Development of a User-Centered Virtual Liver Surgery System

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ABSTRACT

Objective: The present study is to develop a user-centered virtual surgery system called Dr. Liver which has clinical applicability and effectiveness to support liver surgery. **Materials and methods:** The major functions of Dr. Liver include (1) extraction of the liver, vessels, and tumors from abdominal CT images, (2) estimation of the standard liver volume of a patient, (3) volumetry of the extracted liver, vessels, and tumors, (4) segmentation of the liver based on the portal vein structure, and (5) support of surgery planning. A novel semi-automatic liver extraction algorithm was developed and implemented to Dr. Liver for time efficiency and accuracy of extraction. Dr. Liver was evaluated using MDCT data of three patients and compared to the OsriX system in terms of time and accuracy. **Results:** Dr. Liver was found significantly better than the OsriX system by showing an average (SD) time of liver extraction = 4.4 (2.4) min and an average difference between the volume of a manually extracted liver and that of the corresponding semi-automatically extracted liver = 4.2 (8.9) ml. Furthermore, various user-friendly features such as a procedural interface of virtual surgery planning were implemented into Dr. Liver for usability. **Conclusions:** It is concluded that Dr. Liver is a clinically effective tool to support liver surgery planning. More sophisticated features and functions are being developed and implemented to Dr. Liver to provide a surgeon with effective information for rational planning of liver surgery.

Keywords: Virtual liver surgery system, Surgery planning, User-centered system

1. Introduction

A 3D virtual liver surgery planning system provides surgeons with an effective tool for safe and rational surgery. It provides not only visual information such as the structure of the liver vasculature and the segments of the liver but also quantitative information such as the volumes of the liver, remnant, and/or graft.

Most of existing virtual surgery systems such as Rapidia (Infinitt Co., Ltd, South Korea), Voxar 3D (TOSHIBA Co., Japan), Syngovia (SIEMENS Co., Germany), and OsriX (Pixmeo Co., Switzerland) do not provide functions specialized to liver surgery planning. These generic virtual surgery systems have a limited utility to surgeons in pre-operative liver surgery planning. For example, the manual or semi-automatic liver extraction using a generic virtual surgery system is quite cumbersome and time demanding (> 30 min.) to the user.

Existing specialized virtual liver surgery systems like Synapse Vincent (FUJIFILM Co., Japan) (Figure 1) do not meet surgeons' needs in terms of usability and time efficiency. Synapse Vincent supports liver extraction, vessel analysis, liver segmentation, volumetry, and surgery planning; however, some of its user interface such as vessel extraction is not easy for surgeons to use. Furthermore, the region growing method used by Synapse Vincent for liver extraction often extracts adjacent tissues and/or organs with the liver, which leads to intensive manual editing to remove the inaccurately extracted parts. Another specialized virtual liver surgery system called LiverAnalyzer & LiverViewer developed by MeVis Medical Solutions AG is capable of segmentation of the liver, vessels, biliary system, and tumors, volumetry of the remnant and/or graft, evaluation of vascular territories, and surgery planning. However, LiverAnalyzer is not for sale; thus, surgeons need to send CT images to Mevis Medical Solutions AG and wait one or two days for receiving liver analysis results.

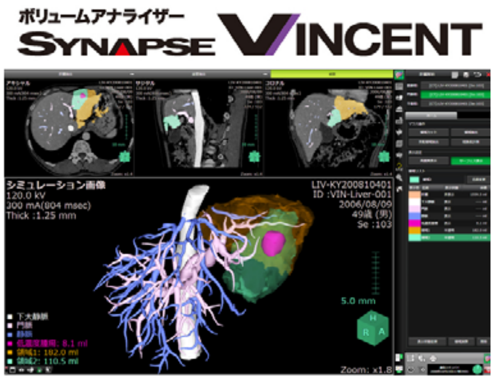


Figure 1. Synapse Vincent System

The present study is intended to develop a user-centered 3D virtual liver surgery system, called Dr. Liver, which provides specialized functions for liver surgery with an intuitive, user-friendly interface so that the surgeon can obtain information necessary for liver surgery planning within a reasonable time.

