Visible Korean Human: Improved Serially Sectioned Images of the Entire Body

Jin Seo Park, Min Suk Chung*, Sung Bae Hwang, Yong Sook Lee, Dong-Hwan Har, and Hyung Seon Park

***Abstract*—The data from the Visible Human Project (VHP) and the Chinese Visible Human (CVH), which are the serially sectioned images of the entire cadaver, are being used to produce three-dimensional (3-D) images and software. The purpose of our research, the Visible Korean Human (VKH), is to produce an enhanced version of the serially sectioned images of an entire cadaver that can be used to upgrade the 3-D images and software. These improvements are achieved without drastically changing the methods developed for the VHP and CVH; thus, a complementary solution was found. A Korean male cadaver was chosen without anything perfused into the cadaver; the entire body was magnetic resonance (MR) and computed tomography (CT) scanned at 1.0-mm intervals to produce MR and CT images. After scanning, entire body of the cadaver was embedded and serially sectioned at 0.2-mm intervals; each sectioned surface was inputted into a personal computer to produce anatomical images (pixel size: 0.2 mm) without any missing images. Eleven anatomical organs in the anatomical images were segmented to produce segmented images. The anatomical and segmented images were stacked and reconstructed to produce 3-D images. The VKH is an ongoing research; we will produce a female version of the VKH and provide more detailed segmented images. The data from the VHP, CVH, and VKH will provide valuable resources to the medical image library of 3-D images and software in the field of medical education and clinical trials.**

***Index Terms*—Anatomical images, CT images, MR images, Visible Korean Human.**

I. Introduction

THE Visible Human Project (VHP) was the first extensive research to release data of the serially sectioned images of the entire human body in 1994 (male) and 1995 (female). The VHP data consists of magnetic resonance (MR) images, computed tomography (CT) images, and anatomical images. After reconstructing the VHP data, three-dimensional (3-D) images and software such as virtual dissection, virtual endoscopy, and virtual operation have been made. The VHP data, however, were not complete enough in certain aspects of data acquisition process. The main reasons of this are as follows. First, the two cadavers used for the VHP data were that of elderly people with obese body and pathological findings. Second, the VHP data did not include complete MR and CT images of the entire body [Fig. 1(a)]. Third, the VHP data did not include the anatomical images between the four blocks of the cadavers [Fig. 1(b), (c)]. Fourth, the anatomical images of the VHP data did not include anatomical structures that were smaller than 0.2 mm since both the interval and pixel size of the images were 0.33 mm or greater. Fifth, the color of the anatomical images of the VHP data were not similar to a living body because formalin was perfused into the cadaver prior to serial sectioning [Fig. 2(a)]. Last, the VHP did not publish the segmented images, which are essential to produce 3-D images of each anatomical organ [1]–[5].

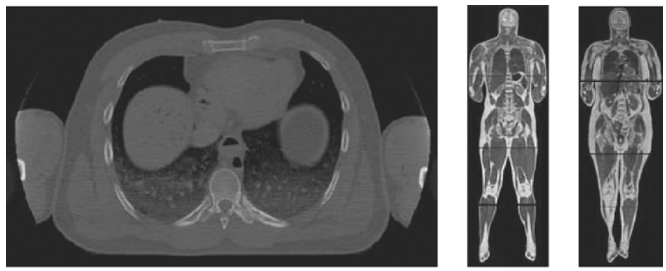

Fig. 1. Data lost in the VHP. (a) Upper limbs' lateral parts are cut off in the CT images. (b)–(c) The anatomical images between the four blocks are missing.

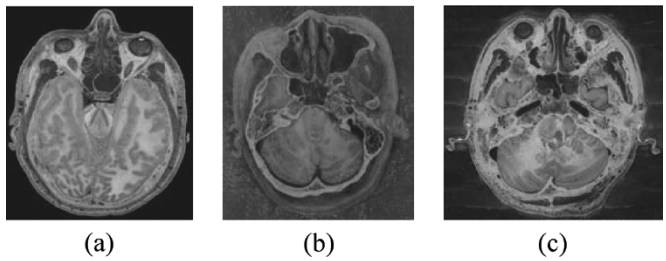

Fig. 2. Comparison of the colors in anatomical images. (a) General colors in the VHP data are relatively white due to the formalin perfusion. (b) Muscle colors in the CVH data are relatively red due to the red gelatin solution perfusion. (c) General colors in the VKH data are similar to a living body.

The Chinese Visible Human (CVH) data were released in 2002 (male) and 2003 (female). The CVH data also included anatomical images that did not have colors similar to a living

Manuscript received August 9, 2004; revised November 30, 2004. This work was supported in part by Department of Medical Sciences, The Graduate School, Ajou University, Republic of Korea under Grant 2001. The Associate Editor responsible for coordinating the review of this paper and recommending its publication was K. H. Hoehne. *Asterisk indicates corresponding author.*

J. S. Park, S. B. Hwang, and Y. S. Lee are with the Department of Anatomy, Ajou University School of Medicine, Suwon, Republic of Korea (e-mail: park93@ajou.ac.kr; hsb75@ajou.ac.kr; doctoryslee@hotmail.com).

*M. S. Chung is with the Department of Anatomy, Ajou University School of Medicine, 5 Woncheon-dong, Yeongtong-gu, Suwon 443-749, Republic of Korea (e-mail: dissect@ajou.ac.kr).

D.-H. Har is with Graduate School of Advanced Imaging Science, Multimedia & Film, Chungang University, Seoul, Republic of Korea (e-mail: dhhar@cau.ac.kr).

H. S. Park is with Center for Computational Biology and Bioinformatics, Korea Institute of Science and Technology Information, Daejeon, Republic of Korea (e-mail: seonpark@kisti.re.kr).

Digital Object Identifier 10.1109/TMI.2004.842454

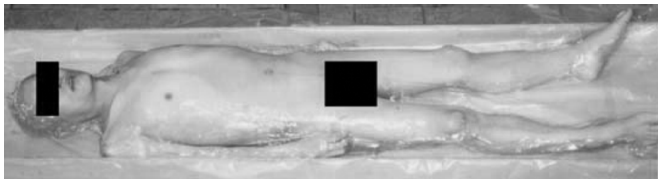

Fig. 3. A Korean male cadaver is laid down in the immobilizing box for MR and CT scanning.

body because red gelatin solution was perfused [Fig. 2(b)]. The CVH data included anatomical images whose intervals were 1.0 mm (male) and 0.5 mm (female) except the head and neck. The CVH data did not publish segmented images [6], [7].

