The Chinese Visible Human (CVH) datasets incorporate technical and imaging advances on earlier digital humans

Shao-Xiang Zhang,[1] Pheng-Ann Heng,[2] Zheng-Jin Liu,[1] Li-Wen Tan,[1] Ming-Guo Qiu,[1] Qi-Yu Li,[1] Rong-Xia Liao,[1] Kai Li,[1] Gao-Yu Cui,[1] Yan-Li Guo,[1] Xiao-Ping Yang,[1] Guang-Jiu Liu,[1] Jing-Lu Shan,[1] Ji-Jun Liu,[1] Wei-Guo Zhang,[3] Xian-Hong Chen,[3] Jin-Hua Chen,[3] Jian Wang,[4] Wei Chen,[4] Ming Lu,[4] Jian You,[4] Xue-Li Pang,[5] Hong Xiao,[5] Yong-Ming Xie[2] and Jack Chun-Yiu Cheng[6]

[1]*Department of Anatomy, College of Medicine, Third Military Medical University, Chongqing 400038, China*
[2]*Department of Computer Science and Engineering, and* [6]*Department of Orthopaedics and Traumatology, Chinese University of Hong Kong, China*
[3]*Department of Imaging Diagnosis, Research Institute of Field Surgery, Daping Hospital, Third Military Medical University, Chongqing 400042, China*
[4]*Department of Radiology, and* [5]*Department of Radiation Oncology, Southwest Hospital, Third Military Medical University, Chongqing 400038, China*

Abstract

We report the availability of a digitized Chinese male and a digitzed Chinese female typical of the population and with no obvious abnormalities. The embalming and milling procedures incorporate three technical improvements over earlier digitized cadavers. Vascular perfusion with coloured gelatin was performed to facilitate blood vessel identification. Embalmed cadavers were embedded in gelatin and cryosectioned whole so as to avoid section loss resulting from cutting the body into smaller pieces. Milling performed at −25 °C prevented small structures (e.g. teeth, concha nasalis and articular cartilage) from falling off from the milling surface. The male image set (.tiff images each of 36 Mb) has a section resolution of 3072×2048 pixels (~170 μm, the accompanying magnetic resonance imaging and computer tomography data have a resolution of 512×512, i.e. ~440 μm). The Chinese Visible Human male and female datasets are available at http://www.chinesevisiblehuman.com. (The male is 90.65 Gb and female 131.04 Gb). MPEG videos of direct records of real-time volume rendering are at: www.cse.cuhk.edu.hk/~crc

Key words 3D reconstruction; Chinese visible human; digital human; cryoembalming; cyrosectioning; human digital images; imaging.

Introduction

The Visible Human Project (VHP) initiated Visible Human Research (VHR) by creating the Visible Human Male (VHM) and Female (VHF), publishing the datasets on the Internet in 1994 and 1995, respectively (Spitzer et al. 1996; Spitzer & Whitlock, 1998; Ackerman, 1999; http://www.nlm.nih.gov/research/visible/visible_human.html). Although the US VHP dataset has been widely used, it has limitations (e.g. it suffers from data loss of the three junctions caused by cadaver segmentation,

and it is only typical of the Caucasian population). Digitized humans are clearly required that are representative of other populations, and the 'Visible Korean Human (VKH)' project was initiated in 2000, with the first VKH dataset being of a 65-year-old patient who had died of cerebroma (Chung & Kim, 2000; Chung & Park, 2003). This therefore cannot represent a complete normal adult human.

In November 2001, the Chinese Visible Human (CVH) project was set up to produce a dataset of a complete normal adult male and female from an Asian population. The CVH project was planned to include digital images derived from computerized tomography (CT) together with magnetic resonance imaging (MRI), and photographic images from cadaver cryosectioning.

