# DEVELOPMENT OF A USER-CENTERED VIRTUAL LIVER SURGERY PLANNING SYSTEM

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The present study is intended to develop a user-centered virtual liver surgery planning system called *Dr. Liver* which has clinical applicability and effectiveness to support liver surgery. Existing virtual surgery systems needs to be customized to liver surgery and improved for better usability and time efficiency. A use scenario of a virtual liver surgery planning system was established through literature review, benchmarking, and interviews with surgeons. Based on the use scenario, detailed liver surgery planning procedures were defined. 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 into 8 segments based on structures of the extracted portal and hepatic veins, and (5) support of surgery planning. Novel algorithms were developed and implemented into Dr. Liver for accuracy and time efficiency. Various user-friendly features such as a procedural interface of virtual liver surgery planning were integrated into Dr. Liver for better usability. Dr. Liver would be applied to safe and rational planning of liver surgery.

## INTRODUCTION

A 3D virtual liver surgery (VLS) planning system can provide surgeons with an effective tool for safe and rational surgery. The safety of major liver resection can be predicted by relative residual liver volume (%RLV), the ratio of residual to total functional liver volume (TFLV = entire liver volume - tumor volume). For example, Schindl et al. (2005) reported that of 104 patients with normal synthetic liver function the incidence of severe postoperative hepatic dysfunction was > 90% for %RLV < 27% and only 13% for %RLV >27%; Ferrero et al. (2007) suggested based on an analysis of 119 patients that hepatectomy can be considered safe if %RLV > 26.5% in patients with healthy liver and >31% in patients with impaired liver function. Next, a rational surgery, which requires the determination of the proper location, orientation, and shape of a cutting plane on the liver, can be planned by localizing a tumor(s) in relation to the three liver vascular trees (portal vein, hepatic vein, and hepatic artery). To support a safe and rational liver surgery, as shown in Figure 1, a 3D VLS planning system needs to provide not only visual information of the location and size of a tumor, the structure of the liver vasculature, and the segments of the liver, but also quantitative information of the volumes of the liver, remnant, and/or graft (Debarba et al., 2010; Reitinger et al., 2006; Sorantin et al., 2008).

Most 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. Thus, these generic virtual surgery systems have a significantly limited utility to surgeons for pre-operative liver surgery planning. For example, the manual or semi-automatic liver extraction of a generic virtual surgery system is quite cumbersome and time demanding (> 30 min.) to the user. Furthermore, functions of identification of liver segments and planning of liver surgery are not provided in the generic virtual surgery systems.

Several specialized systems to liver surgery such as LiverAnalyzer™ (MeVis Medical Solutions AG, Germany) and Synapse Vincent™ (FUJIFILM Co., Japan) have been developed, but their user interfaces and algorithms need to be improved for better usability and time efficiency. LiverAnalyzer is not for sale, but is known to have capabilities of segmentation of the liver, vessels, biliary system, and tumors, volumetry of the remnant and/or graft, evaluation of vascular territories, and surgery planning. Only a distant web service is available for LiverAnalyzer—CT images are sent to Mevis Medical Solutions AG and then a liver analysis report is delivered within one or two days depending on selected payment option. The liver analysis report is viewed by LiverViewer, provided free of charge by the company; however, LiverViewer shows only analysis results without presenting CT images so that surgeons have difficulty to cross-check the accuracy of the analysis results. In contrast, Synapse Vincent is for sale and supports liver extraction, vessel analysis, liver segmentation, volumetry, and surgery planning. However, some user interfaces and algorithms of Synapse Vincent such as those for liver extraction and vessel extraction from CT images are cumbersome to use. For example, the region growing method used by Synapse Vincent for liver extraction often extracts adjacent tissues and/or organs along with the liver, which leads to intensive manual editing to remove parts inaccurately extracted.