The purpose of our research, the Visible Korean Human (VKH), is to enhance the serially sectioned images so to compensate the VHP and CVH data; subsequently, to promote the development of improved 3-D images and software that will be helpful in the field of medical education and clinical trials. In the VKH, a Korean male cadaver was chosen and nothing was perfused into the cadaver. The cadaver's entire body was MR and CT scanned at 1.0-mm intervals to produce MR and CT images. After embedding the cadaver's entire body, it was serially sectioned at 0.2-mm intervals; each sectioned surface was inputted into a personal computer to produce anatomical images (pixel size: 0.2 mm) without any missing images. Eleven anatomical organs in the anatomical images were segmented to produce segmented images. The anatomical and segmented images were stacked and reconstructed to produce 3-D images.

II. Methods

A donated Korean male cadaver was selected. For the preliminary experiment, two Korean male cadavers were chosen; their age, body size, and pathological findings were not considered adequate for the final experiment. To ensure good quality for the images, a young adult cadaver with no obesity nor pathological findings was selected for the final experiment, anatomists and diagnostic radiologists judged dozens of donated Korean cadavers in advance. As a result, a male cadaver, who died of leukemia on March 26, 2001, was chosen for the final experiment; he was young (33 years old), and the body size (1640 mm, 55 kg) was Korean average. Neither fixative nor dye was perfused into the cadaver. Hairs were removed using scissors and razors, and entire body was washed with water and soap (Fig. 3).

The cadaver was put into an immobilizing box. The immobilizing box (inner size: width, 505 mm $\times$ height, 90 mm $\times$ length, 2060 mm; outer size: width, 525 mm $\times$ height, 100 mm $\times$ length, 2080 mm) was made of wood. The outer size of the immobilizing box was maximized to enable the box to enter the MRI and CT machines. The cadaver was laid down parallel to the longitudinal axis of the immobilizing box. A thread was attached longitudinally to the immobilizing box to verify symmetry of the cadaver's head, body, and limbs. A pillow was supported under the head to prevent the head from extending. The palms were placed on each side of the trunk to make the attention posture (Fig. 3). The direction and posture of the cadaver were fixed with an immobilizing agent (Mev-Green), which is a foaming and solidifying agent generally used in radiation therapy.

The entire body of the cadaver was MR scanned by 1.0-mm intervals on March 27, 2001. The immobilizing box containing the cadaver was placed on the bed of the MRI machine (GE Signa Horizon 1.5-tesla MRI System, Milwaukee, WI) parallel to the longitudinal axis of the bed; a laser light guided parallel positioning. Using body coil, the cadaver was horizontally MR scanned at 1.0-mm slice thickness and 0-mm interslice gap to produce 1718 MR images (intervals: 1 mm) (Table I). Since it was impossible to do an MR scanning of the entire body at once, it was processed in two series: from head to knee and from knee to toe. After MR scanning the entire body, two series of the MR images were combined and aligned on a personal computer. Field of view and resolution of the MR images was 480 mm $\times$ 480 mm and 512 $\times$ 512, respectively, so the pixel size of the MR images was approximately 1.0 mm. While MR scanning, a makeshift T1 method was used to distinguish the various anatomical structures. Repetition time was fixed at 800 ms and echo time was fixed at 8 ms to increase the signal/noise ratio. Interleave method was used to remove interference between neighboring MR images (Fig. 4).

As soon as MR scanning was completed, the immobilizing box containing the cadaver was frozen in a deep freezer on March 28, 2001. A freezer consisting of two compartments (inner size of each compartment: width, 645 mm $\times$ height, 650 mm $\times$ length, 2100 mm) was made. The cadaver in the immobilizing box was wrapped with plastic sheaths to avoid a freeze-dry phenomenon during the long period of storage in the freezer. The cadaver in the immobilizing box was put into the freezer 36 h after death; the temperature was maintained at $-70\,^{\circ}\mathrm{C}$.

The entire body of the cadaver was also CT scanned by 1.0-mm intervals. The immobilizing box containing the cadaver was placed on the bed of the CT machine (GE High Speed Advantage, Milwaukee, WI) parallel to the longitudinal axis of the bed; a laser light guided parallel positioning. The entire body of the cadaver was horizontally CT scanned at 1.0-mm slice thickness and 0-mm interslice gap to produce 1718 spiral CT images at 1.0-mm intervals (Table I). The first CT image series, from head to knee, and the second CT image series, from knee to toe, were scanned separately, then combined and aligned as the same procedure of MR scanning. Field of view and resolution of the CT images was 480 mm $\times$ 480 mm and 512 $\times$ 512, respectively, so the pixel size of the CT images was approximately 1.0 mm. During CT scanning, standard algorithm was used, voltage was fixed at 120 kV, and the electric current time was fixed at 280 mAs in order to make the soft tissue distinct (Fig. 4). As soon as CT scanning was complete, the immobilizing box was again frozen in the deep freezer.

MR and CT images were transferred to a personal computer using picture archiving and communication system (PACS). The MR and CT images were converted from digital imaging and communication in medicine (DICOM) files (16 bits gray) to tag image file format (TIFF) files (8 bits gray) on the PiView software (Infinitt Co) (Table I).