The CVH project set out to produce high-quality data and maintain image integrity through two

Correspondence

Dr Shao-Xiang Zhang, Department of Anatomy, College of Medicine, Third Military Medical University, Chongqing 400038, China.
E: Zhangsx@mail.tmmu.com.cn

improvements to the sectioning procedures. First, the milling machine table was made large enough to mount a whole embedded human body so as to avoid data loss caused by fragmenting the body before cryomacrotoming. Second, milling was performed in a laboratory where the temperature was maintained at or below −25 °C, to prevent small structures (including tooth, concha nasalis and articular cartilage) from falling off the milling surface. The CVH male and female were completed in October 2002 and in February 2003, respectively.

Materials and methods

Acquisition of the dataset

Specimen preparation

Ten cadavers of each sex were gifted by the citizens of Chongqing. A key aspect of the CVH project was to use cadavers that were from relatively young adults (20−40 years), and of typical height (160−190 cm) and weight (e.g. no evidence of obesity or emaciation). Those meeting these criteria were screened macroscopically to exclude those with any superficial evidence of organic pathology. The remaining cadavers then underwent preliminary CT and MRI examinations to exclude those with internal lesions or pathology. The final cadavers were then transported to the Third Military Medical University Imaging Center to capture CT and MR images, which were kept to compare with later anatomical images, whereas those cadavers with internal lesions or pathology were further excluded.

The man whose body was used as the CVH male was 35 years old at the time of death. He was 170 cm tall and weighed 65 kg. He had died of carbon monoxide poisoning, and the body was received 2 h after his death. CT and MR images were obtained of each region of the body in the laboratory of the hospital. At 8 h after death, the cadaver underwent measurement of height, weight and configuration. The skin and subcutaneous tissue were then cut below the mid-point of right inguinal (Poupart's) ligament and, the right femoral artery was opened longitudinally. Two tubes were inserted, one cranially and the other caudally, and the cadaver was perfused with 125 000 units of heparin in 200 mL of physiological saline and 11.5 litres of 5% formalin was then injected into the artery (10 litres of formalin was injected into the vessel cranially, and 1.5 litres caudally). The right femoral vein was opened

and approximately 2 litres of venous blood flow was drained. Two hours later, the femoral artery was perfused with a 20% gelatin solution, which was coloured red with food dye: 1300 mL of the gelatin solution was perfused into the artery cranially, and 200 mL caudally. The femoral cut was then sutured layer by layer. At 10 h after death, the cadaver was transferred in the anatomical position to a specially constructed freezer, where the temperature was maintained at −70 °C.

The CVH female was 22 years old at the time of death. She was 162 cm tall and weighed 54 kg. She had died of food poisoning and the body was received 3 h after her death. The CVH female was prepared in essentially the same way as the male. At 9 h after death, after undergoing CT and MRI examinations, the cadaver was perfused with 5% formalin into the right femoral artery. We injected 8 litres into the vessel cranially, and 1 litre caudally. Two hours later, the femoral artery was perfused with 20% red gelatin solution: 1000 mL of the gelatin solution was perfused into the artery cranially, and 150 mL caudally. At 12 h after death, the body was transferred in the anatomical position to the low-temperature freezer.

CT and MR imaging

CT transverse images were collected every millimetre (in all, there were 1696 CT images for the male and 1618 CT images for the female; see Fig. 1a).

A 1.0-tesla superconducting magnetic resonance imager (Siemens Medical Systems, Germany) was used for MR imaging. Spin-echo T1-weighted images were obtained in the axial plane with the following parameters: repetition time (TR) 580−600 ms, echo time (TE) 15 ms, field of view (230−380) × 256 mm, slice thickness: 1.5 mm for the head and cervix region and 3.0 mm for the other regions, pixel matrix 256 × 256, number of acquisitions 2. In total, 683 MR images were acquired for the male and 656 MR images for the female (Fig. 1b).