The present study is intended to develop a user-centered 3D virtual liver surgery planning system called *Dr. Liver* which provides user interfaces and algorithms specialized to liver surgery so that the surgeon can obtain information necessary for preoperative liver surgery planning within a reasonable time (< 30 min) by using intuitive, user-friendly interfaces. A use scenario for Dr. Liver was established, user interfaces with novel features such as a procedural diagram

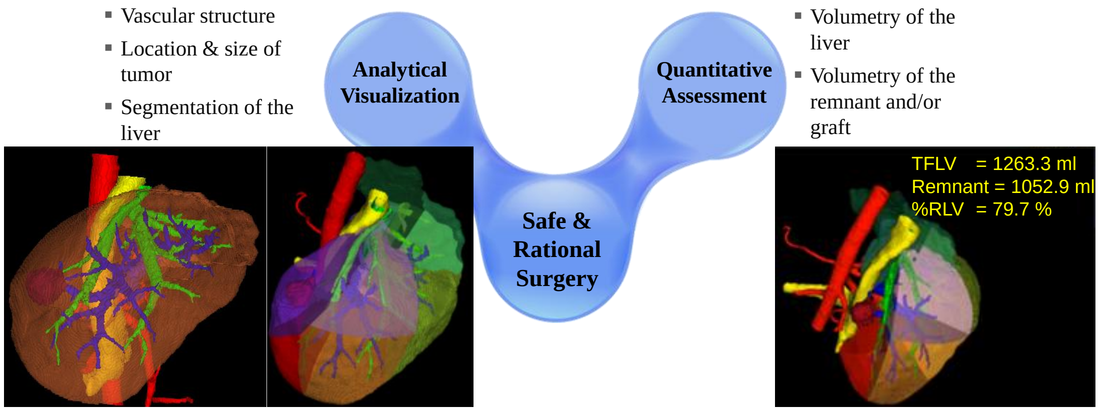



Figure 1. Requirements for safe and rational liver surgery

and a procedure status color coding scheme were designed, and novel algorithms were developed and implemented into Dr. Liver.

## SYSTEM DEVELOPMENT

### Use Scenario

A use scenario consisting of a five-step process was established for Dr. Liver through literature review, benchmarking of virtual surgery systems, and interviews with surgeons: (1) liver extraction, (2) vessel extraction, (3) tumor extraction, (4) liver segmentation, and (5) surgery planning. Dr. Liver was designed to provide good usability and accuracy for the surgeon and take an entire processing time of less than 30 min from liver extraction to surgery planning. For each step, detailed sub-steps were determined and then user interfaces were designed. Then, for each sub-step, algorithms were applied or developed to obtain results with an acceptable level of accuracy within a designated duration of time.

### User Interface

The customized user interface of Dr. Liver was designed to provide surgeons with good usability. Based on the use scenario established for Dr. Liver, a hierarchical user interface with two levels was designed as illustrated in Figure 2. The design of button size, color, font size, and color is kept consistent for the same hierarchical level. Next, for the high-level tasks, a procedure status indication coding scheme (circle: not conducted; bar in the circle: in progress; cross in the circle: completed) is employed; for the low-level tasks, a procedure status color coding scheme (grey: completed or not conducted; blue: in progress) is applied. Lastly, a procedural diagram is applied for low-level tasks and arrow lines for tasks which may need an iterative execution until a satisfactory result is obtained.

### Liver Extraction Module

The liver is extracted from abdominal CT images by following a seven-step procedure (Figure 3) using a novel semi-automatic liver extraction algorithm proposed in the present study: (1) denoising of CT images, (2) selection of multiple seed points from different CT slices, (3) detection of an initial