TABLE I
FEATURES OF THE MR, CT, ANATOMICAL, AND SEGMENTED IMAGES OF THE VKH DATA (FINAL EXPERIMENT)

	Intervals (mm)	Number	Resolution	Bits depth	One file size (KB)	Total file size (GB)
MR images	1.0	1718	505 X 276	8 bits gray	147	0.2
CT images	1.0	1718	505 X 276	8 bits gray	147	0.2
Anatomical images	0.2	8590	3040 X 2008	24 bits color	17890	146.4
Segmented images	0.2	8590	3040 X 2008	8 bits color	5900	50.7
Total						197.5

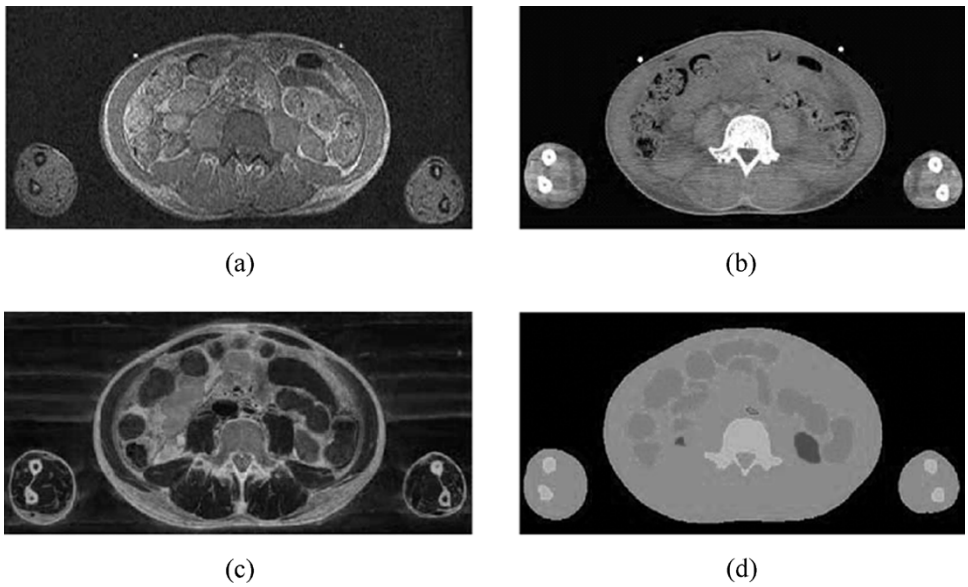

Fig. 4. Corresponding VKH data of abdomen. (a) MR image. (b) CT image. (c) Anatomical image. (d) Segmented image.

Fig. 5. Procedures for embedding and freezing. (a) Cadaver is laid down into the embedding box with alignment rods. (b) Embedding agent is poured into the embedding box. (c) Embedding box, which is already serially sectioned in half, is put into the freezer.

An embedding box was made and alignment rods were inserted into the embedding box. The embedding box (inner size: width, 570 mm × height, 410 mm × length, 2000 mm; outer size: width, 640 mm × height, 430 mm × length, 2090 mm) was made of steel (headboard, footboard, and bottomboard) and wood (two sideboards). The outer size of the embedding box was made to fit the inside of the freezer. Several holes (each diameter: 15 mm) were drilled through the headboard and footboard of the embedding box and four alignment rods made of white polyacetylene (length, 2090 mm; diameter, 15 mm) were inserted into these holes. The direction of the four alignment rods was maintained parallel to the longitudinal axis of the embedding box [Fig. 5(a), (b)].

The cadaver was put into the embedding box. Blue embedding agent (gelatin: 30 g, methylene blue: 0.5 g, distilled water: 1000 ml) was poured into the embedding box until the agent filled about a quarter of the embedding box; the temperature was maintained at $-70\,^{\circ}\mathrm{C}$ in the freezer. After flattening the upper surface of the frozen embedding agent, the cadaver was taken out of the immobilizing box and laid down in the embedding box without changing the cadaver's direction. A thread was attached to the embedding box in a longitudinal direction to verify symmetry of the cadaver's head, body, and limbs [Fig. 5(a)].

The cadaver was embedded and frozen. A small quantity of embedding agent was poured into the embedding box and frozen to $-70\,^{\circ}\mathrm{C}$ in the freezer. This process was repeated until

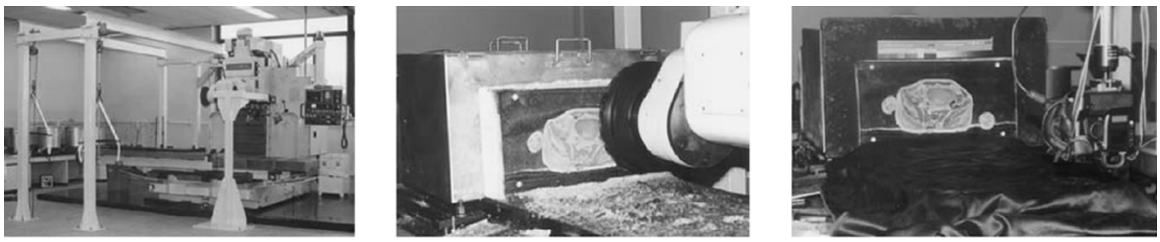

Fig. 6. Procedure for serial sectioning and photographing. (a) Cryomacrotome in the laboratory. (b) Embedding box is serially sectioned by the cutting blade. (c) Sectioned surface is photographed by the digital camera.

the embedding box was fully filled with the embedding agent. These repeated processes were necessary in order to prevent the freezing embedding agent from pressing the cadaver and the alignment rods. Wood panels were connected the upper parts of the two sideboards in order to prevent the freezing embedding agent from widening the two sideboards [Fig. 5(b), (c)].

A cryomacrotome was manufactured in order to serially section the entire body at 0.2-mm intervals. A regular milling machine was remodeled into a cryomacrotome (Hanwon) for the VKH. In order to mill the entire body, the cryomacrotome was built large (width, 3 m $\times$ height, 4 m $\times$ length, 5 m) and the laboratory wall had to be removed to transport it into the laboratory; the cryomacrotome was so heavy (15 ton) that the underground columns and thick floor had to be reconstructed in the laboratory [Fig. 6(a)]. The cryomacrotome for milling at 0.2-mm intervals was so precise that moving error was estimated at just $\pm 1\ \mu\mathrm{m}$. The main components of the cryomacrotome were a milling table and a cutting blade. The milling table was designed to fix and move the embedding box. Optimal moving speed (20.8 mm/s) of the milling table for serial sectioning was determined in the preliminary experiment. The cutting blade (diameter: 360 mm), containing 20 teeth, was designed to serially section the cadaver, the embedding agent, and the wooden sideboards of the embedding box. Optimal rotating speed (628 rpm) of the cutting blade as well as optimal quality and angle of 20 teeth were also determined in the preliminary experiment. The teeth were replaced with new ones regularly during the final experiment.

