3D Visualization of Liver and Its Vascular Structures and Surgical Planning System

－Surgical Simulation－

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Abstract- **Successful liver surgery requires a clear understanding of the differences in liver shapes and vessel distribution in different individuals. Furthermore, in clinical medicine, there is a high demand for surgical assistance systems for individual patients. Therefore, we aim to segment the liver on the basis of the CT volume data, semi-automatically extract the vessels from the segmented livers and then visualize the 3D shape and the extracted vessel distribution using a virtual operation system. In addition, to improve the operability and accuracy of information recognition in the virtual operation system, prior knowledge and the clinical experiences of doctors are integrated into the visualization system for a practical virtual surgery. A 3D visualization of the liver, allows the user to easily recognize abnormal regions, which need to be removed, and to simply select this region using a 3D pointing device. Furthermore, 3D visualization, allows details in the structure of the human liver to be better understood and a more practical surgical simulation system can be implemented in our developed system.**

I. INTRODUCTION

The complex distribution of vessels in the human liver and the significant variations in its geometric size and shape with different individuals can complicate liver surgery operations. To ensure a safe and appropriate liver surgery, it is essential to understand the liver structure and vessel distribution unique to the individual through surgical planning before the actual surgery. With the recent development of medical imaging equipment, imaging data can be obtained with a resolution of 0.5 mm, which can provide a detailed structure of human organs and any possible abnormality information. The obtained medical data play an important role in examination of abnormal regions, early diagnosis of diseases and planning of surgery or treatment. For practical applications, developing a method to extract useful information from the large amount of obtained data is an important research objective in diagnosis assistance. Therefore, using high-resolution medical images, 3D visualizations of human organs and surgery planning systems have been studied by many researchers [1]-[4]. The Mevis Company in Germany has developed a visualization system that semi-automatically extracts the liver and vessels from CT volume data [8]. However, a more practical surgery simulation system that can adapt to different surgical scenarios is needed to ensure efficient surgical planning and training of doctors and medical students. Therefore, we aim to simulate real liver surgical procedures using a 3D display and construct a surgical planning assistance system for clinical doctors and medical students. The developed system can provide real-time visualizations and interactive control according to user requirements during surgical simulation procedures. Our surgical simulation system consists of three blocks: liver segmentation, vessel extraction, and surgical visualization and simulation, which are shown in Fig.1. First we segment the liver organ from the CT volume data using our previously proposed approach. Then, we extract different types of vessels in three CT imaging phases with a multi-scale filter. Finally, the segmented liver and extracted vessels are rendered in the visualization system for surgical planning simulations.

The remainder of this paper is organized as follows. We introduce the procedures of liver segmentation and vessel extraction from CT volume data in Sec.2. In Sec.3, we describe the visualization modeling of the liver using the segmented liver and extracted vessel. Sec.4 explains the interactive virtual surgery system and visualization with a 3D display. Finally, Sec.5 concludes the paper.

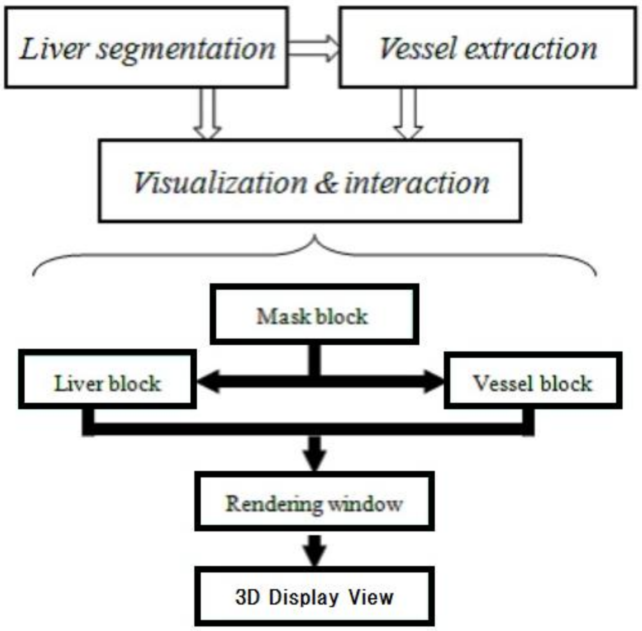

Fig.1. Flow chart of the developed liver surgery visualization and simulation system

