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Construction and visualization of high-resolution three-dimensional anatomical structure datasets for Chinese digital human

LI AnAn[1], LIU Qian[1†], ZENG ShaoQun[1], TANG Lei[2], ZHONG ShiZhen[2] & LUO QingMing[1]

[1] The Key Laboratory for Biomedical Photonics of the Ministry of Education, Wuhan National Laboratory for Optoelectronics, Department of Biomedical Engineering, Huazhong University of Science and Technology, Wuhan 430074, China;
[2] Department of Anatomy, Southern Medical University, Guangzhou 510515, China

The objective of the China Digital Human Project (CDH) is to digitize and visualize the anatomical structures of human body. In the project, a database with information of morphology, physical characteristics and physiological function will be constructed. The raw data of CDH which was completed in the Southern Medical University is employed. In Huazhong University of Science and Technology (HUST), the frozen section images are preprocessed, segmented, labeled in accordance with the major organs and tissues of human beings, and reconstructed into three-dimensional (3D) models in parallel on high performance computing clusters (HPC). Some visualization software for 2D atlas and 3D models are developed based on the new dataset with high resolution (0.1 mm × 0.1 mm × 0.2 mm). In order to share, release and popularize the above work, a website (www.vch.org.cn) is online. The dataset is one of the most important parts in the national information database and the medical infrastructure.

Chinese Digital Human, anatomical atlas, extremely large data processing, three-dimensional modeling, visualization

The study of digital human aims at digitizing and visualizing the anatomical structures of human body, and constructing the database of the morphological information, physical characteristics and physiological function. It is a focused field in recent years and develops faster and faster. The study originated from the Visible Human Project (VHP) launched by the United States National Library of Medicine (NLM) in 1989[1]. The VHP published the first western male anatomy dataset in 1994 and another female edition in 1995. South Korea began their five-year plan of Visible Korean Human (VKH) in 2000, and got the first dataset in the next year[2]. At present, the VHP datasets have become the most popular sectional anatomy dataset of human beings. Based on the VHP, researchers in the world have made significant achievements in image processing, 3D modeling, visualization software development, physical simulation, and many other fields[3−5].

In November 2001, the 174th Xiangshan Science Conference was held in Beijing, and the theme was science and technical issues of digital virtual human body in China[6]. Plans and suggestions for the China Digital Human Project (CDH) were proposed in the conference. Since then the CDH project was launched formally. Up till now, some high resolution 2D datasets have already been acquired in Southern Medical University and Third Military Medical University. Image processing and organ modeling based on the 2D datasets have been carried out in some research institutions[7−9].

Construction of the 3D structure dataset is the basic application of the CDH, witch is related to the medical, industrial design, education, etc. With this applications, work can be more economical and effective, regardless of some ethics issues in medicine, etc. The 3D structure

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†Corresponding author (email: qianliu@mail.hust.edu.cn)
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dataset of human is most widely used in medical field, including new treatment methods, surgical navigation, virtual surgery, clinical diagnosis, assessment of nuclear radiation, radiation therapy, medical education, and so on. In this paper, 3D modeling of human organs and 3D visualization techniques of using CDH dataset were studied, and a high-resolution 3D anatomy dataset of the human was constructed.

1 Materials

The dataset of CDH No. 2 (CDH M2) was employed, which is the world's highest-resolution sectional image dataset of human beings, and obtained in March, 2005[7].

Table 1 Comparison of the digital human datasets

	VHP	VKH	CDH M2
Spacing (mm)	1	0.2	0.2
Total of section	1878	8590	9320(8952)
Image size	2048×1216	3040×2008	4080×5440
Pixel depth (Bit)	Non-digital(color)	24(color)	24(color)

The original data of CDH M2 was derived from a male body without any physical injury. 9320 horizontal sectional images (4080 × 5440 × 24 bit) were obtained using the frozen section milling and digital imaging techniques. The file size with the RAW (original image data storage format) format reached about 260 GB (Giga Byte, Giga is 10^9), and the spatial resolution was about 0.1 mm × 0.1 mm × 0.2 mm.

2 Methods

The study begins from the raw data, and Figure 1 is the flow diagram of the whole work. Image processing is the beginning of the study, involving image registration, image compression, image segmentation, etc (Figure 2). The next step is 3D reconstruction, and it was also considered as 'the level of understanding' of the image processing. Visualization is based on the 2D image dataset and 3D modeling dataset.