The embedding box was placed on the milling table of cryomacrotome and firmly fixed. Due to the heavy weight (1 ton) of the embedding box, a cart was used to transfer it from the freezer to the cryomacrotome and a crane was used to place it on the milling table. When the embedding box was placed on the milling table, the footboard was directed to face the cutting blade. As a result, serial sectioning was performed feet to head so that the direction of the sectioned surfaces became the same as that of MR and CT image. The embedding box was carefully placed on the milling table parallel to the longitudinal axis of milling table and firmly fixed using several holes and screws. Footboard of the embedding box was removed before the first serial sectioning.

The process of serially sectioning the embedding box was performed for five months (November, 2001–March, 2002) to make the sectioned surfaces. The embedding box on the milling table was moved toward the cutting blade at 0.2-mm interval. During the cutting blade rotated constantly at optimal speed, the embedding box was moved at optimal speed parallel to the cutting blade; as a result, the embedding box was serially sectioned at 0.2-mm interval [Fig. 6(b)]. After each serial sectioning, every sectioned surface was moved to a constant position for photographing the sectioned surface. These movements of the embedding box and cutting blade were performed repeatedly by a program composed of numerical control language in the automated control box of the cryomacrotome. After a day's serial sectioning, the embedding box was returned to the freezer [Fig. 5(c)] and the cadaver debris and embedding agent debris were collected to be sent to the crematory.

While serial sectioning, the embedding box was prevented from melting as follows. The embedding box was kept in the freezer at $-70\,^{\circ}\mathrm{C}$ all the time except when performing sectioning work [Fig. 5(c)]. In addition, all sectioning work was carried out in the cold season with the laboratory windows opened to keep the air temperature under 5 $^{\circ}\mathrm{C}$. When serial sectioning, an n-shaped stainless steel box containing dry ice was placed on the upper and side surfaces of the embedding box and a large block of dry ice was sometimes placed on the sectioned surfaces of the embedding box [Fig. 6(b)].

The sectioned surfaces were treated as follows. If air cavity of the digestive and respiratory tracts with a diameter greater than 1 mm appeared on the sectioned surfaces, the blue embedding agent was poured into the air cavity and frozen with dry ice. A scalpel was used to manually cut off the dense connective tissue protruding from the sectioned surfaces. Frost on the sectioned surfaces was removed with ethyl alcohol just before the sectioned surfaces were photographed. A black plate with a gray scale and color patch attached and a black cloth were placed around the sectioned surfaces [Fig. 6(c)].

The location and direction of the digital camera, which was connected to the personal computer, were determined and fixed. We used a digital camera (DSC 560 Kodak, resolution: 3040 $\times$ 2008) with 50-mm micro lens (Canon) and a polarizing filter (Kenko). The connection between the digital camera and personal computer was accomplished through IEEE 1394 adapter (HotConnect 8920, Adaptec) and operation of the camera was controlled by DCSTwain software (Version 5.9.3.1, Kodak) in the personal computer. The digital camera was positioned to photograph 600 mm (width) $\times$ 400 mm (height) sized sectioned surfaces, which included the cadaver, embedding agent, alignment rods, gray scale, and color patch; the digital camera was directed to face the center of the sectioned surfaces. After determining the position and direction of the digital camera, the digital camera was firmly fixed on a camera supporter, which was anchored to the laboratory floor [Fig. 6(c)].

TABLE II
ELEVEN ANATOMICAL ORGANS, WHOSE CONTOURS ARE SEGMENTED IN THE ANATOMICAL IMAGES OF THE VKH DATA

Anatomical organs	Contents
Skin	
Bones	
Liver	
Lungs	
Kidneys	
Urinary bladder	
Heart	
Brain	Cerebrum, Cerebellum, Brain stem
Digestive tract*	Oral cavity, Pharynx, Esophagus, Stomach, Small intestine, Large intestine
Respiratory tract*	Nasal cavity, Pharynx, Larynx, Trachea, Bronchi, Lobar bronchi, Segmental bronchi
Arteries*	Ascending aorta, Coronary arteries, Aortic arch, Brachiocephalic trunk, Common carotid arteries, External carotid arteries, Subclavian arteries, Axillary arteries, Brachial arteries, Radial arteries, Ulnar arteries, Thoracic aorta, Abdominal aorta, Celiac trunk, Renal arteries, Common iliac arteries, Internal iliac arteries, External iliac arteries, Femoral arteries, Popliteal arteries, Anterior tibial arteries, Posterior tibial arteries

*In the case of digestive tract, respiratory tract, and arteries, the luminal contours are segmented.

The location and direction of two strobe heads and their accessories were determined and fixed. In order to make the laboratory dark, black curtains were hung on the laboratory windows and the fluorescent lights in the laboratory were turned off. Two strobe reflectors (Compact Reflector, Elinchrom) were attached on two strobe heads (Digital S, Elinchrom) to prevent strobe lights from dispersing. A power pack (Digital 2, Elinchrom) was used to supply the strobe heads with constant electric power. Two strobe heads were located as high as the sectioned surfaces and were directed to face the sectioned surfaces at 45° angles. The position and direction were adjusted until constant brightness of all areas of the sectioned surfaces during flashing of two strobe lights was verified using an incident exposure meter (Auto Meter IV F, Minolta). After determining the position and direction, the two strobe heads were firmly fixed on two strobe supporters, which were anchored to the laboratory floor.

The sectioned surfaces were photographed using the digital camera to produce anatomical images, which were transferred to the personal computer. Every sectioned surface was photographed under constant conditions (F value: 10, shutter speed: 1/250 s, focusing: manual) of the digital camera while two strobe lights were flashed [Fig. 6(c)]. The anatomical image made by photographing the sectioned surface was transferred to the personal computer and its quality (brightness, color, focus) was verified on the computer monitor. Then the anatomical image was saved as TIFF file on two personal computers before the next serial sectioning. This photographing was continuously performed after serial sectioning, which resulted in 8590 anatomical images (Table I). Constant brightness of the anatomical images was verified by checking the red, green, blue values of the gray scale and color patch in the serial anatomical images. Alignment of the anatomical images was verified by examining four alignment rods and each anatomical structure's contours in the serial anatomical images [Fig. 4(c)].

