a] stomach,[a] small intestine,[a] large intestine[a]
Respiratory tract	Nasal cavity,[a] pharynx,[a] larynx,[a] trachea,[a] bronchi,[a] lobar bronchi,[a] segmental bronchi[a]
Arteries	Ascending aorta,[a] aortic arch,[a] brachiocephalic trunk,[a] common carotid arteries,[a] external carotid arteries,[a] subclavian arteries,[a] axillary arteries,[a] brachial arteries,[a] radial arteries,[a] ulnar arteries,[a] thoracic aorta,[a] abdominal aorta,[a] celiac trunk,[a] renal arteries,[a] common iliac arteries,[a] internal iliac arteries,[a] external iliac arteries,[a] femoral arteries,[a] popliteal arteries,[a] anterior tibial arteries,[a] posterior tibial arteries[a]
Brain	Cerebrum,[b] cerebellum,[b] brain stem,[b] globi pallidi,[b] putamens,[b] caudate nuclei,[b] amygdaloid bodies,[b] thalami,[b] pituitary gland,[b] lateral ventricles,[a,b] third ventricle,[a,b] mesencephalic aqueduct,[a,b] fourth ventricle,[a,b] dural venous sinus[a,b]
Heart	Heart, right atrium,[a,b] left atrium,[a,b] right ventricle,[a,b] left ventricle,[a,b] right coronary artery,[a,b] left coronary artery,[a,b] tricuspid valve,[b] mitral valve,[b] pulmonary valve,[b] aortic valve[b]

[a]Luminal contours are segmented.

[b]Fourteen brain components and 10 heart components are further segmented.

images were 0.2 mm, resulting in 8,590 pairs of anatomic and segmented images. Each anatomic image had 3,040 × 2,008 resolution, 24 bits color, and 17,890 KB file size, while each segmented image had a similar resolution, 8 bits color, and 5,900 KB file size. The file size of the MR, CT, anatomic, and segmented images (full-sized data) was 197.5 GB in total (Table 1) (Park et al., 2005a).

The MR and CT images revealed relatively distinct anatomic structures, which were consistent throughout the entire cadaver. The anatomic images were aligned, which was verified using the alignment rods as a frame of reference. Every MR and CT image (1.0 mm intervals) corresponded to every fifth anatomic image (0.2 mm intervals) (Table 1). The anatomic images displayed consistent brightness, which was verified by examining the color and gray scale. The images also showed distinct anatomic structures with realistic colors. The contours of the 11 segmented anatomic structures were accurate as compared to the serially segmented images (Fig. 4) (Park et al., 2005a).

Virtual Anatomy Software

The data generated by the main experiment led to the creation of additional segmented images of the head and thorax, virtual dissection software, and virtual endoscopy software (September 2003 to February 2005). Of the 790 anatomic images of the head obtained in the main experiment, 158 images were selected by choosing one out of every five images. Of these 158 images of the head, 14 brain components were further segmented in the same manner as the main experiment to produce 158 additional segmented images. Likewise, of the 128 anatomic images of the thorax (including the heart), 10 heart components were further segmented to make additional 128 segmented images (Fig. 5, Tables 2 and 3).

Volumetric reconstruction was used to produce 3D anatomic and segmented images after stacking paired anatomic axial and segmented axial images of the head and thorax. Virtual dissection software, on which the 3D images could be sectioned, selected, and rotated, was then created on Visual C++ (Microsoft, version 6.0). The 3D images were virtually sectioned to produce coronal and sagittal images. Comparison of the anatomic and segmented images enabled us to verify the anatomic accuracy of specific structures (Fig. 6). Using the volume ray casting method, the 3D images could then be displayed and rotated (Fig. 7).

Following stacking of anatomic and segmented images of the digestive and respiratory tracts, 3D anatomic and segmented images were also made by volumetric reconstruction. Virtual endoscopy software, by which the lumina of the anatomic structures could be explored, was then produced by using the volume ray casting method. The view point, which was the lighted endoscope tip, was placed in the lumen of the 3D image of the digestive and respiratory tracts. From the view point, the view ray was cast radially to the 3D segmented image to find the coordinates of the luminal contour. The coordinates were applied to the 3D anatomic image to find the real color of the luminal contour. The real color was cast back concentrically to the view point to display the 3D image of the luminal contour. At this time, a perspective effect was applied to create depth and to elucidate the luminal topography. As in real endoscopy, the view point was moved along the lumen and the view direction was changed at arbitrary angles. The same virtual endoscopy software was also made from CT images of the VKH (Fig. 8).