Cadaver embedding

The specimen needed to be embedded in a suitable medium so that it could be cut in the milling machine. For this, a box was made of corrosion-resistant material (inner dimensions: 450 mm × 500 mm × 1800 mm). Four plastic tubes that had been positioned longitudinally served as fiducial rods for three-dimensional (3-D)
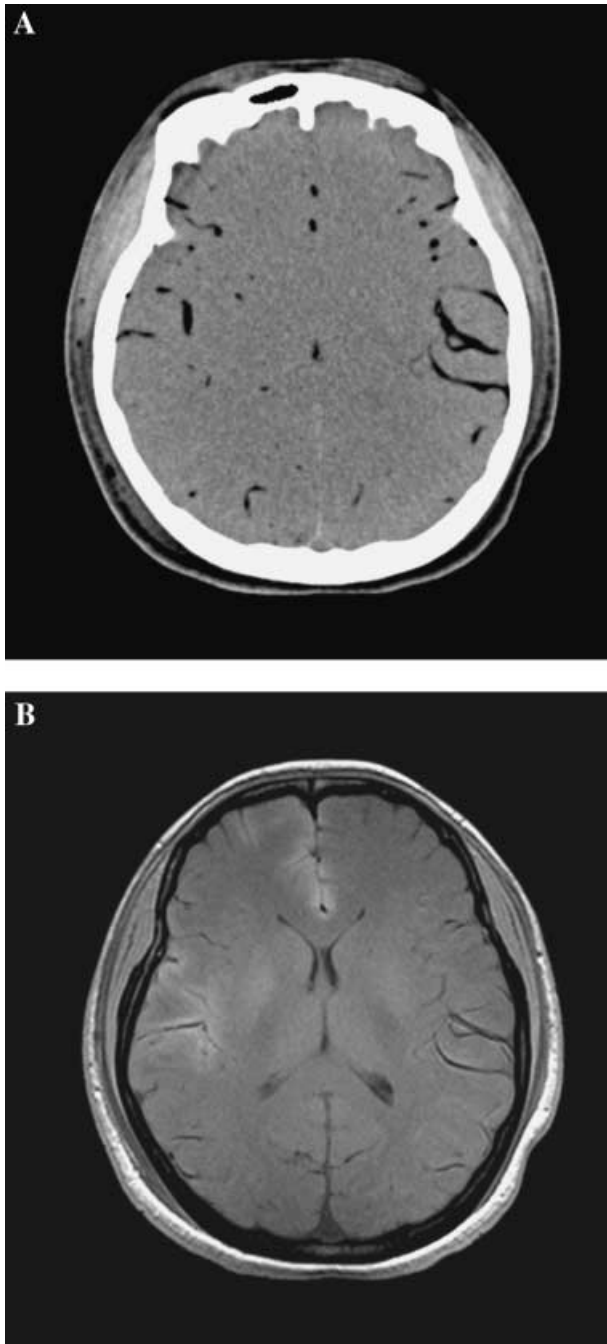
Fig. 1 CT and MR images of the CVH male (a) and female (b) head.

reconstruction (Fig. 2). The specimen was then transferred from the ultra freezer and placed in the box in the anatomical position, and the box was then filled with 5% gelatin solution coloured blue with food dye. The box was placed in a freezer (−30 °C) for 1 week so that the body was frozen in an ice block 450 mm wide × 500 mm long × 1800 mm deep.

Sectioning of the cadaver

To keep the ice block hard enough to keep the cutting surface slick and to avoid the ejection of small segments of tissue from the block, we constructed a low-temperature chamber (5.0 m long × 5.0 m wide × 2.2 m high) that could be maintained at or below −25 °C. The milling machine was placed in the chamber, but its electronic control system was kept outside. For sectioning, the ice block was transferred to the chamber and mounted to the cryomacrotome table of the milling machine.

Sectioning of the intact block was performed using an improved TK-6350 numerical control milling machine with a milling accuracy of 0.001 mm (the numerical control system was made in Japan and the mill made in France; engineers from our team and the Hanzhong Machine Tool Factory, China, designed and implemented necessary modifications).

Slices of each body were then milled layer by layer, from head to toes, at −25 °C in the low-temperature chamber. The serial cross-sections were photographed with a Canon high-resolution digital camera and scanned into an animation computer (Fig. 2). Images from the structural dataset are shown in Figs 3–5.