The MR and CT images were aligned to the anatomical images. Excessive margins of the MR and CT images, which did not include the body images, were deleted. The extent of deletion was determined to allow MR and CT images of increased resolution to be aligned to the corresponding anatomical images [Fig. 4(a)–(c)]. As a result, resolution (512 × 512) of the MR and CT images was reduced to 505 × 276 (Table I).

Eleven important anatomical organs were semi-automatically segmented to produce segmented images on the Adobe Photoshop (version 7.0, Adobe) for one year (September, 2002–August, 2003). Contours of eight anatomical organs (skin, bones, liver, lungs, kidneys, urinary bladder, heart, brain) and luminal contours of the three anatomical organs (digestive tract, respiratory tract, and arteries) were chosen to be segmented (Table II). The contours of the anatomical organs were semi-automatically drawn on all 8590 anatomical images with the magnetic lasso tool of the Adobe Photoshop. The contours of each anatomical organ were automatically filled with a specific color to produce 8590 segmented images [Fig. 4(d) and Table I].

The anatomical and segmented images were stacked and volume-reconstructed to produce 3-D images. All 8590 anatomical images (3040 × 2008 pixels) were stacked at 0.2-mm intervals and subsequently volume-reconstructed to produce a 3-D image, which consisted of 3040 × 2008 × 8590 voxels. The segmented images were made into a 3-D image in a likewise manner.

The 3-D images of the anatomical and segmented images were sectioned to produce coronal and sagittal images. The 3-D image of anatomical images was coronally sectioned to produce 2008 coronal anatomical images (3040 × 8590 pixels) and sagittally sectioned to produce 3040 sagittal anatomical images (2008 × 8590 pixels). Likewise, 2008 coronal segmented images and 3040 sagittal segmented images were made of the 3-D image of segmented images (Fig. 7).

In the coronal and sagittal images, smoothness of the four alignment rods and each anatomical structure's contours were examined to verify alignment of the anatomical images and correctness of the segmented images (Fig. 7).

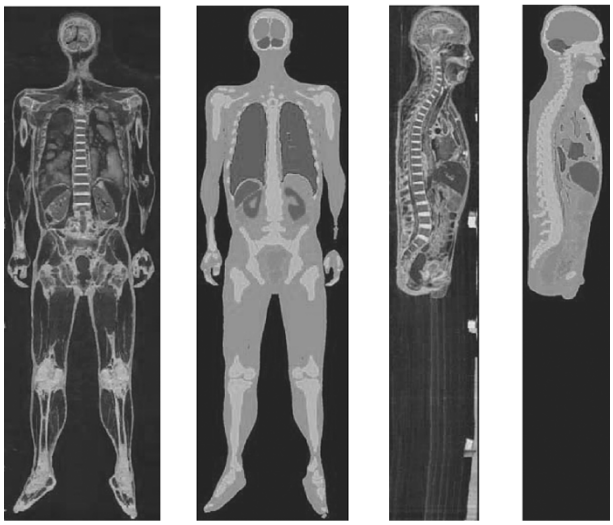

Fig. 7. Coronal and sagittal images from the VKH data. (a) Coronal anatomical image. (b) Coronal segmented image. (c) Sagittal anatomical image. (d) Sagittal segmented image.

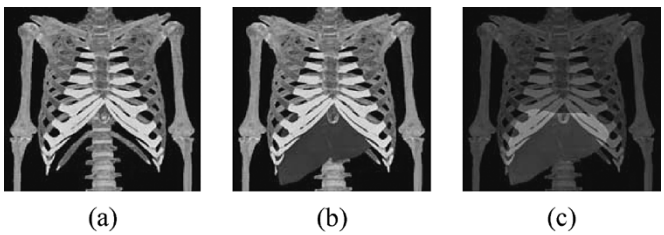

Fig. 8. Three-dimensional images made of the VKH data. (a) Three-dimensional image of bones. (b) Three-dimensional image of bones and liver. (c) Three-dimensional image of semitransparent bones and opaque liver.

Three-dimensional images of selected anatomical organs were displayed and rotated. From the 3-D image of anatomical images, the 3-D image of an anatomical organ was extracted and displayed with reference to the 3-D image of the corresponding segmented image. Likewise, 3-D images of several anatomical organs were extracted and displayed; some anatomical organs were semitransparently displayed (Fig. 8). The 3-D images were rotated at free angles (Fig. 9).

Three-dimensional images of selected anatomical organs were examined to verify that the stereoscopic shape and location of 3-D images were fit to anatomical knowledge, which meant the correct anatomical and segmented images (Figs. 8 and 9).

III. Results

There were 1718 pairs of MR and CT images and 8590 pairs of anatomical and segmented images acquired. While the height of the cadaver was 1640 mm, the length of the cadaver lying on the bed was 1718 mm because the feet were plantarflexed. Intervals of the MR and CT images were 1 mm, so that 1718 pairs of MR and CT images were acquired. Each cropped MR and CT image (TIFF file) had 505 $\times$ 276 resolution (pixel size: about 1.0 mm), 8 bits gray, and 147 KB file size. Intervals of the anatomical images were 0.2 mm; the segmented images were made on the basis of the anatomical images, so that 8590 pairs of anatomical and segmented images were acquired. Each anatomical image had 3040 $\times$ 2008 resolution (pixel size: about 0.2 mm), 24 bits color, and 17 890 KB file size while each segmented image had 3040 $\times$ 2008 resolution, 8 bits color, and 5900 KB file size. The file size of the MR, CT, anatomical and segmented images was 197.5 GB in total (Fig. 4 and Table I).

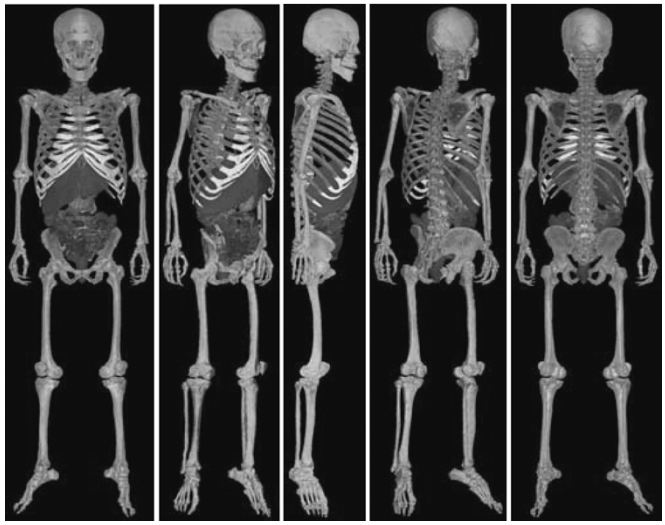

Fig. 9. Three-dimensional rotating images made of the VKH data.