DISCUSSION

The preliminary experiments allowed us to identify the most appropriate techniques for sectioning and studying human cadavers. For soft tissues such as the brain, heart, and lung, a meat slicer was used for serial sectioning (Chung et al., 2000; Chung and Kim, 2000). For the embalmed foot, a bone slicer proved to be superior, as this study involved slicing through osseous structures. For the entire body, a cryomacrotome, which was a modified milling machine, was the only way to make sectioned surfaces with 0.2 mm intervals (Kathrein et al., 1996).

A scanner with 600 dpi resolution was initially used to scan sections, which were then converted to computerized anatomic images (Fig. 1). Technically, however, scanning the wet sectioned slices was extremely difficult. Thus, in subsequent preliminary experiments, the sections were photographed with a digital camera, which also resulted in images with more realistic color. The digital camera used in the preliminary experiment on the embalmed foot (2,160 × 1,440 resolution) was changed to a digital camera with higher resolution (3,040 × 2,008) for subsequent photography of the VKH because of the larger cross-sectional area of the entire cadaver.

CorelDRAW was used to manually draw the indistinct contours of the brain, heart, and lung that could not be distinguished by the computer (Fig. 1). As manual segmentation was extremely tedious and also subject to significant intraobserver and interob-

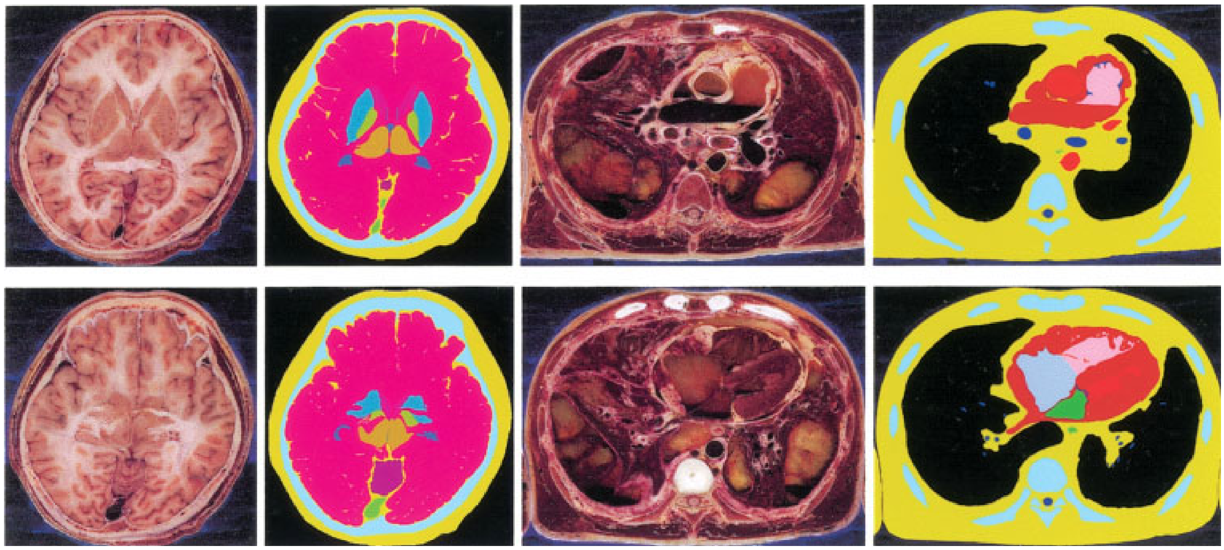

Fig. 5. Anatomic images (1st column) and segmented images (2nd column) of head. Anatomic images (3rd column) and segmented images (4th column) of thorax. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