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II. LIVER SEGMENTATION AND VESSEL EXTRACTION

A. Liver Segmentation

For liver segmentation, we use our recently proposed approach [3], in which a low-accuracy segmentation using the K-means method is performed, and then, a high-accuracy segmented liver is obtained using the geodesic active contour (GAC) method. In this approach, we need to first select a slice with the maximum liver region from the CT volume data, and manually segment the liver region from the other parts, which can also guide the liver organ region decision of the next and previous slices for automatic segmentation as an initial mask. Then, with the manual segmented liver region of one selected slice, the liver for other slices can be segmented one by one automatically. The procedure of automatic liver segmentation is shown in Fig. 2 and is as follows:

(1) Assuming that the intensity of the image in the liver region has a Gaussian distribution with mean μ and standard deviation σ, we can initially determine whether a pixel belongs to the liver or other organs on the basis of its intensity using the EM method. To avoid misclassification of liver pixels as other organ pixels, we set a narrow band $[\mu-\beta\sigma, \mu+\beta\sigma]$ with $\beta=0.7$ to retain a subset of the liver pixels denoted as liver candidates. These candidates have intensity values close to the mean of the Gaussian distribution. A slice with pixels belonging to the liver after this step is shown in Fig.2 (b).
(2) The liver pixel candidates are clustered on the basis of the spatial distance between the candidate pixel and initial mask, which is the liver mask of the previous slice segmented by the K-means method. If the spatial distance between the liver pixel candidate and initial mask is large, it can be considered a non-liver region and can be deleted from the pixel candidates. Then, the retained pixels are recognized as liver pixels according to prior knowledge of its previous slice and are denoted by index pixels, as shown in Fig.2 (c).
(3) The probabilities of the pixels are calculated with the intensities in the wide band $[\mu-3\sigma, \mu+3\sigma]$, which is the inverse of the shortest spatial distance between the index pixels and the focused pixel. Therefore, the smaller the spatial distance between the focused and index pixels, the greater would be the probability. This is shown in Fig.2 (d).
(4) The initial contour of the processed slice is obtained by thresholding the probability image. Finally, GAC is used to obtain an accurate contour of the liver region, which is shown in Fig.2 (e).

After obtaining the contour of each slice in the CT volume data, we can render (model) the liver surface as shown in Fig. 3.

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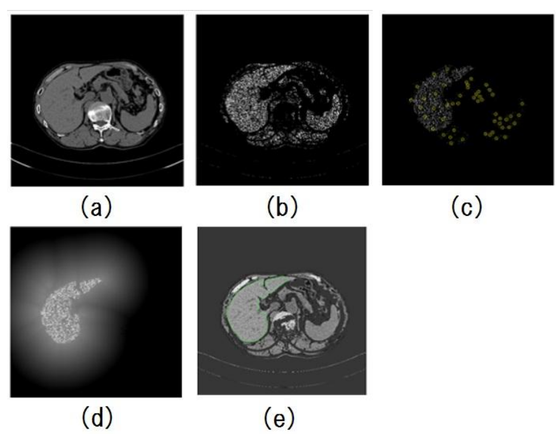

Fig.2 (a) A CT slice image, (b) Liver pixel candidates with narrow band classification, (c) Cluster center by the K-means method, (d) Probability image, (e) Liver contour by GAC.

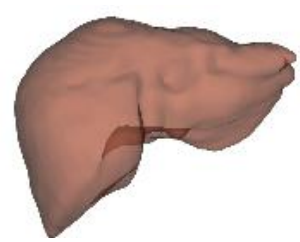

Fig.3 Liver area modeling

B. Vessel Extraction

Vessel information is very important for surgical simulations, and is also a key factor to be considered by doctors during surgery procedures. Therefore, we aim to obtain the accurate positions of different types of vessels in our surgical simulation system. In addition, vessel extraction is an essential preliminary procedure. In this study, we extract the line-like structure (vessel structure) using the Hessian matrix proposed by Frangi [11]. The eigen vectors of the Hessian matrix for each pixel can represent the shape orientation on some scale. For the vessel structure, the corresponding eigenvector of the smallest eigenvalue shows the flow direction of the vessel, and the corresponding eigenvector of the largest eigenvalue indicates the vertical direction of the flow. Given the eigenvalues λ_1, λ_2 and λ_3 with $|\lambda_1| \leqq |\lambda_2| \leqq |\lambda_3|$, the relationship between the shape of the structure and eigenvalues can be summarized as shown in Table 1.