In the study, the volume of the data is huge: the average task of data processing amounts to 100 GB level, the complete set amounts as high as TB (Tera Byte, Tera is 10^{12}) level. So it is too large to be treated with the traditional methods and hardware, or more efficient data processing methods. And better data processing methods and hardware are needed. In this study, computing is realized on an HPC, which has 17 computing nodes. The nodes have two CPU (Intel Xeon 2.4 GHz) each, and connect with each other using the InfiniBand high-speed switching technology. In short, the total computing capacity of the device is about 100 billion times.

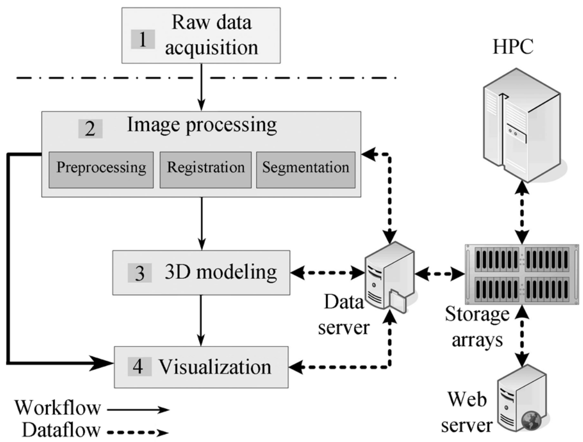

Figure 1 Flow diagram of the work.

2.1 Imaging preprocessing

Imaging preprocessing of the study includes the release of RAW files, registration, extraction for the region of interest (ROI), and lossless image compression. The purpose of the operation is to minimize the space and exposure errors from the acquisition process, reduce the redundancy data and get rid of some difficulties for later processing.

At first, RAW files were released as TIFF (Tagged Image File Format) format without compression. It has to be mentioned that the RAW format is a kind of equipment related data packets rather than image format, and requires a certain tool for decoding.

After that, images were registered by using spatial transformation in the environment of Mathworks Matlab[10]. As the relative position between camera and specimen is unstable in the process of image acquisition, it is necessary to make registration to eliminate the deviations. In order to reduce the difficulty in image registration, 4 copper cables were embedded in the corpse in the direction of the lying body. The cables used as registration markings for section planes were clear and regular. The markings' positions provide information and the cause of deviations, which can be simplified into three spatial transformations: displacement, rotating and zooming. For each image, only one space-transform matrix can be founded and used in inverse transform.

Till now, we had not obtained a suitable result as yet, and the ROI extraction and lossless image compression

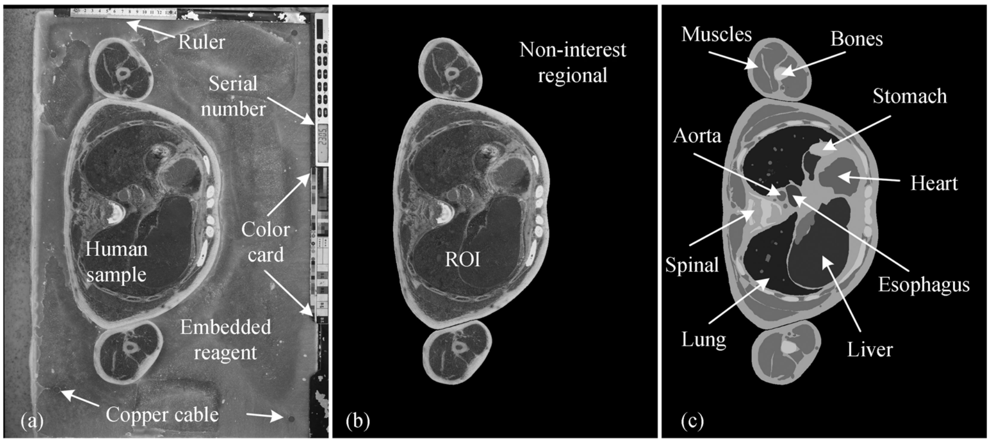

Figure 2 Image processing for the section No. 2305. (a) Original section; (b) imaging preprocessing; (c) segmentation and identification.

were needed. The purpose we did it in this way was to remove redundant data and make the storage and transmission for massive data achievable. Here, the ROI refers to the region within the contours of the human body. And on the contrary, the non-region-of-interest only contains embedded reagent, color cards, container, and any other non-human materials. The proportion of ROI area and total area is defined as image utilization. The average image utilization of the CDH M2 dataset is only 15%. In other words, 85% of the data is redundant. An effective way to increase the utilization is to fill the non-region-of-interest with black color and to use image compression algorithm. The PNG (Portable Network Graphic Format) is a good choice for lossless image compression, and it has a very good performance in the network transmission and displaying speed. The JPEG/JPG (Joint Photographic Experts Group) format is also a good way if the high-resolution is not very necessary, and the compression ratio can reach 1%.