MR and CT images were acquired as expected. The lateral parts of the upper limbs' MR and CT images were not cut off because body size of the cadaver was within the field of view (480 mm $\times$ 480 mm) of MR and CT images. Every MR and CT images (intervals: 1.0 mm) corresponded to one out of every five anatomical images (intervals: 0.2 mm) (Table I). Anatomical structures in the MR and CT images were relatively distinct [Fig. 4(a), (b)].

Anatomical images were acquired as expected. The anatomical images were aligned, which was verified by examining the alignment rods and anatomical structures in the horizontal, coronal, and sagittal anatomical images [Figs. 4(c) and 7(a), (c)] and by referring to the corresponding MR and CT images [Fig. 4(a), (b)]. The anatomical images had consistent brightness, which was verified by checking the gray scale and color patch in the anatomical images. The anatomical images showed clear anatomical structures with colors similar to living body [Figs. 2(c) and 4(c)].

Segmented images were acquired as expected. The contours of 11 anatomical organs in the segmented images were correct, which were verified by examining the coronal and sagittal segmented images [Fig. 7(b), (d)] and the 3-D images of anatomical organs (Figs. 8 and 9).

IV. Discussion

In the preliminary experiment with two cadavers, new equipments and techniques were developed for the VKH. In the final experiment, the MR, CT, anatomical, and segmented images were made by the following principles.

It is necessary to choose an adequate cadaver. The VHP dealt with Caucasian cadavers [Fig. 10(a)] [4], [5]. It is desirable to

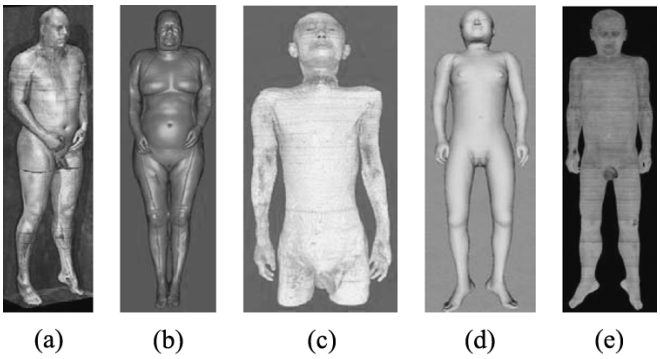

Fig. 10. Comparison of cadavers' posture and body shape. (a) Palms are placed in front of the trunk in the VHP male. (b) Body is obese in the VHP female. (c) Head is extended in the CVH male. (d) Head is extended too in the CVH female. (e) Palms are placed on each side of the trunk, head is not extended, and body is not obese in the VKH.

present data of various racial and ethnic groups, which is a merit for producing CVH and VKH. The VHP dealt with a female cadaver whose age was 59 years old and had an obese body shape [Fig. 10(b)] [5]. In the VKH, a cadaver, who was relatively young (33 years old) and had an average body size of Korean male, was chosen [Figs. 3 and 10(e)]. The VHP data dealt with male and female cadavers, who had shown pathological findings. In the VKH, dozens of donated Korean cadavers were examined and judged by researchers in order to select one reliable candidate for the final experiment; nevertheless, the chosen cadaver had pneumonia and splenomegaly. In the next research, we will attempt to select a better cadaver, even though no such thing as a perfect cadaver exists.

It is necessary to keep the cadaver in adequate posture. In the VHP, palms were placed in front of the trunk, so that anatomical structures of the hands were difficult to be identified in the VHP data [Fig. 10(a), (b)] [4]. In the VKH, palms were placed on each side of the trunk to make the attention posture [Figs. 3 and 10(e)]. Besides, in the CVH, the head was extended so the CVH data of the head were not horizontal [Fig. 10(c), (d)] [6], [7]. In the VKH, a pillow was supported under the head to prevent the head from extension [Figs. 7(c), (d) and 9].

It is necessary to acquire MR and CT images of the entire body. In the VHP, only MR images of the head were acquired at 1.0-mm intervals, so that the MR images of the trunk and limbs were not included [4]. In the VKH, MR images of the cadaver's entire body were acquired at 1.0-mm intervals. Only T1 weighted MR images were acquired because the cadaver should be frozen as soon as possible after MR images acquisition [Fig. 4(a), (b)]. In the VHP male, the upper limbs' lateral parts were cut off in the CT images because of the large cadaver size [Fig. 1(a)] [4]. In the VKH, fortunately, body size of the cadaver was within the field of view (480 mm $\times$ 480 mm) of MR and CT images, so that complete MR and CT images of the entire body could be acquired [Fig. 4(a), (b)]. Intervals (1.0 mm) of the MR and CT images were similar to pixel size (about 1 mm) of the MR and CT images (Table I), so that 1.0 mm-sized voxels could be made of the MR and CT images.

It is necessary that the MR and CT images correspond to the anatomical images. The anatomical structures of the MR and CT images could be easily identified when the MR and CT images were compared with the corresponding anatomical images. One of the most important factors of the correspondence was the horizontal direction of all MR, CT, and anatomical images. In the VKH, to achieve the horizontal direction, the following trials were performed. The cadaver was laid down in the immobilizing box parallel to the longitudinal axis of the immobilizing box, and the cadaver's direction was fixed with the immobilizing agent. The immobilizing box was placed on the beds of the MRI and CT machines parallel to the longitudinal axes of the beds. The cadaver was transferred from the immobilizing box into the embedding box without any change of the cadaver's direction. The embedding box was placed and firmly fixed on the milling table of the cryomacrotome parallel to the longitudinal axis of the milling table. The excessive margins of MR and CT images were cropped to allow MR and CT images of increased resolution to be aligned to the corresponding anatomical images [Fig. 4(a)–(c)]. This procedure for MR images was easy in particular because the MR images of the entire body were scanned with body coil.