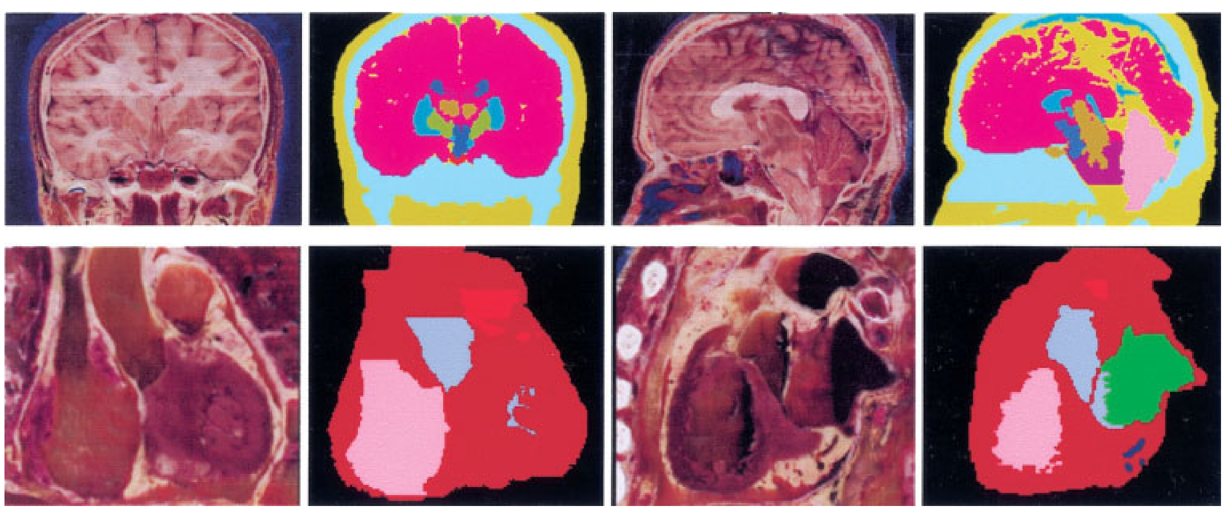

Fig. 6. Coronal anatomic images (1st column), coronal segmented images (2nd column), sagittal anatomic images (3rd column), and sagittal segmented images (4th column) of head (top row) and thorax (bottom row). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 3. Segmented Images of Head Including 14 Brain Components and Segmented Images of Thorax Including 10 Heart Components

	Intervals (mm)	Number	Resolution	Bit depth	Single file size (KB)	Total file size (GB)
Segmented images of head	1.0	158	3,040 × 2,008	8 bits color	5,900	0.9
Segmented images of thorax	1.0	128	3,040 × 2,008	8 bits color	5,900	0.7