2.2 Segmentation and identification of the organs

Segmentation is the base of 3D modeling, and it separates the image into regions of different meanings based on sectional image and anatomical knowledge. Accuracy and speed are the bottleneck for segmentation. There are two kinds of segmentation methods, automatic segmentation and interactive segmentation.

Automatic segmentation method is a good idea, but it requires a high degree of image contrast which can hardly be reached under normal circumstances. There are only a limited number of organs and tissues suitable for the use of the automatic methods in CDH M2 dataset, such as the cartilage, artery, body contour and red bone marrow. Here, ITK (Insight Toolkit) is used to segment the above-mentioned several targets. Practice has proved that the human-machine-interactive (HCI) can effectively improve the effectiveness of automatic segmentation. However, ITK is unable to provide visualization and graphical user interface (GUI). Therefore, other two toolkits were added: Visualization Toolkit (VTK) and Fast Light Toolkit (FLTK, a kind of GUI toolkits).

An interactive image segmentation approach based on the Adobe Photoshop software is the most important method for us. Photoshop has many advantages, such as the powerful image segmentation features, massive data processing capability, batch processing and easiness in operation. Although the interactive method can enable us to get better results than the automatic methods, but it requires enormous workload, and moreover, the operators have to have sufficient knowledge of anatomy. Therefore, image segmentation becomes the most difficult task in the study. In order to ensure the objectivity and accuracy, some anatomy experts were invited.

Every result from the segmentation will have a unique identification, which is the file name of the images, and also will be recorded into database. MeSH (Medical Subject Headings)[11] was used as the standard for naming system. The name is unique, and it has its own hierarchy consisting of physiological system classification, organ classification, structural position of the physiology, original serial number and so on. Among them, the physiological system classification means nervous system, movement system, circulatory system, etc. The structural position of the physiology means head, chest, belly, etc. The organ classification means heart, kidney, spleen, etc.

The new results were kept by the JPEG/JPG format, which had a high compression ratio. And the color depth and image size had no change.

2.3 3D modeling of the massive data

3D reconstruction is the most common modeling method, which expands the 2D information into 3D space, and makes the information more intuitive and vivid. Because of the massive data problem, parallel algorithm actualized by using the MPI (Message Passing Interface) and VTK has to be used for reconstruction.

Massive data processing poses the major difficulty in 3D modeling. For the complete structure of the body (such as skin), at least 100 GB memory in a single PC is needed. Therefore, a single PC is unable to finish such a task without sampling. Some small organs can be reconstructed on a workstation, such as vertebra and testicle. Regularly, the memory consumption is proportional to the number of voxel. So it can lighten the burden for each computing unit through splitting the large data into small chips (Figure 3(c)). In this work, HPC was used for reconstruction. The approach could enable the high resolution of models to support big organs at a high speed.

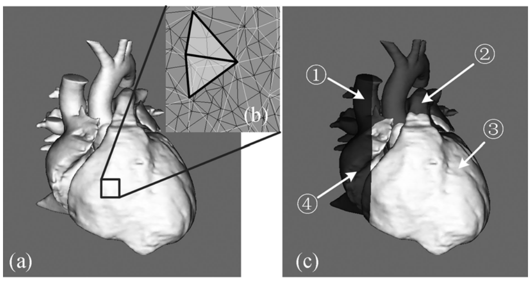

Figure 3 3D reconstruction of the heart. (a) Original surface rendering; (b) triangle mesh topology of surface model; (c) schematic diagram of parallel computing. ①—④, Four different gray-scale regional representatives of different computing nodes output.

All the models only have the contour information by using the marching cube algorithm, and the structure of the data is polygonal[12] as shown in Figure 3(b). It's a good way to reduce the costs in visualization. In addition, the lower-resolution models can be obtained by reducing the number of polygonal.

The 3D models are kept as the private format of the VTK with binary mode. The other commonly format of the 3D model can be transformed through the IO interfaces of VTK or some other business software. The binary mode is so important that it can economize the storage space, and also increase the efficiency of reading and writing.