2. Use Scenario

Dr. Liver consists of a five-step procedure (see Figure 2) of virtual surgery planning: (1) liver extraction, (2) vessel extraction, (3) tumor extraction, (4) liver segmentation, and (5) surgery planning. The system is planned to take an entire processing time of 25 to 30 min. from liver extraction to surgery planning.

2.1 Liver Extraction

To extract the liver from abdominal CT images, a fast and accurate semi-automatic algorithm was developed in the present study. The liver extraction algorithm consists of five steps (Figure 3): (1) denoising of CT images, (2) selection of multiple seed points, (3) detection of an initial liver region, (4) propagation of the liver region, and (5) post-processing. In step 1, an anisotropic diffusion filter (Perona and Malik, 1990) is applied to remove noises from CT images. In step 2, multiple seed points are selected interactively by mouse clicking. In step 3, initial liver region is extracted by a fast marching level set method (Sethian, 1996). In step 4, the initially extracted liver region propagates to reach the liver boundaries. In step 5, holes within the liver boundaries are filled and the liver surface is smoothed. Figure 4 shows an extracted liver in 3D view.

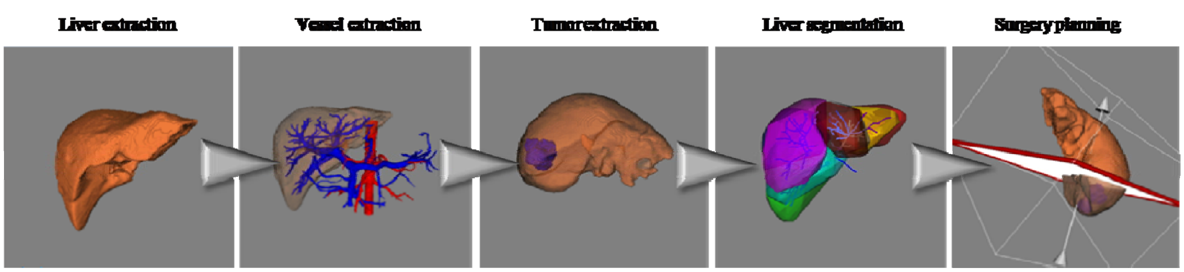


Figure 2. Liver surgery planning process

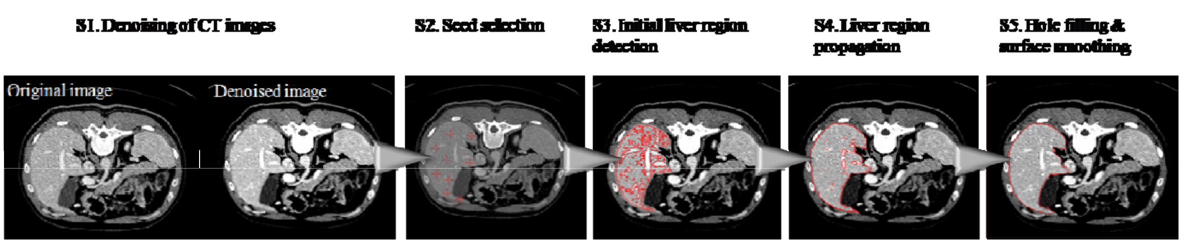


Figure 3. Liver extraction process

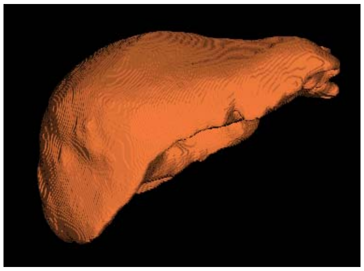


Figure 4. 3D view of extracted liver

2.2 Vessel Extraction

After the liver is extracted, the vessels including hepatic artery (HA), portal vein (PV), hepatic vein (HV), and inferior vena cava (IVC) are extracted. A region growing method (Ibanez et al., 2005) is applied to extract the former three vessels, while the extraction of IVC follows the same method and process applied to liver extraction. A 6-step procedure (Figure 5) has been developed to extract PV, HA, and HV. In step 1, the CT images are denoised like liver extraction. In step 2, a seed point is interactively selected by mouse clicking. In step 3, a threshold interval is interactively explored until the vessel of interest becomes neither dark nor bright by visual inspection. In step 4, the vessel is extracted by the region growing method. In step 5, holes within the vessel are filled and the vessel surface is smoothed. In step 6, an interactive 3D cutting is performed to remove neighboring tissues and vessels from the vessel extraction result. Figure 6 shows an extracted PV in 3D view.