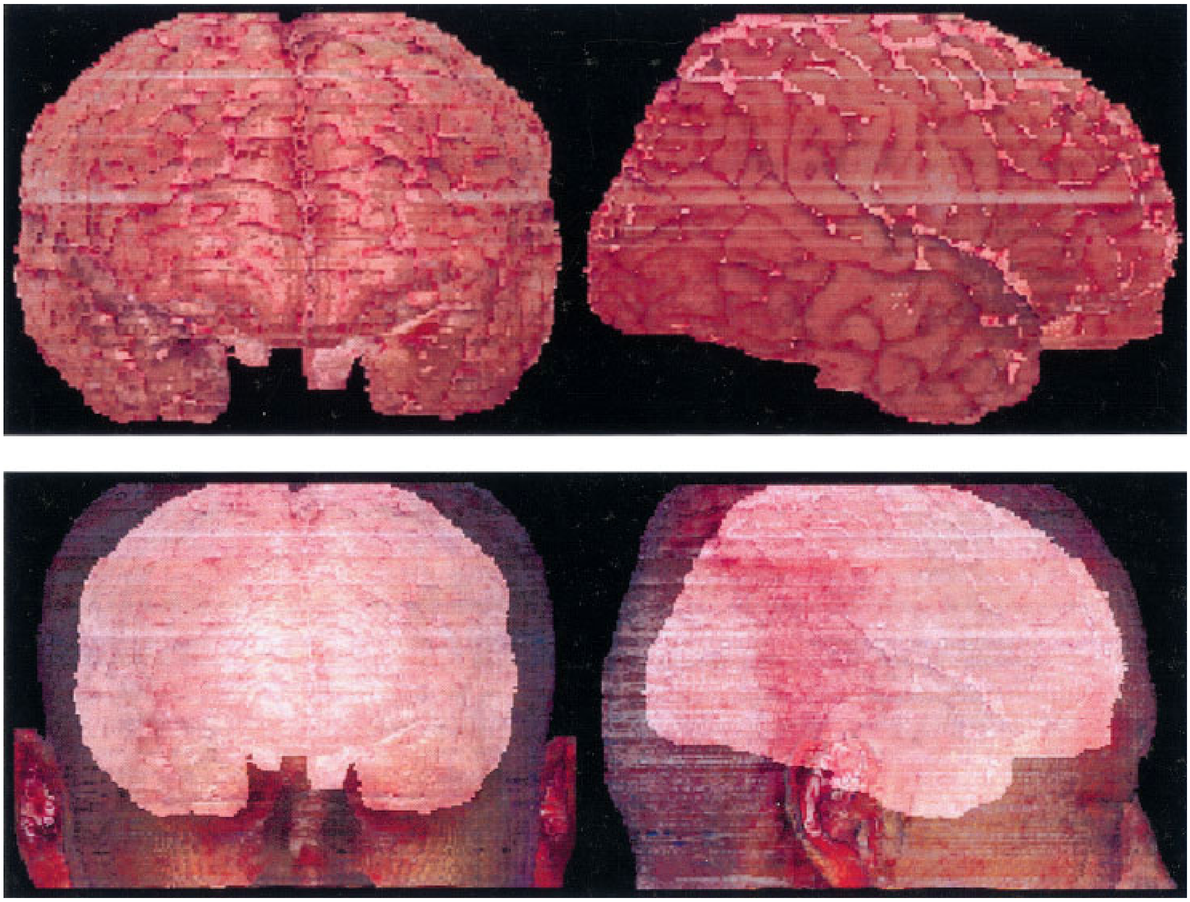

Fig. 7. Rotated 3D image of cerebrum (top) and that of semitransparent skin and cerebrum (bottom). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 8. Virtual endoscopy of the digestive tract (left) and respiratory tract (center) made from anatomic images and that of the digestive tract made from CT images (right). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

server errors, semiautomatic segmentation using Adobe Photoshop was performed in subsequent experiments.

When creating a 3D library of cadavers in their entirety, we recognized the importance of maintaining a consistent body direction for axial scanning and serial sectioning. This resulted in MR, CT, anatomic, and segmented images that could be directly compared and correlated (Fig. 4). Use of an immobilization box, immobilizing agent, embedding box, and embedding agent was critical in maintaining the cadaver direction, as described in the VHP (Spitzer et al., 1996). Because of the limitations in the translation of the table through the MR machine, the cadavers were scanned from head to knee, and then scanned distal to the knee separately. This same technique was used for CT imaging.

As segmentation is extremely labor intensive and time-consuming, it would be beneficial for other researchers to have free access to the images for study and research. This would avoid the redundancy of work and efficiently propel the development of a 3D anatomic library. For ease of data use and storage, we reduced the file size of the VKH data from 200 GB to 1.8 GB by primarily decreasing the resolution (Table 1). This has facilitated easier distribution of data through our website (www.anatomy.co.kr).

For future experiments, we recommend that various human subjects of different ages and pathologies should be sectioned. This would greatly enrich the 3D library for students and researchers. Serial sectioning at the histological level could also be done in future experiments to produce anatomic images with 0.1-mm sized intervals and pixel size. This could be achieved using a cryomacrotome calibrated to 0.1 mm intervals and a digital camera with doubled resolution (6,000 × 4,000).

The VKH has exciting potential applications in the fields of virtual surgery, virtual endoscopy, and virtual cardiopulmonary resuscitation (CPR). For example, virtual brain surgery could be performed by comparing a patient's MR images with compatible anatomic and segmented images from the VKH. As a result, 3D images of the skin, skull, and brain components, which is fit for the patient, could be produced in high resolution and true color (Fig. 7). On the basis of these 3D images, neurosurgeons could practice and plan for the best surgical approach. Furthermore, referencing 3D images during surgical procedures would be useful for identifying anatomic landmarks to maintain orientation. Performing virtual endoscopy or bronchoscopy with real color would also be a useful learning tool for physicians in training (Fig. 8). A program for virtual CPR could also be designed based on 3D images created from anatomic and segmented images of the thorax. A mannequin with pressure sensors and haptic devices would be linked to a computer displaying 3D images of the thoracic wall, heart, and lungs. These images would transform in real-time according to how the mannequin is manipulated. Each performance of CPR could also be judged against a standard and scored.

Multidisciplinary cooperation between experts in various fields (anatomists, diagnostic radiologists, machinery engineers, photographers, computer engineers, and clinicians) is necessary to create anatomic images for medical education and research. It is our hope that the fundamental techniques in this report will aid other researchers in developing their own serially sectioned anatomic images, which will contribute to a growing 3D anatomic library.

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