2.4 Visualization of the CDH datasets

Visualization is a process of translating the data into graphics and display by using the computer graphics and image processing technology, and it is often combined with interactive and stereoscopic display technology. To meet different purposes and datasets, some software were developed: stand-alone version of 2D atlas browser, stand-alone version of 3D model browser, automatic demonstration system with stereo, fictitious operation system, web version of 2D atlas browser, remote anatomy teaching system, etc (Figure 4).

VTK and Mercury Open Inventor (OIV) were used to develop the stand-alone software, and the development environment was Microsoft Visual Studio 6. OIV is greatly advantageous over VTK in 3D stereo display, automatic engine and development cycle, but it has such disadvantages as high cost of secondary development and the underlying algorithm.

JavaScript and Virtual Reality Modeling Language

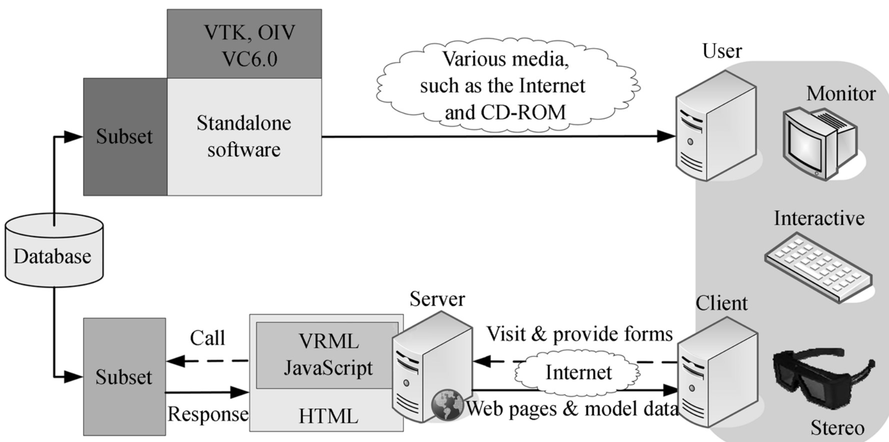

Figure 4 Visualization of CDH datasets.

(VRML) were used to realize the web-based visualization, and the web page was developed by using HTML (Hyper Text Markup Language). The remote client can use the resources from server by accessing to relevant web pages on internet.

3 Results and discussion

3.1 Construction of the datasets

Two kinds of datasets were constructed, that is, 2D image datasets and 3D model datasets. The two datasets can be further divided into smaller ones, called sub-datasets.

The 2D image datasets include several sub-datasets, which are the interim results after preprocessing, registration, segmentation and compression. Below are some useful sub-datasets: the original dataset before decompression (A1), the original dataset after decompression (A2), the images after registration (A3), the lossless compressed dataset without background (A4), the compressed dataset without background (A5) and the results of segmentation (A6) (Table 2).

Table 2 Statistics of 2D image datasets

Dataset	Total section	Size (GB)	Format	Depth (Bit)	Resolution
A1	9320	260	RAW	–	4080×5440 Pixel
A2	8952	552	TIFF	24	
A3	8952	552	TIFF	24	
A4	8952	40.8	PNG	24	
A5	8952	2.79	JPEG	24	
A6	>100000	>40	JPEG	8	

Table 3 Tissues and organs that have been completely segmented[a)]

Physiological systems	Name of tissues or organs
Locomotor	skeletal muscle, bones (a total of 200, not including six ossicles), cartilage (ribs, ears, thyroid cartilage, etc.)
Digestive	salivary glands, pharynx, esophagus, stomach, intestine, liver, gallbladder, pancreas
Respiratory	bronchus, lung
Urogenital	kidney, adipose capsule of kidney, attached testicle, bladder, ureter, sponginess, prostate, spermaduct, spermatophore gland, testicle, urethra ball-gland, urethra
Circulatory	heart, coronary artery, vein, artery, spleen, thymus
Nervous	gray matter, white matter, cerebellum, brainstem, spinal cord
Endocrine	pituitary, adrenal gland, thyroid
Other	body contour, eyeball, lacrimal gland, tongue, ocular

a) Some organs may have symmetric structure, not listed separately, such as lung and kidney.