The cutting process required three operators, two mill operators, one in the low-temperature chamber (appropriately clothed) and the other outside, together with a computer operator. Communication was either visually through a glass window in the chamber wall or using a microphone. The process was as follows: the mill operator outside the room set the starting location of the block and recorded the x, y and z positions using the keyboard on the control table. After completing a newly cut surface, the operator in the room rotated the worktable through 90° so that the camera was in the proper position to catch the image. The surface was then cleared with compressed air and sprayed with absolute ethyl alcohol, and a ruler and a chromatogram label were then placed on the surface. The mill operator told the computer operator that preparation of the block surface was complete and optimal for photography. This was performed by the computer operator outside the low-temperature chamber, who then viewed the image (another image was taken if the first was not satisfactory), confirmed the slice number and saved the image on the hard drive of the computer. The mill operator in the chamber then rotated the worktable of the mill back to the original position while the mill operator outside the room
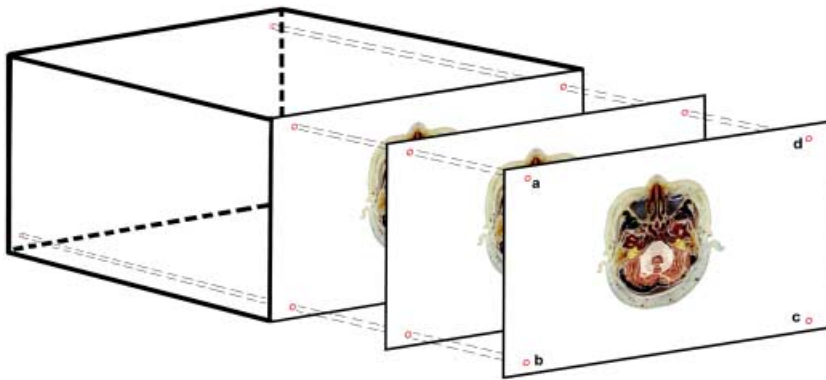
Fig. 2 Four plastic tubes (a–d) were positioned longitudinally to serve as fiducial rods for 3-D reconstruction and as markers for cross-sections. The image of the block surface as the camera viewed it: the colour normalization strip is included at the top and the ruler is included at the bottom of each sectional image.

Fig. 3 Transverse section image of head (CVH female): 1, optic nerve; 2, mesencephalon; 3, cerebellum; 4, occipital lobe; 5, temporal lobe.

set new x and z positions for the block for the next cycle.