It is necessary to show distinct anatomical structures in the MR and CT images. Anatomical structures in the MR and CT images of the cadaver are more distinct than those of the living person because the cadaver is completely stabilized in the MRI and CT machines and exposure of excessive radiation does not cause any problems to the cadaver. Additionally in the VKH, conditions of MR and CT scanning were adjusted in order to distinguish the anatomical structures in the MR and CT images [Fig. 4(a), (b)].

It is necessary to not have any missing anatomical images. In the VHP, before embedding and serial sectioning, the cadaver was divided into four blocks using a saw, which yielded missing anatomical images between the four blocks [Fig. 1(b), (c)] [4], [5]. In the VKH, to obtain the entire body's anatomical images, the cadaver's entire body was embedded and serially sectioned. In order to embed and section the entire body, the embedding box, freezer, cryomacrotome, cart, crane, and laboratory, all of which were large sized, had to be prepared (Figs. 3, 5, and 6). In the VHP, the cadaver in each block stood in the embedding box, and the superior surface of the embedding box faced toward the cutting blade [4], [5]. In the VKH, the cadaver's entire body was laid down in the embedding box, and footboard of the embedding box faced toward the cutting blade: new techniques for embedding, serial sectioning, and photographing had to be developed (Figs. 5 and 6).

It is desirable to make the anatomical images from feet to head. In the VHP and CVH, serial sectioning was performed from head to feet, so that the sectioned surfaces were superior surfaces of the cadavers [4]–[7]. In this method, fingertips or toe tips could easily be sucked away from the sectioned surfaces by negative pressure of the rotating cutting blade. And the anatomical images had to be reversed from right to left in order to make the anatomical images corresponding to the MR and CT images. In the VKH, to solve the problems, serial sectioning was performed from feet to head, so that the sectioned surfaces were inferior surfaces of the cadaver.

It is necessary to keep the anatomical images at 0.2-mm intervals and 0.2-mm pixel size. In the VHP, intervals of the anatomical images were 1.0 mm (male) or 0.33 mm (female). The pixel

size was 0.33 mm due to the limit of resolution (2048 × 2048) of the digital camera, so anatomical structures smaller than 0.33 mm may not appear in the anatomical images [4], [5]. In the CVH male, intervals of the anatomical images were 0.5 mm in the head and neck, 1.0 mm in the trunk and limbs; and in the CVH female, the intervals were 0.25 mm in the head and neck, 0.5 mm in the trunk and limbs [6], so that the anatomical structures smaller than the intervals may not appear in the anatomical images. In the VKH, to reduce the limits, the following trials were performed. The cadaver was serially sectioned at 0.2-mm intervals, which were the same intervals as the anatomical images. Size of the sectioned surfaces was 600 mm × 400 mm and resolution of the digital camera was 3040 × 2008, so that approximate pixel size of the anatomical images was 0.2 mm (Table I). As a result, 0.2 mm-sized voxels could be made of the anatomical images.

It is necessary to keep alignment of the anatomical images. Unlike the MR and CT images, anatomical images may not be aligned, which causes distorted 3-D images. In the VKH, to achieve the alignment of the anatomical images, the following trials were performed. The embedding box was placed on the proper place of the cryomacrotome and firmly fixed. While photographing, not only constant position of every sectioned surface but also constant direction of the digital camera was maintained [Fig. 6(c)]. Alignment of the anatomical images was verified by examining four alignment rods and each anatomical structure's contours in the horizontal, coronal, and sagittal anatomical images [Figs. 4(c) and 7(a), (c)], and by referring to the corresponding MR and CT images, which had been already aligned [Fig. 4(a), (b)].

It is necessary to keep constant brightness of the anatomical images. In the VHP, both embedding box and cryomacrotome were small; and in the CVH, the laboratory was small, so that constant brightness of the anatomical images was relatively easy to keep. In the VKH, the embedding box, cryomacrotome, and laboratory were so large that constant brightness was difficult to keep [Fig. 6(a)]. To achieve constant brightness of the anatomical images, the following trials were performed. Laboratory was made dark by using black curtains, plate, and cloth [Fig. 6(c)]. Constant brightness of the sectioned surfaces was maintained by using two strobe heads, strobe reflectors, and a power pack. Constant brightness of all areas of the sectioned surface was verified by using the incident exposure meter. Constant brightness of the anatomical images was maintained by photographing under constant conditions (F value and shutter speed) of the digital camera. Constant brightness of the anatomical images was verified by examining gray scale and color patch in the anatomical images [Fig. 6(c)].

It is necessary that the anatomical images have even and parallel sectioned surfaces with constant intervals. If the sectioned surfaces are not even, or not parallel to each other; or intervals of the sectioned surfaces are not constant (0.2 mm), the anatomical images will become the source of the distorted 3-D images. In the VKH, to achieve the exact sectioned surfaces, the following trials were performed. The precise cryomacrotome with only 1 μm moving error was made. The embedding box was placed on the proper place of the cryomacrotome and firmly fixed. During serial sectioning, the embedding box was moved exactly by a program in the control box of the cryomacrotome [Fig. 6(a), (b)].

It is necessary to keep the sectioned surfaces of the anatomical images clear. The sectioned surfaces on which anatomical structures appear clearly can be decided by two important factors: hard frozen state of the embedding box and fine sharp of the cutting blade's teeth. In the CVH, laboratory was so cold ($-25\,^{\circ}\mathrm{C}$) that the hard frozen embedding box was easy to maintain [6], [7]. In the VKH, which was performed in a regular laboratory, to maintain the hard frozen embedding box, the following trials were performed. The embedding box was hard frozen before and after a day's serial sectioning [Fig. 5(c)]. The embedding box was serially sectioned in the cold seasons with the laboratory windows opened. Dry ice was placed on the embedding box during serial sectioning [Fig. 6(b)]. In addition, in the VKH, 20 teeth of optimal quality were mounted on the cutting blade at optimal angle; the teeth were replaced with new ones regularly. The cutting blade was rotated at optimal speed; the embedding box was moved at optimal speed too [Fig. 6(b)]. Nevertheless, some dense connective tissues were not cut off during serial sectioning. In this case, the dense connective tissues were manually cut off by a scalpel in the same manner as that of VHP [4].