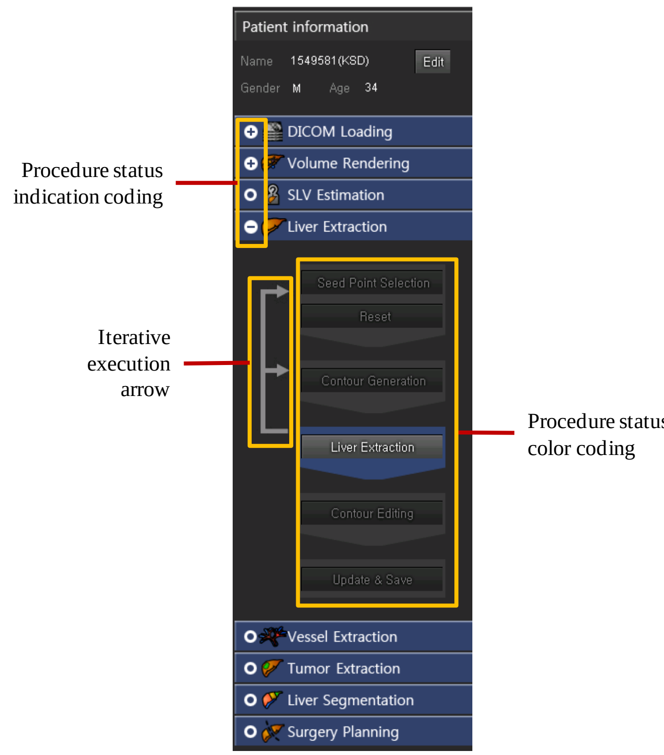



Figure 2. A hierarchical user interface of Dr. Liver

liver region, (4) propagation of the liver region, (5) post-processing, (6) 2D editing of the extracted liver, and (7) updating and saving of the editing results. In step 1, an anisotropic diffusion filter (Perona & Malik, 1990) is applied to remove noises from CT images. In step 2, multiple seed points are selected interactively by mouse clicking from different CT slices. In step 3, an 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 boundary by a threshold-based level-set method (Hsu et al., 2010; Lefohn et al., 2003). In step 5, holes within the liver boundary are filled and the liver surface is smoothed. In step 6, an interactive 2D editing function is provided which uses a scalable circle to remove a falsely extracted part and/or add a missing part. Lastly, in step 7 the editing results are updated and saved.

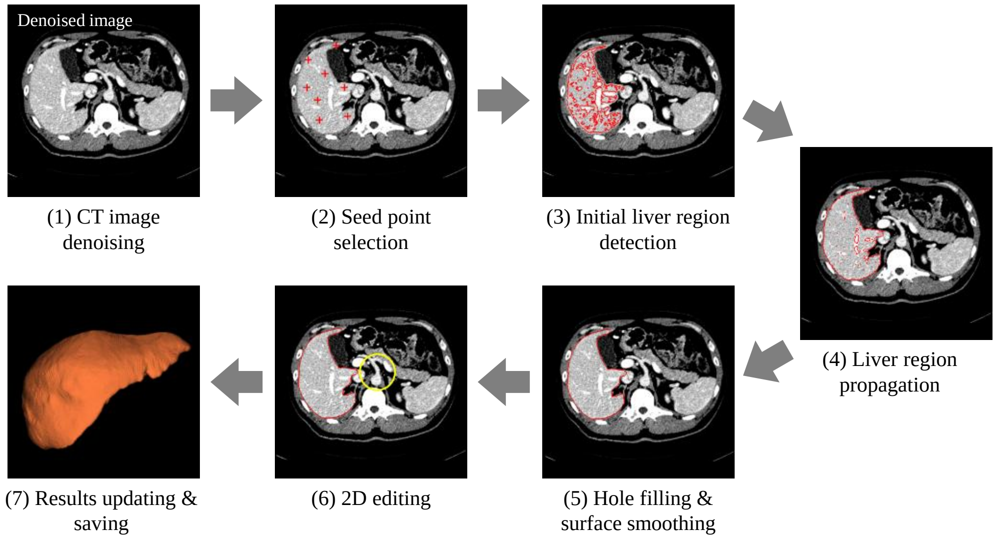



Figure 3. Liver extraction procedure

**Vessel Extraction Module**

After the liver is extracted, the vessels are extracted including hepatic artery (HA), portal vein (PV), hepatic vein (HV), and inferior vena cava (IVC). The former three vessels are extracted by a region growing method (Ibanez et al., 2005), while the IVC by following the same process applied to liver extraction. A seven-step procedure 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 K-means classification method is applied to identify a proper threshold interval for the vessel to be extracted. In step 4, the vessel is extracted by the region growing method. In step 5, holes within the vessel are filled. In step 6, either an interactive 2D editing function or 3D cutting function is performed to remove neighboring tissues or vessels from the vessel extraction result. In step 7, the editing results are updated and saved.

**Tumor Extraction Module**

A tumor(s) is extracted by a threshold-based level-set method (Hsu et al., 2010; Lefohn et al., 2003). A seven-step procedure is implemented: (1) denoising of CT images, (2) automatic identification of a threshold interval by K-means classification method, (3) interactive selection of multiple seed points, (4) tumor extraction, (5) hole filling and surface smoothing, (6) 2D editing of the extracted liver, and (7) updating and saving of the editing results.