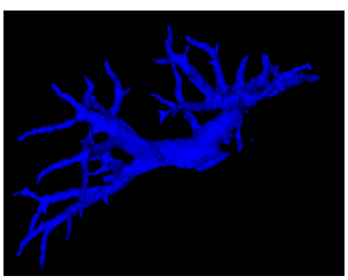


Figure 6. 3D view of extracted PV

2.3 Tumor Extraction

Tumors are extracted by a threshold-based level set method (Lefohn et al., 2003). A 5-step procedure is implemented: (1) denoising of CT images, (2) interactive selection of a threshold interval, (3) interactive selection of multiple seed points, (4) tumor extraction, and (5) hole filling and surface smoothing. Figure 7 shows an extracted tumor (in green color) in the liver.

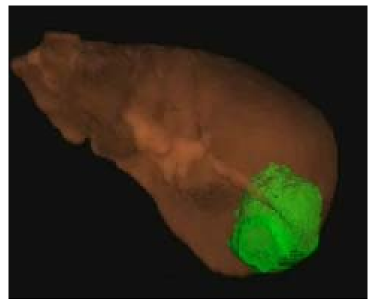


Figure 7. 3D view of extracted tumor (green color)

2.4 Liver Segmentation

The segmentation method of Dr. Liver follows the Couinaud model (Couinaud, 1957) which divides the liver into 8 or 9 segments according to the structure of PV. A 4-step procedure (Figure 8) has been developed to segment the liver. In step 1, the extracted PV is skeletonized. In step 2, 8 or 9 branches of PV are interactively selected by mouse clicking in 3D view. In step 3, the PV is classified according to the selected branches. Different colors are assigned to those branches. In step 4, the liver region is segmented in accordance with the classified PV branches.

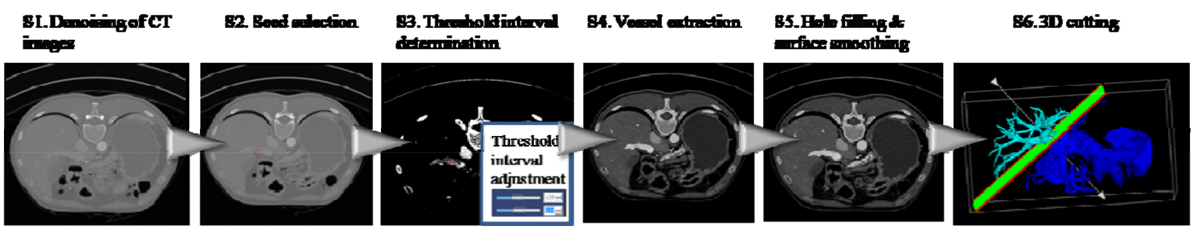


Figure 5. Vessel extraction process

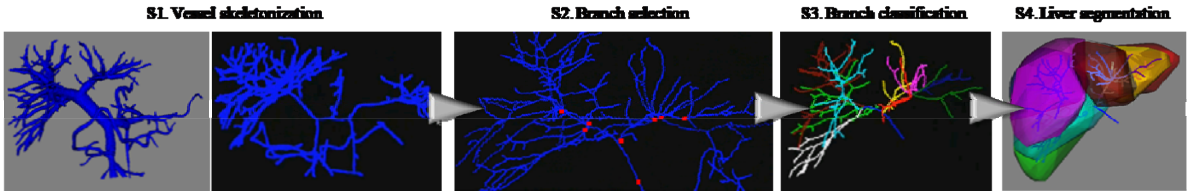
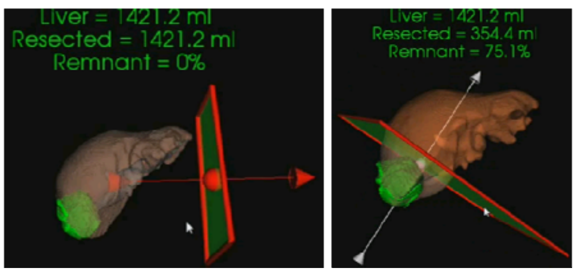


Figure 8. Liver segmentation process

2.5 Surgery Planning

A cutting plane is generated to simulate liver surgery. Through interactive manipulation of the location and orientation of the cutting plane, an optimal resection location, surface, and angle for liver surgery can be determined by referring to volume information of remnant liver parenchyma and vessel analysis results (Figure 9).