Cutting of the CVH male block began on 2 March 2002 and finished on 8 August 2002. Cutting of the CVH female block began on 1 October 2002 and finished on 8 February 2003. The axial anatomical images of the CVH male were obtained at 0.5-mm intervals for the head and neck regions, 0.1-mm intervals for the skull base, and 1.0-mm intervals elsewhere. There were 2518 serial images (tagged image file format, tiff), each of 36 Mb, and the complete data files occupy 90.65 Gb. The axial anatomical images of the CVH female were obtained at 0.25-mm intervals for the head and 0.5-mm intervals for the other regions. In all, there were 3640 serial slices, with each tiff file occupying 36 Mb (3072×2048 pixels, approximate pixel size was 170 μm). The complete dataset occupies 131.04 Gb.
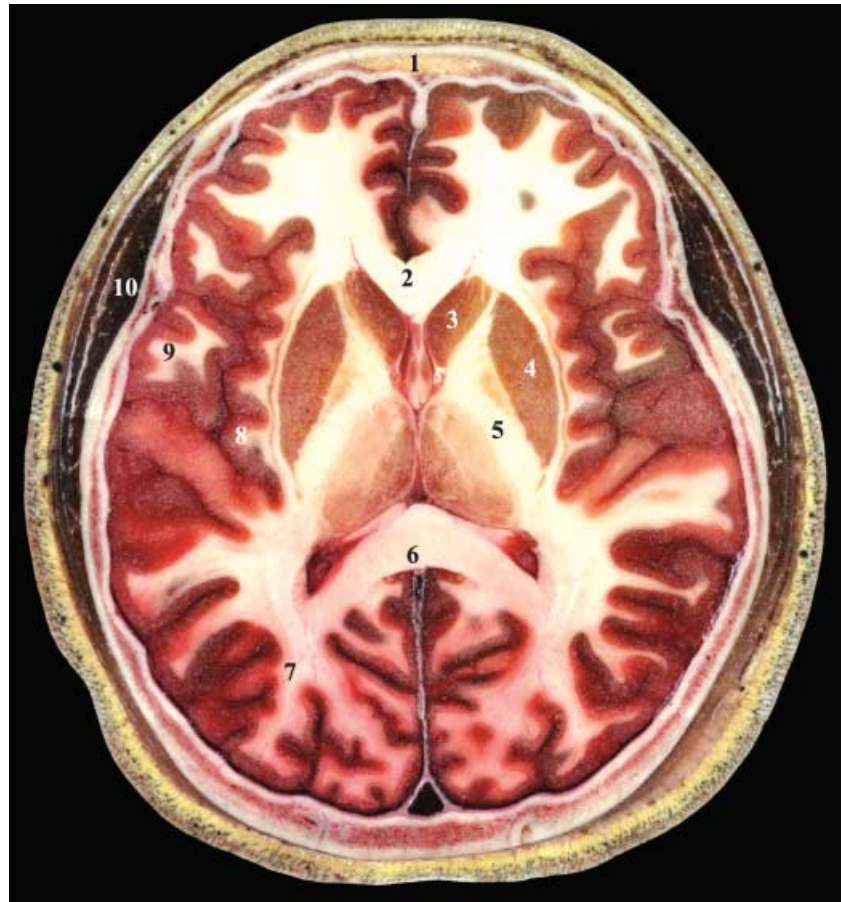
Fig. 4 Transverse section image of head (CVH male): 1, frontal bone; 2, corpus callosum, genu; 3, caudate nucleus; 4, putamen; 5, internal capsule, posterior limb; 6, corpus callosum, splenium; 7, occipital lobe; 8, insula; 9, temporal lobe; 10, temporalis muscle.
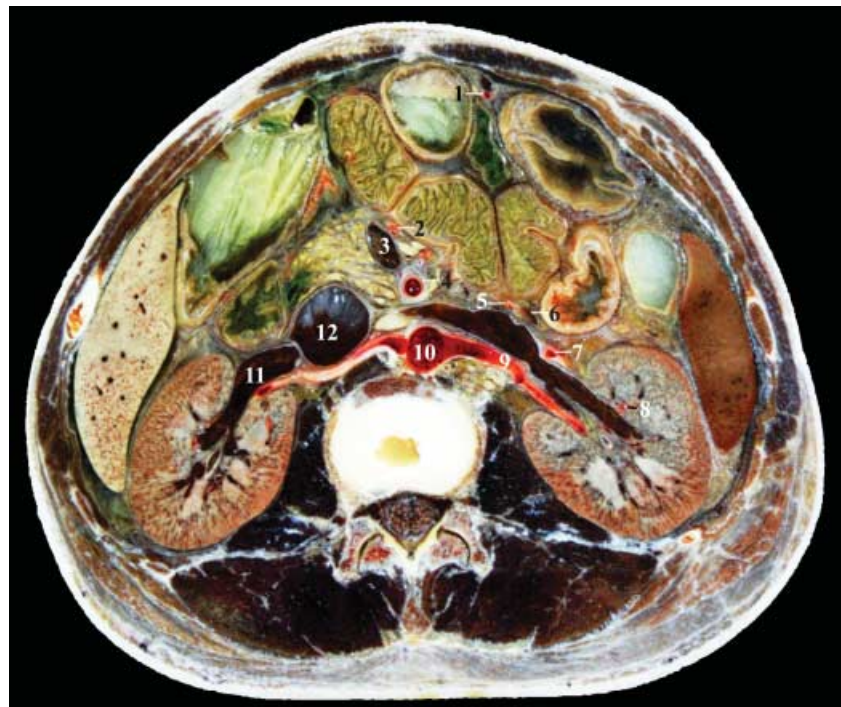