The 3D model datasets were all developed from the original 3D model which was generated from the VTK program. Up to now, at least 260 models have been reconstructed that belong to the locomotor system[14], circulatory system[10], nervous system, etc (Table 3 and Figure 5). The dataset of the original 3D model has a higher resolution (0.1 mm × 0.1 mm × 0.2 mm) than the VIP-MAN developed by Xu et al.[5] with a resolution of 0.33 mm × 0.33 mm × 1 mm. Depending on the format conversion and polygonal decimation, there were 4 different 3D model datasets: the original dataset (B1), the simplified version of B1 (B2), the VRML models (B3) and the OIV models (B4) (Table 4).

Table 4 Statistics of 3D model datasets

Dataset	Father dataset	Size (MB)	Format	Coding	Visualization platform
B1	A6	950.2	VTK	ASCII	VTK
B2	B1	105.7	VTK	Binary	VTK
B3	B2	293.8	WRL	ASCII	VRML, OIV, VTK, 3DMax
B4	B3	252.4	IV	ASCII	OIV
	B3	104.7	IV	Binary	OIV

3.2 Several visualization methods

The concrete realization of the visualization needs some application programs, including the stand-alone version of 2D atlas browser called CDH Atlas, the stand-alone version of 3D model browser called Clairvoyance Man, the automatic demonstration system with stereo called CDH 3DProjector, the remote anatomy teaching system, etc (Figure 6).

The CDH Atlas is a powerful sectional anatomy atlas of the human body. Based on A4 and A6 datasets, it provides the atlas on three orthogonal planes. The software also provides some useful tools like magnifier, ruler, area calculator, marker, organ probe, etc. And it becomes substitution of traditional anatomical atlas.

The Clairvoyance Man based on the B4 dataset is a 3D model browser with highly interactive. The operation is simple and easy. The user can self-define the color, light, position and the models' components. And it provides the introduction of each organ or tissue on the right side of the interface. The content is so abundant and lively that it is very suited to science popularizing and anatomy teaching.

The CDH 3DProjector based on the B4 dataset is an automatic demonstration system, and needs the support of 3D stereo equipment. Figuratively speaking, the software is like a stage, the models are just like some actors, and the operation of the software is a drama. The audiences can feel reality and immersion by using the stereographic projection and glasses. CDH 3D Projector is a good choice for some exhibition occasion, and suitable for other 3D models.

The remote anatomy teaching system is a web site for 3D model browser and online education. It's very similar to the Clairvoyance Man in software function. A complete person can be assembled by dragging and dropping the mouse, like building up the toy bricks.

4 Prospect

The development of digital human research needs the supports of the other fields, such as compute science, information science, physics, mathematics, medicine, national defense industry, sports industry, aerospace industry, automatics, etc. The plan proposed in 174th Xiangshan Science Conference involve four stages—the visible human, the physical human, the physiological human and the intelligent human. The visible human is our goal at the present stage.

Visible human is a long-term and difficult project, especially the image segmentation. Constantly updating the quality of image processing, VHP is constructing the meticulous model in 20 years. The CDH M2 is superior to VHP in some aspects, but brings greater difficulties in image processing. 2005 was the year of full challenge for us, and about fifty organ models were reconstructed within three months through 24 graduate students' hard work. The fifty models are the basis of our study. Just as the VHP datasets, the CDH M2 datasets will possibly give good support to other researchers.

In HUST, further study is still continuing. Our present goal is to improve the performance of the image processing and parallel computation, to construct more models, and to develop more practical visual software. It is our expectation that the achievement might inspire as many as possible applications. In addition, we are start-