It is necessary that the sectioned surfaces of the anatomical images are free from artifacts. Air cavity of digestive and respiratory tracts may appear on the sectioned surfaces, which can cause the base of air cavity to appear repeatedly on several anatomical images. In the VKH, to avoid the artifact, a blue embedding agent was poured into the air cavity and frozen in the same manner as that of VHP. And frost on the sectioned surfaces was removed with ethyl alcohol in the same manner as the VHP [4].

It is necessary to show the anatomical images in similar colors to a living body. In the VHP (male), 19 liters of 1% formalin and anticoagulant was perfused into the cadaver and drained in order to prevent membrane depolarization, which could be caused by court-ordered lethal injection. As a result, the colors of the anatomical images became relatively white [Fig. 2(a)] [4]. In the CVH, 20% red gelatin solution was perfused into the cadavers to demonstrate the arterial network of the anatomical images. As a side effect, the red gelatin solution escaped from the arteries to tissues, especially to muscles, which became red in the anatomical images [Fig. 2(b)] [6], [7]. In the VKH, to preserve the colors of a living body, nothing was perfused into the cadaver, which was helpful in making the anatomical images and 3-D images realistic [Figs. 2(c), 4(c), 7(a), (c), 8, and 9].

It is necessary to publish the segmented images. In the VHP and CVH, the segmented images were not published [4]–[6], so researchers who want to produce each anatomical organ's 3-D image of the VHP and CVH data have to segment the anatomical organ themselves. In the VKH, 11 important anatomical organs, including skin and bones, were segmented on the basis of the anatomical images [Fig. 4(c), (d)]. Even though the segmented images may not be enough especially in quantity to every researcher, at least the segmented images can be the basis for further segmentation. Our segmented images will be presented free of charge, which will reduce the time and effort in part of other researchers.

It is desirable to semi-automatically make the segmented images on the Adobe Photoshop. If the anatomical organs' contours were manually drawn, segmentation would require tedious work and long time; and segmentation is not guaranteed to be objective. Reversely, if the contours were automatically drawn, segmentation itself would not be possible because most anatomical organs in the anatomical images can be identified not by the computer but by the medical experts. In the VKH, the contours were semi-automatically drawn on the Adobe Photoshop. Magnetic lasso tool of the Adobe Photoshop was adequate for the semiautomatic segmentation, so specific software for this purpose was not necessary.

It is necessary to verify the segmented images. Incorrect analysis may occur during segmentation of 11 anatomical organs on 8590 anatomical images. In the VKH, to verify the correctness of the segmented images, smoothness of each anatomical organ's contours was examined in the coronal and sagittal segmented images [Fig. 7(b), (d)]; and stereoscopic shape and location of the 3-D images were examined (Figs. 8 and 9).

It is necessary to make 3-D images of the anatomical and segmented images. If 3-D images are not made of the anatomical and segmented images, it is difficult to finally verify alignment of the anatomical images and correctness of the segmented images. In the VKH, the 3-D images were made by volume-reconstruction. As a result, the 3-D images could be sectioned and rotated to verify the anatomical and segmented images (Figs. 7–9).

V. Conclusion

In order to compensate the VHP and CVH, we have produced VKH from a Korean male cadaver as follows: MR and CT images of the entire body (intervals: 1.0 mm, pixel size: 1.0 mm), anatomical images without missed images (intervals: 0.2 mm, pixel size: 0.2 mm) with colors similar to a living body, and segmented images of 11 anatomical organs. The VKH is an ongoing research: we are willing to produce VKH female data as well, and to produce the segmented images in more detail. The VKH data will be distributed worldwide free of charge. The VHP, CVH, and VKH data will complement each other at the present and future, and are expected to be valuable resources to the medical image library of 3-D images and software in the field of medical education and clinical trials.

References

[1] M. J. Ackerman, "The Visible Human project. A resource for education," *Acad. Med.*, vol. 74, pp. 667–670, 1999.

[2] M. S. Chung and S. Y. Kim, "Three-dimensional image and virtual dissection program of the brain made of Korean cadaver," *Yonsei Med. J.*, vol. 41, pp. 299–303, 2000.

[3] A. Pommert, K. H. Hoehne, B. Pflesser, E. Richter, M. Riemer, T. Schiemann, R. Schubert, U. Schumacher, and U. Tiede, "Creating a high-resolution spatial-symbolic model of the inner organs based on the Visible Human," *Med. Image. Anal.*, vol. 5, pp. 221–228, 2001.

[4] V. M. Spitzer, M. J. Ackerman, A. L. Scherizinger, and D. G. Whitlock, "The Visible Human male: Technical report," *J. Am. Med. Inform. Assoc.*, vol. 3, pp. 118–130, 1996.

[5] V. M. Spitzer and D. G. Whitlock, "The Visible Human dataset. The anatomical platform for human simulation," *Anat. Rec.*, vol. 253, pp. 49–57, 1998.

[6] S. X. Zhang, P. A. Heng, Z. J. Liu, L. W. Tan, M. G. Qiu, Q. Y. Li, R. X. Liao, K. Li, G. Y. Cui, Y. L. Guo, X. P. Yang, G. J. Liu, J. L. Shan, J. J. Liu, W. G. Zhang, X. H. Chen, J. H. Chen, J. Wang, W. Chen, M. Lu, J. You, X. L. Pang, H. Xiao, and Y. M. Xie, "Creation of the Chinese Visible Human data set," *Anat. Rec.*, vol. 275B, pp. 190–195, 2003.

[7] S. X. Zhang, P. A. Heng, Z. J. Liu, L. W. Tan, M. G. Qiu, Q. Y. Li, R. X. Liao, K. Li, G. Y. Cui, Y. L. Guo, X. P. Yang, G. J. Liu, J. L. Shan, J. J. Liu, W. G. Zhang, X. H. Chen, J. H. Chen, J. Wang, W. Chen, M. Lu, J. You, X. L. Pang, H. Xiao, Y. M. Xie, and J. C. Y. Cheng, "The Chinese Visible Human (CVH) datasets incorporate technical and imaging advances on earlier digital humans," *J. Anat.*, vol. 204, pp. 165–173, 2004.