For implementation, the normalized Gaussian filter is used to improve the contrast between the vessels and background, thus enabling easy detection. However, as stated before, vessel sizes can vary, and therefore, it is difficult to enhance the contrast using a Gaussian filter with a single scale. A multi-scale filter that can adjust the filter width according to the pixel intensity information is usually used to enhance vessel structures with different sizes [11]. After liver segmentation, we can extract vessels with different sizes from the segmented liver region using a multi-scale filter. In this study, the three types of vessels hepatic artery, portal vein, and hepatic vein are extracted from the CT imaging volume data including arterial, portal, and delayed phases, respectively. Fig.4 shows the extracted vessel modeling from different CT imaging volume data.

Table.1 Eigenvalue results

λ_1	λ_2	λ_3	Pattern
N	N	N	noisy, no preferred direction
L	L	H−	Bright plate structure
L	L	H+	Dark plate structure
L	H−	H−	Bright tubular structure
L	H+	H−	Dark tubular structure
H−	H−	H−	Bright blob structure
H+	H+	H+	Dark blob structure

N: Noisy L: Low value H: High value +/−: sign

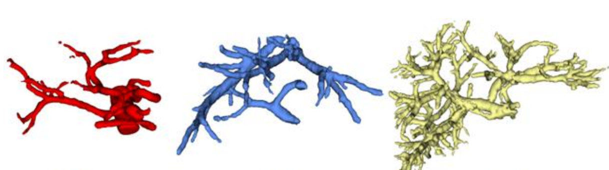

Fig.4 Extraction results of the main vessels (a) arterial phase, (b) delayed phase, (c) portal phase

III. 3D Visualization Of Liver

Using the segmented liver and extracted vessels, we visualize them together using the Visualizing Tool Kit (VTK) library, which has been widely used in 3D visualization systems by many researchers [13]. Fig.5 shows our developed visualization system for surgical simulations, which mainly consists of liver, mask, and vessel blocks. The liver and vessel blocks segment the liver region and model the vessel surface respectively, according to the same procedure involving the following five steps. First, the segmented liver and extracted vessels are read, and then re-sampled using a shrinkage factor to increase the speed of applications. Next, the contour can be extracted for surface rendering. To cut a part of the liver, a clipping filter is used to simultaneously prepare several masking patterns and remove several parts of the liver or vessels. Finally a smoothing filter is applied to the extracted surface for making actor, and then is sent to the mask block. The mask block mainly aligns the liver and the vessel model in the same virtual space and then visualizes them together to guide doctors while cutting the liver using a knife.

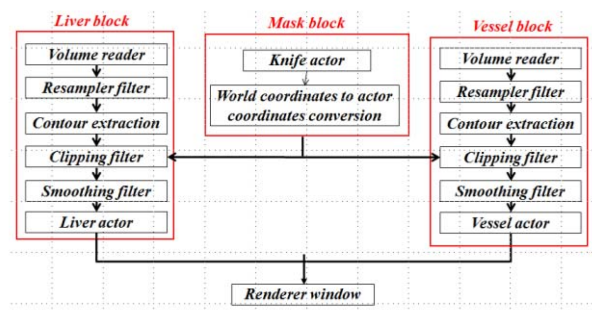

Fig.5 Diagram of the visualization module using VTK

IV. Interactive Surgical System

In our study, we aim to not only visualize the liver and the vessel model but also simulate an interactive surgical procedure, in which a liver is cut according to the visualization information. Our developed surgical simulation system consists of three parts: the position of the virtual knife, re-rendering of liver modeling, and determination of the cutting region, as shown in Fig.7. Given the input position of the virtual knife that can be represented by a green ball in real-time, the cutting position in virtual space is calculated. According to the pushing situation of the virtual knife on the liver, the desired liver cutting region can be estimated, and then, the surface after liver cutting can be smoothly re-rendered. Depending on the doctors' experience, first, a region smaller than the desired region is usually selected for cutting, and then the process is repeated several times until complete removal This can prevent extensive bleeding during surgery. Therefore, our surgical simulation system can accurately replicate a real surgical procedure. Next, we introduce the 3D device used (3D display and 3D pointing device) in our simulation system.