Fig. 5 Transverse section image of abdomen (CVH male) to show the blood vessels (inferior aspect): 1, left gastroepiploic artery; 2, ileocolic artery; 3, superior mesenteric vein; 4, superior mesenteric artery; 5, jejunal artery; 6, left colic vein; 7, accessory renal artery; 8, renal segmental artery; 9, renal artery; 10, abdominal aorta; 11, renal vein; 12, inferior vena cava.

Image capture and photography

Images were captured by an external computer using a high-resolution Canon EOS-D60 digital camera (resolution 3072×2048 [6 291 456] pixels) protected in a wooden box that had been placed in the chamber before the temperature in the laboratory was lowered. To protect the camera, the temperature was lowered slowly over 2 weeks from 25 °C to −25 °C.

Once a newly milled surface was complete, cleaned, positioned and labelled (see above), the photography light was turned on and the picture captured and transferred to the animation computer. The computer operator then viewed the image to ensure that the image was of the required standard, assigned it the proper slice number and saved it on the computer's hard drive. The mill operator outside the room also recorded the *x*, *y* and *z* position from the screen of the controlling table of the milling machine, confirmed that the slice number was correct and made a note of any features of interest.

Three-dimensional reconstruction and visualization of CVH dataset

After data acquisition of the CVH male and female were completed, 3-D reconstruction was achieved by surface rendering and volume rendering reconstruction.

Surface rendering reconstruction

Triangular meshing of the boundary surface of the CVH male and female was achieved using the Marching Cube Algorithm. This was then rendered using OpenGL (i.e. the same method that others have used for the original visible human dataset).

Volume rendering reconstruction

Volume rendering reconstruction was achieved through graphics hardware acceleration supported by OpenGL 1.4. Our algorithm consists of the following steps: (1) polygonization of the complete volume data through layer-by-layer processing and generating corresponding image texture; (2) carrying out all essential transformations through vertex processor operations; (3) dividing polygonal slices into smaller fragments, where the corresponding depth and texture coordinates are recorded; and (4) in fragment processing, deploying the vertex shader programming technique to enhance the rendering of fragments.

According to the red–green–blue (RGB) components, the image data of the volume cross-sectional plane can be processed and displayed in both greyscale and colour mode. Using voxels as the basic modelling unit, we can render the body directly without performing any segmentation. In this way, we can visualize the whole human body with great flexibility. Figure 6 shows two cut views of the CVH male and female.

Traditionally, the size limitation of texture memory has made real-time rendering of large-volume datasets difficult as existing hardware-accelerated volume rendering cannot render datasets exceeding the specified size limit. We have developed a programmable graphics accelerator and appropriate visualization techniques to enable real-time visualization of the CVH dataset in a 3-D virtual environment.

The 3-D reconstruction of visible human slices can also be stereoscopically viewed in real time. Using our modified volume-rendering pipeline, we can interactively rotate the 3-D images around any spatial axis and/or section them in any orientation. Our visualization system, which is based on the initial transverse images, can display sagittal, coronal and arbitrarily orientated sections by 3-D reconstruction. It can also display organs separately, or as part of the whole by defining approximate multiple oblique clipping planes to single-out the organ/region of interest.

Real-time stereoscopic visualization of the $512 \times 512 \times 512$ dataset can be achieved on a PC with the following configuration: Pentium 4, 1.5 GHz, 2 Gb RAM, 1000 Gb hard-disk and equipped with a display card that supports OpenGL 1.4 and 128 Mb texture memory.