(a) before surgery planning (b) after surgery planning

Figure 9. Surgery planning

3. Evaluation Methods

3.1 Participants

Three patients different in age, gender, and liver volume were selected for evaluating the performance of Dr. Liver. Their CT data sets, provided by Chonbuk National University Medical School, are 12 bit DICOM images with a resolution of 512 × 512 and a thickness of 1 mm.

3.2 Compared System

Dr. Liver was compared with OsiriX in terms of time and accuracy. OsiriX provides five ways to extract the liver: manual method, 2D semi-automatic method (2D method), 3D semi-automatic method (3D method), 2D semi-automatic method with editing (2D & Editing method), and 3D semi-automatic method with editing (3D & Editing method). The 2D and 3D methods employ the region growing method. In the 2D method, the liver is extracted in 2D slice by slice and one seed point needs to be selected for each slice. In the 3D method, the liver is extracted in 3D and selection of only one seed point is required for the entire liver CT images. In both the 2D and 3D methods, a seed point is selected interactively by clicking the mouse on the liver region. After obtaining the liver from the 2D or 3D method, manual editing is performed slice by slice in 2D to correct an extracted liver contour, which forms the 2D & Editing or 3D & Editing method.

3.3 Measures

For efficiency evaluation, the time of liver extraction was compared between Dr. Liver and OsiriX. For accuracy evaluation, the volume measurement error (VME) (see Eq. 1) (Lee, Kim et al., 2007) was measured. The volume of the liver manually extracted by an expert was considered as the golden standard.

$$VME = \left(\frac{volume_{automatic}}{volume_{manual}} - 1 \right) \times 100\% \qquad (1)$$

4. Results

4.1 Efficiency

The liver extraction time of Dr. Liver was compared with those of the 2D, 3D, 2D & Editing, and 3D & Editing methods of OsiriX as shown in Table 1. The average processing time of the 3D method was 1.5 ± 0.3 min, which is shortest among the five methods. Except the 3D method, Dr. Liver is most efficient.

Table 1. Assessment of efficiency

Patient	Dr. Liver extraction time (min)	OsiriX extraction time (min)			
		2D	3D	2D & Editing	3D & Editing
1	7.1 ± 1.5	26.1 ± 14.1	1.8 ± 0.1	47.1 ± 6.2	42.3 ± 0.1
2	3.2 ± 0.1	9.6 ± 0.3	1.2 ± 0.1	25.1 ± 0.4	21.8 ± 4.3
3	2.8 ± 0.1	8.4 ± 1.2	1.4 ± 0.1	23.7 ± 1.6	25.6 ± 0.1

4.2 Accuarcy

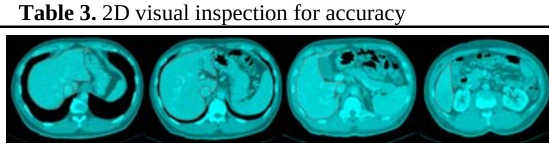
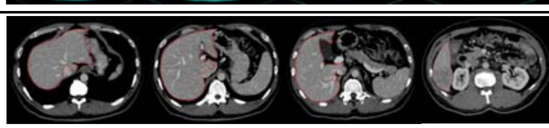
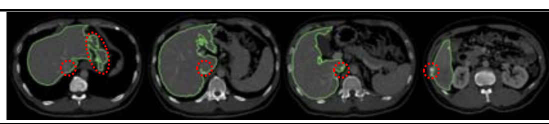
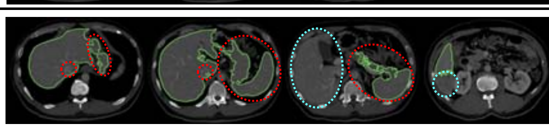
The VME results of the five liver extraction methods are shown in Table 2. The average absolute value of volume measurement error of Dr. Liver is 0.59 ± 0.49%, which is smaller than those of 2D & Editing (2.23 ± 0.68%) and 3D & Editing (2.04 ± 0.49%) methods. However, the VMEs of the 2D and 3D methods should not be directly interpreted due to their large false positive and negative errors. Therefore, Dr. Liver is much more accurate than the four methods in OsiriX.