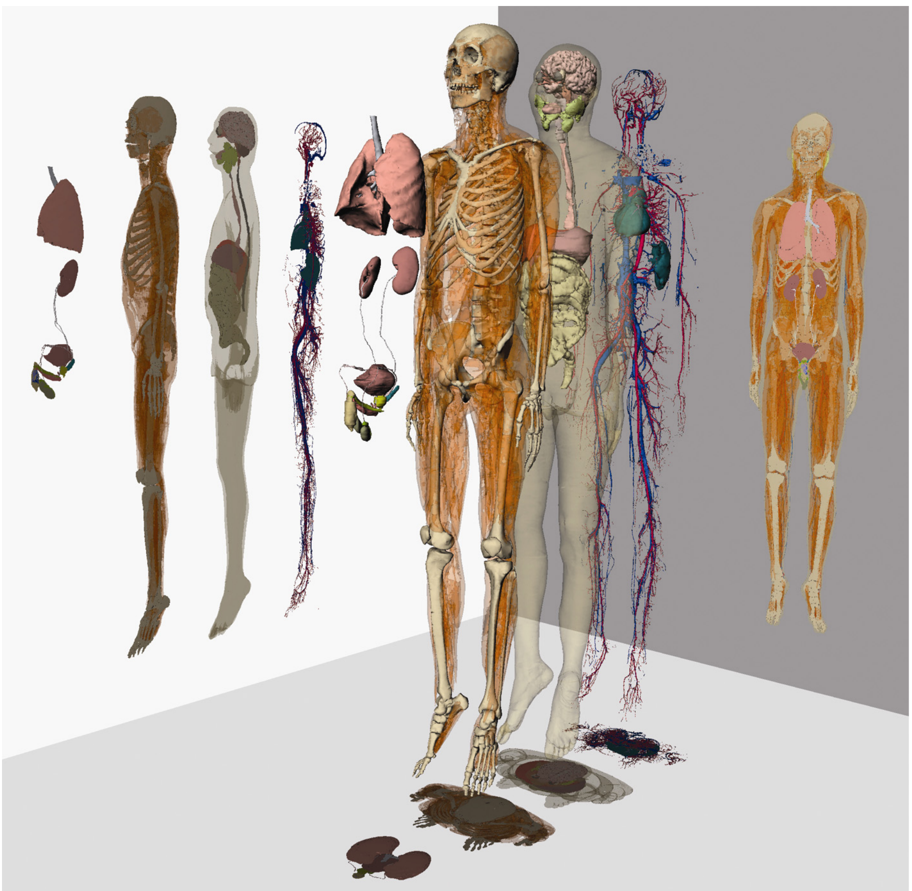

Figure 5 Portfolio effects of 3D structural model of human (B4). Come back from the front: combination of the respiratory and urogenital system; the locomotor system; combination of the nervous, digestive and body contour; circulatory system. Three planar projection are side view, top view and former view of the 3D model.

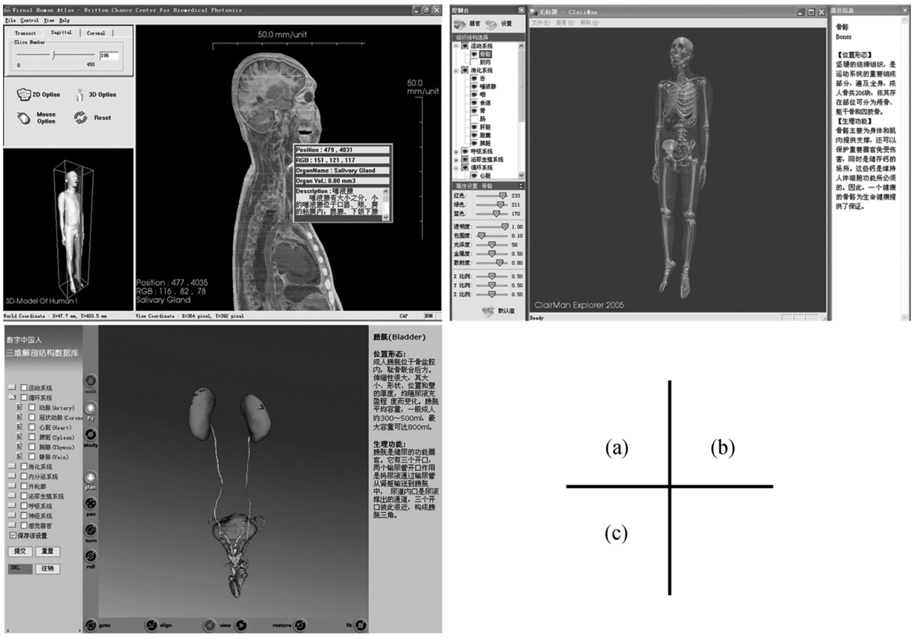

Figure 6 Different visualization methods (only Chinese edition). (a) The user interface of CDH atlas, currently displaying a sagittal image, the location of the mouse is salivary gland; (b) user interface of Clairvoyance Man; (c) the web page of teaching system for human anatomy, the current model is the urogenital system.

ing the study on the second stage (the physical human) with some representative projects including fictitious operation, mechanics simulation, radiation simulation, etc.

In a word, the technology of digital human has a bright future with the progress of other technologies[16]. It is not a dream that we can mould out an actual person in computer.

We thank all those who participated in the CDH Project from Huazhong University of Science and Technology. And we thank Prof. Yu Y T and Prof. Li Z H for the guidance in anatomy.

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