Dataset access

The CVH male and female datasets are held at http://www.chinesevisiblehuman.com. The complete dataset of the CVH male is 90.65 Gb in size, and the CVH female is 131.04 Gb in size, and can be distributed via FTP or DVDs. The full datasets are available from the Third Military Medical University (TMMU) under a licence agreement (enquiries should be addressed to The Chinese Visible Human Project at the TMMU). In addition, several MPEG videos of direct records of real-time volume rendering of the Chinese Visible Human datasets can be accessed at www.cse.cuhk.edu.hk/~crc.

Results and discussion

Acquisition of the 2518 anatomical cross-sectional images for the CVH male took 6 months. The dataset also includes CT, MR and radiographic images. Axial and coronal MR images of the head and neck and axial sections through the rest of the body were obtained at 3.0-mm intervals and in matrices of 512×512 pixels (256 grey levels, approximate pixel size 440 µm). CT data consisted of axial scans through the body at 1.0-mm intervals. CT images are 512×512 pixels, in which each 256-bit pixel value is related to the electron density of the specimen at that point. The MR and CT axial images have been aligned with the anatomical cross-sections. All digital images of milled surfaces had 6 291 456 (3072×2048) pixels. The data file of each section occupies 36 Gb. The complete data files occupy 90.65 Gb.

Acquisition of the 3640 anatomical cross-sectional images for the CVH female took 4 months. The visible female dataset has the same characteristics as the male with the following exceptions. The serial sections were sampled at 0.25-mm intervals for the head and 0.50-mm intervals for other regions. CT data consisted of axial scans through the entire body at 1.0-mm intervals. The data file of each section occupies 36 Mb. The complete data files occupy 131.04 Gb.

The Korean VKH project initiated in March 2000 is still in progress, but the first VKH dataset has the limitation that the 65-year-old male patient had died of cerebroma and it thus has a pathological lesion.

These images are at a higher resolution and are more complete than those produced by the 'Visible Human Project', in which intervals between adjacent sections of the visible male and female are 1.0 mm and 0.33 mm, respectively, with the image for each section being 2048×1216 pixels. Each uncompressed data file was 7.9 Mb, with the complete male and female data files occupying 15 Gb and about 40 Gb, respectively. In addition, the VHP dataset is incomplete: according to the US VHP, the physical limitations of the cutting system required that the cadaver had to be cut into four segments before sectioning, causing a loss of 1.5 mm between blocks. Furthermore, because of the