A visual inspection on both 2D (see Table 3) and 3D results (see Table 4) identified that Dr. Liver, the 2D & Editing method, and the 3D & Editing method extract the liver accurately, while the 2D and 3D methods of OsiriX have much lower accuracy than the former three methods. Also, the visual inspection identified that Dr. Liver, the 2D & Editing method, and the 3D & Editing method produce similar results to that of manual extraction in terms of shape and size. The 2D method mistakenly extracts adjacent organs with the liver. The 3D method not only extracts adjacent organs with the liver but also misses some parts of the liver. Between the 2D and 3D methods, the 3D method has lower accuracy than the 2D method since the output of the 3D method is more different from that of manual extraction.

Table 2. Assessment of accuracy

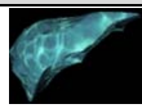
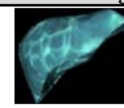
Patient	Manually extracted volume (ml)	Hybrid extracted volume (ml)	OsiriX extracted volume (ml)				Volume measurement error (%)				
							Hybrid	OsiriX			
			2D	3D	2D & Editing	3D & Editing		2D	3D	2D & Editing	3D & Editing
1	1250.5 ± 23.3	1258.3 ± 4.0	1260.3 ± 11.2	1255.7 ± 3.7	1232.8 ± 7.8	1220.9 ± 4.8	-0.65	N/A	N/A	1.60	1.49
2	1226.0 ± 11.3	1227.0 ± 8.3	1252.4 ± 0.1	1253.1 ± 24.5	1252.4 ± 0.1	1253.1 ± 24.5	0.08	N/A	N/A	2.15	2.21
3	1424.0 ± 2.8	1409.0 ± 3.7	1382.0 ± 16.5	1389.4 ± 19.2	1382.0 ± 16.5	1389.4 ± 19.2	-1.05	N/A	N/A	-2.95	-2.43

Table 3. 2D visual inspection for accuracy

Manual (Reference)	
Hybrid	
2D	
3D	

Note: [red dotted circle]: false positive; [blue dotted circle]: false negative

Table 4. Three-dimensional visual inspection for accuracy

Hybrid	OsiriX			
	2D	3D	2D & Editing	3D & Editing
				

5. Discussion

The present study developed a user-centered virtual liver surgery system called Dr. Liver which has clinical applicability and effectiveness to support liver surgery. Various user-friendly features such as a procedural interface of virtual surgery planning were implemented into Dr. Liver for better usability. A novel semi-automatic liver extraction algorithm was developed and implemented to Dr. Liver for time efficiency and accuracy of extraction. Dr. Liver was found significantly better than the OsriX system by showing the average (SD) time of liver extraction = 4.4 (0.6) min and the average difference between the volume of a manually extracted liver and that of the corresponding semi-automatically extracted liver = 4.2 (8.9) ml.

Compared with other systems, the procedural interface of Dr. Liver is easy to learn and use. The procedural interface is simple and organized. The highlight of a step under processing informs the user which step they are in. By following the steps of the menu one by one, surgeons can easily conduct the surgery planning work.

The high accuracy of Dr. Liver for estimating liver volume supports successful pre-operative planning of liver resection surgery. Liver volume information is important for liver surgery planning with a rational safety margin of liver resection. Inaccurate results may result in violation of safety margin. For example, if an over-estimated liver volume is used, the resection volume would be larger than necessary, which may exceed the safety margin.

The short processing time (25 to 30 min from liver extraction to surgery planning) is of benefit to surgeons. Surgeons can make a pre-operative plan in a short time. However, when a generic virtual surgery system is used, intensive manual drawing is necessary to extract the liver from CT images. The manual extraction requires a significant amount of effort and time (> 1 hour) to complete the task. Moreover, some hospitals send a patient’s CT images to an image processing agent for surgery planning; however, it takes one or two days to receive results from the agent.

More sophisticated features and functions are still needed to be developed and implemented to Dr. Liver to provide a surgeon with effective information for rational planning of liver surgery.

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