**Liver Segmentation Module**

The liver segmentation method of Dr. Liver follows the Couinaud model (Couinaud, 1957) which divides the liver into 8 segments according to the structure of PV. A 7-step procedure has been developed to segment the liver. In step 1, segment 1 was formed by a trunked cone. In step 2, the liver is separated into the left and right lobes by a plane passing through middle hepatic vein, the entrance of right portal vein, and the gallbladder fossa (Figure 5). In step 3, the right lobe is separated into the anterior and posterior sectors along the right

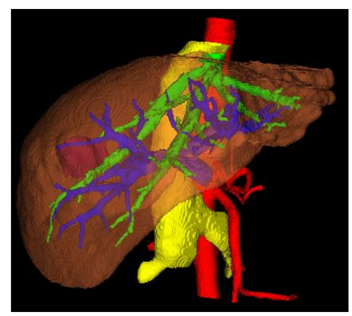


Figure 4. Result image with extracted liver, vessels (green: HV; blue: PV, red: HA; yellow: IVC), and tumor (dark red)

hepatic vein. In step 4, the left lobe is separated into medial and lateral sectors along the left hepatic vein. In step 5, the posterior sector is separated into segments 6 and 7 according to the right portal vein structure. In step 6, the anterior sector is separated into segments 5 and 8 according to the right portal vein structure. In step 7, the lateral sector is separated into segments 2 and 3 according to the left portal vein structure. The liver segmentation can be conducted fully or partially according to the needs of a user.

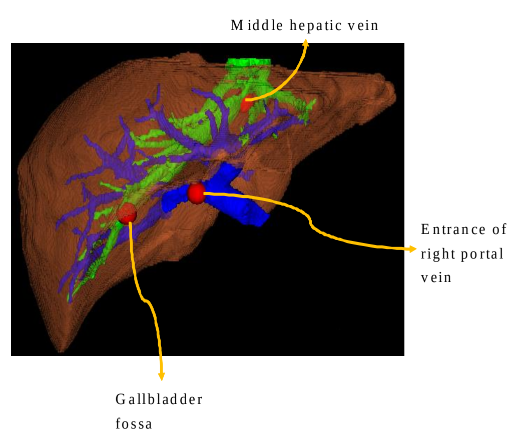



Figure 5. Points for segmenting the left and right lobes

### Surgery Planning Module

Two sub-modules, (1) resection by a plane and (2) resection by liver segments are provided for surgery planning (Figure 6). In the former module, a cutting plane is generated on the extracted liver, vessels, and tumor(s) (in dark red color) 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 volumetry information such as TFLV, remnant volume, and %RLV. In the later module, liver segments which contain a tumor(s) are resected by clicking corresponding checkboxes.

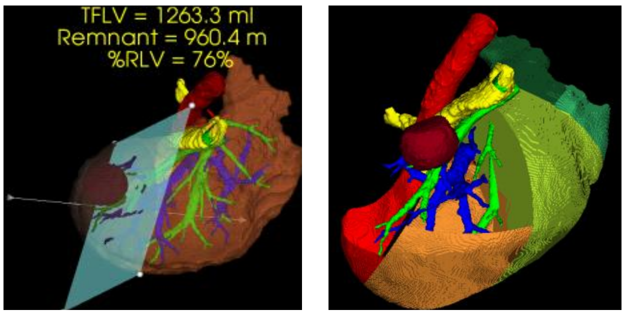



Figure 6. Surgery planning: resection by a plane (left), resection by liver segments (right)

## EVALUATION OF LIVER EXTRACTION MODULE

### Patient Dataset

15 patients of different age, gender, and liver volume were selected for evaluating the performance of the liver extraction module of Dr. Liver. Their CT data sets, provided by Chonbuk National University Medical School, South Korea, were 12-bit DICOM images with a resolution of $512 \times 512$ and a thickness of 1 mm.

### Liver Extraction Accuracy

For accuracy assessment, the semi-automatically extracted liver using our Dr. Liver system was compared with a manually traced liver (ground truth) by a radiologist. Three measures were utilized for comparison: *false positive error* (FPE), *false negative error* (FNE), and *similarity index* (SI). FPE is defined as the ratio of the total number of semi-automatically extracted voxels, which are not included in the manual extraction result to the total number of manually extracted voxels (Eq. 1). FNE is the ratio of the total number of manually extracted voxels, which are not included in the automatic extraction result to the total number of automatically extracted voxels (Eq. 2; Klein et al., 2009). SI is the overlap ratio of the semi-automatically extracted voxels and the manually extracted voxels (Eq. 3; Zijdenbos et al., 1994).