Fig. 6 Sagittal and coronal sections of CVH, 3-D reconstructed. (a) Sagittal section of CVH male: 1, cerebrum; 2, cerebellum; 3, left lung; 4, heart; 5, liver; 6, spleen; 7, left kidney. (b) Coronal section of CVH female: 1, cerebrum; 2, left lung; 3, stomach; 4, liver; 5, uterus; 6, urinary bladder.
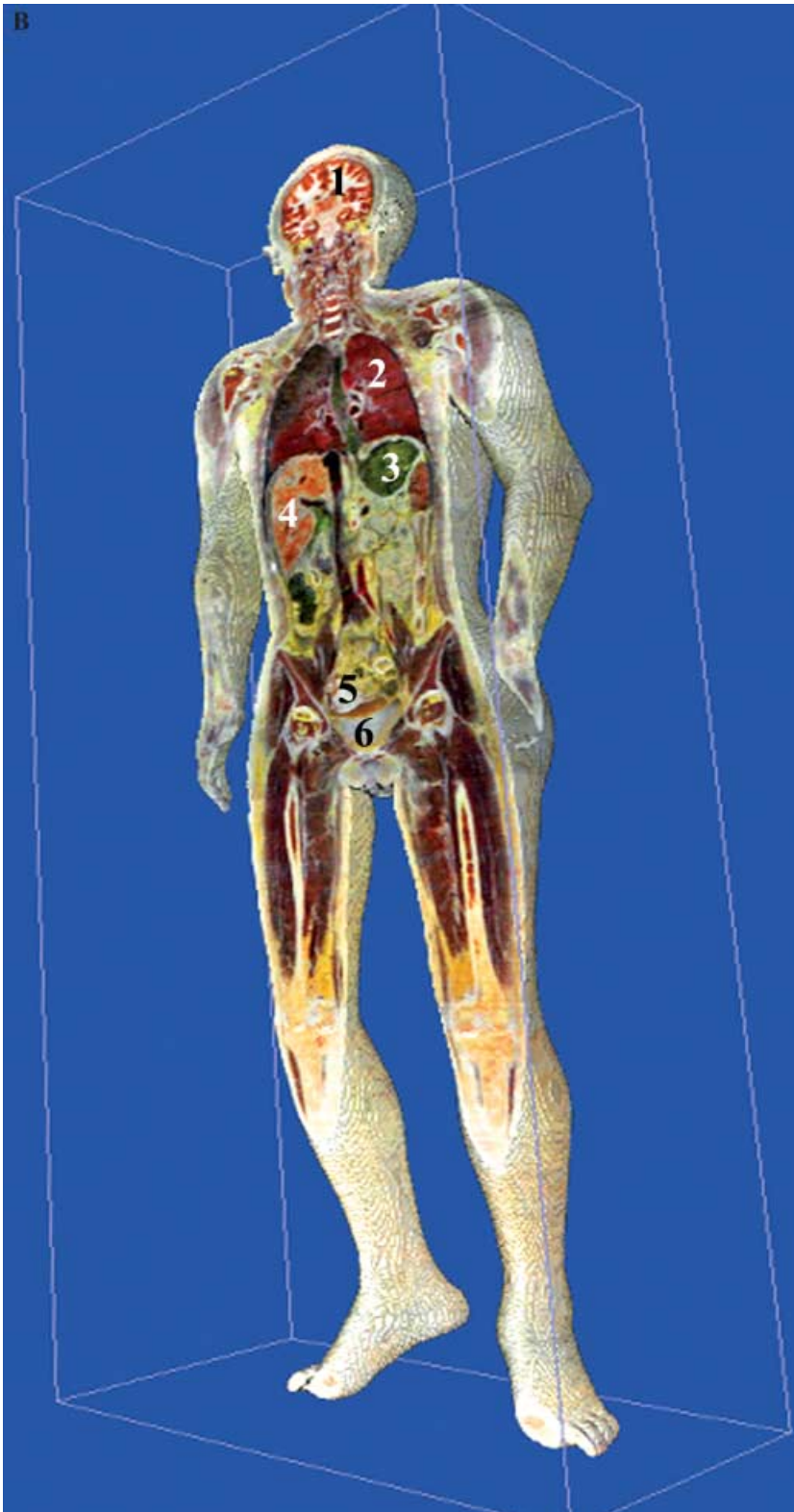
Fig. 6 *Continued*

ejection of small segments of tissue from the block, some images of the VHP were imperfect.

Our methodology was designed to avoid these problems. We improved the milling machine to make its

table large enough for a complete body, and, by keeping the body in a frozen matrix at −25 °C, kept all tissues in place that otherwise risked being lost (the last few millimetres of the condyles of the femur, some bones

of the hand, foot, teeth, the concha nasalis, the articular cartilage, the temporal lobe of the brain, the cerebellum, etc.). The CVH male and female reported here as additions to the visible human dataset are more complete, representative and accurate than those hitherto published.

Acknowledgements

References

Ackerman MJ (1999) The visible human project: a resource for education. *J. Acad. Med*. **74**, 667–670.

Chung MS, Kim SY (2000) Three-dimensional image and virtual dissection program of the brain made of Korean cadaver. *Yonsei Med. J*. **41**, 299–303.

Chung MS, Park HS (2003) Another trial for making serially sectioned images (Visible Korean Human). In *International Workshop on Visible Human*, pp. 2–9. Chongqing, China: Third Military Medical University.

Spitzer VM, Ackerman MJ, Scherzinger AL, Whitlock D (1996) The visible human male: a technical report. *J. Am. Med. Inform. Assoc*. **3**, 118–130.

Spitzer VM, Whitlock DG (1998) The Visible Human dataset: the anatomical platform for human simulation. *Anat. Rec*. **253**, 49–57.