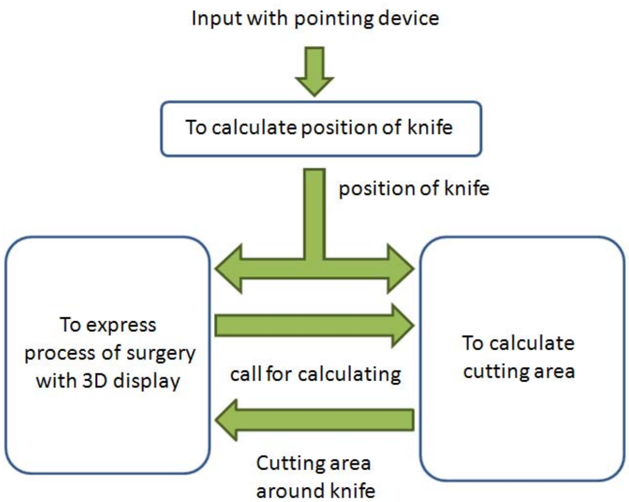

Fig.7 Flow of surgical simulation

A. *3D Liver Visualization Using a 3D Display*

Our simulation system is developed on a computer with the specifications shown in Table.2. The display has a refresh rate of 120 Hz, and can show a 3D structure, which can be viewed using liquid crystal shutter glasses. Fig.6 shows a photograph of the experimental setup. Using a 3D display, the relative position of the vessels can be instinctively determined for an easy simulation of a real surgery. Our system uses the four screens in Fig.7, to show the locally visible liver and vessels (in detail) or the global vessels from different angles. The image in the upper right window is the main screen reflecting the relative position between the virtual knife and liver being modeled, and the image in the upper left corner is a magnified version of the main screen, which can guide a doctor regarding the removal of the desired liver region. The lower right image is the main image rotated by 90° and the lower left is an opaque version with the same situation presented in the main image. Using a transparent display such as the one in Fig.7, the vessel structure near the desired cutting region can be easily confirmed, whereas it will be necessary to cut the liver to view the structure of the vessel in the opaque display. Therefore, our simulation system can provide useful information by transparently visualizing the segmented liver and extracted vessels during a real surgical procedure.

Table.2 Equipment for 3D visualization

Graphic board	GeForce 8700M GT 1.52GB
CPU	Intel Core2 Duo 2.40GHz
Memory	4.00GB
3D display	Samsung SyncMaster2233RZ
3D glasses	NVIDIA 3DVision

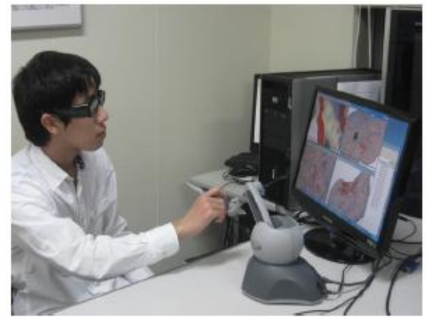

Fig.6 Interactive Simulation System

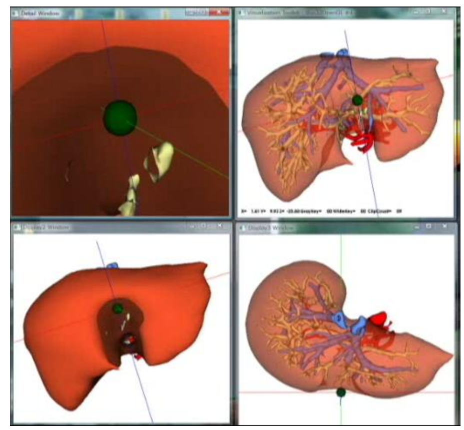

Fig.7 Screen of simulation

B. *3D Pointing Device*

In surgical simulations, the shape of the modeled liver in virtual space can be deformed or cut-out, depending on the pressure with which the virtual knife is pushed. Determining the pushing pressure of the virtual knife and the deformation or cutting region of the liver is a issue. Furthermore, it is impossible to accurately control the input position of the virtual knife using conventional input devices such as a keyboard and a mouse. In simulation surgery system, it prospect that the input device can reenact the move trend of a real knife. In our study, a 3D pointing device similar to a pen, where the position of its pen-like tip reflects the knife position in virtual space, is used to simulate a real knife. In addition, the pushing pressure on the 3D pointing device can be automatically estimated for determining the deformation or cutting region of the liver.

V. Simulation Result

Our developed surgical simulation system is constructed to simplify real applications by implementing the experience and prior knowledge of clinical doctors. We performed several simulation experiments using our developed system to evaluate the ability of the simulation results to satisfy the needs of clinical doctors. The simulation experiments are conducted using two normal livers and an abnormal liver. In the normal livers, we attempt to remove the left hepatic lobectomy and posterior region, respectively, and remove a tumor from the abnormal liver. Next, we introduce the detailed simulation procedure for the three experiments.