$$FPE = \frac{|V_{manual} \setminus V_{semi\text{-}automatic}|}{|V_{manual}|} \times 100\% \qquad (1)$$

$$FNE = \frac{|V_{semi\text{-}automatic} \setminus V_{manual}|}{|V_{semi\text{-}automatic}|} \times 100\% \qquad (2)$$

$$SI = 2\frac{|V_{Semi\text{-}automatic} \cap V_{manual}|}{|V_{Semi\text{-}automatic}| + |V_{manual}|} \times 100\% \qquad (3)$$

where $V_{manual}$ = a set of the manually extracted voxels
$V_{semi\text{-}automatic}$ = a set of the semi-automatically extracted voxels

Through comparison, we found that the average of SI was $96.5 \pm 1.3\%$. The average of FPE was $2.2 \pm 1.1\%$. The average of FNE was $4.6 \pm 2.5\%$. The visual inspection of liver extraction accuracy (Table 1) shows that the semi-automatically extracted liver is close to the ground truth.

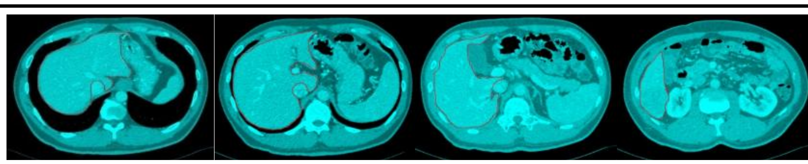
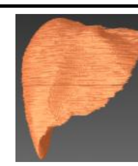
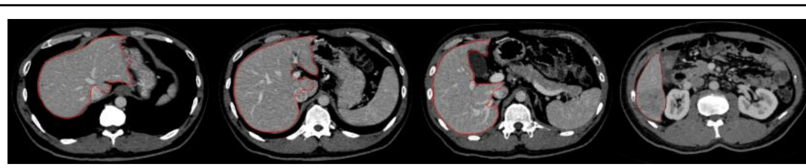
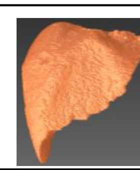
### Time Efficiency

The average processing time per data set for liver extraction using our Dr. Liver system was $4.8 \pm 0.8$ min. The average number of slices per data set was $222 \pm 38$. Therefore, the average processing time per slice was 1.3 sec.

## DISCUSSION

The present study developed a user-centered virtual liver surgery system called Dr. Liver to support liver surgery. A use scenario, user interfaces, and image processing algorithms customized to liver surgery planning were developed and implemented in the study to provide good usability and accurate information within an acceptable time for surgeons.

Table 1. Visual inspection of liver extraction accuracy

| Method | 2D inspection | 3D inspection |
|---|---|---|
| Manual (Ground truth) |  |  |
| Dr. Liver |  |  |

The Dr. Liver use scenario is unique compared with existing virtual surgery systems such as Osrix, LiverAnalyzer, and Synapse Vincent. The major tasks of Dr. Liver include extraction of the liver, vessels, and tumors, identification of liver segments, and planning of liver surgery, which are similar to some of the existing systems. However, in contrast to the existing systems, the high level and low-level tasks in Dr. Liver are performed in a hierarchical and sequential manner with a customized user interface. Furthermore, unlike LiverAnalyer, Dr. Liver allows a surgeon to inspect and edit the extracted liver analysis results overlaid original CT images once the semi-automatic liver extraction is finished.

We evaluated the performance of the liver extraction module of our Dr. Liver system. Compared with other system, like OsiriX, our Dr. Liver system has better accuracy and time efficiency for liver extraction. The SI of OsiriX 2D liver extraction method was 94.2 ± 1.8%, which is smaller than Dr. Liver system (96.5 ± 1.3%). The average processing time of OsiriX 2D liver extraction method was 9.6 ± 2.3 min, which is longer than Dr. Liver system (4.8 ± 0.8 min).

Lastly, the clinical usability testing of Dr. Liver has been undergoing and updates have been made to Dr. Liver. Surgeons with a specialty of liver surgery from various hospitals including university hospitals in South Korea have tried Dr. Liver and provided suggestions for better usability and clinical applicability. More sophisticated features such as curved liver resection plane and touch screen interface are being added to Dr. Liver.

## ACKNOWLEDGMENTS

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