(1) To remove the left hepatic lobectomy from the normal liver, it is necessary to cut off the left half of the liver along the hepatic vein. In a real surgical operation, the liver is cut in small segments along its current surface. The simulation procedure is shown in Fig. 8. In the simulation, we first cut the liver center along the vertical direction, and then, the vessel structure inside the liver can be confirmed. The upper and lower left images illustrate the opaque images, where the cutting parts are displayed in different colors to indicate the cutting position.
(2) Figure 9 shows the procedure for removing the posterior region of the liver. In our system, the angle for displaying the liver and the vessel model can be changed according to the cutting position, which is decided by the input position of the virtual knife. Using this function of varying the display angle according to the input position, the cutting procedure of any liver region will be the same as that of the frontal one. In addition, the display screens can be easily changed to opaque or transparent according to the situation and the requirement of the doctor.
(3) Figure 10 shows the simulation experiment for removing a tumor from an abnormal liver. The tumor is manually extracted from a CT image under a doctor's guidance, and is modeled for visualization together with the liver and vessels. As mentioned in Sec. IV, a region smaller than the tumor is first cut out, and this is repeated several times until complete removal. This can also be adapted for the removal of different sizes and shapes of tumors, and to reproduce real surgical procedures involving the interactive cutting of tumors similar to a normal liver.

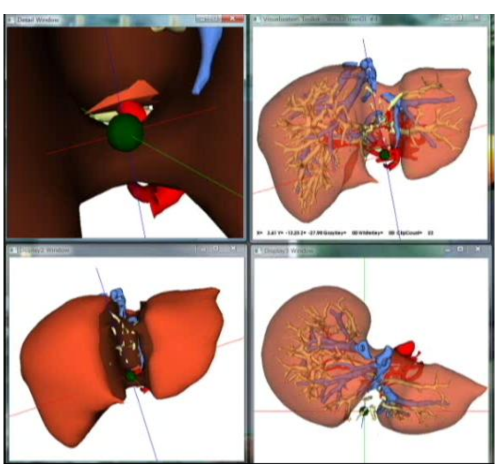

Fig.8 Simulated experiment for the removal of the left hepatic lobectomy

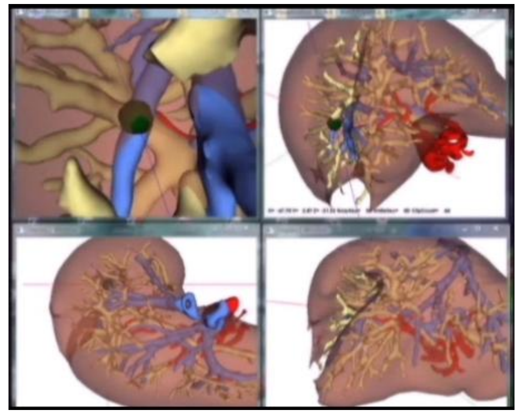

Fig.9 Simulated experiment for the removal of the posterior region

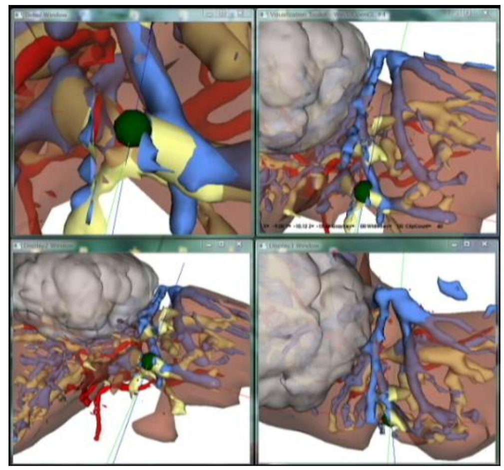

Fig.10 Simulated experiment for the removal of a tumor

VI. Conclusion

In this study, we constructed a liver surgery simulation and assistance system that considers variations in the liver shape and size with patients. In our system, the liver and vessel are first segmented and extracted from the CT volume data and then a model is built allowing them to be visualized together in virtual space. Our system employs a 3D display and 3D a pointing device to enable intuitive understanding of the surgical procedure. The simulation system can reproduce real surgical procedures for guiding doctors' operations. In addition, for the interactive operation and 3D visualization doctors' experience and prior knowledge for specific patients are implemented. Therefore, it can be used to not only assist in planning for surgeries but also for the training and education of doctors prior to real surgeries. The future work is prospect to

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