Development and Usability Testing of a User-Centered 3D Virtual Liver Surgery Planning System

Xiaopeng Yang[1], Hee Chul Yu[2], Younggeun Choi[1], Wonsup Lee[1], Jaedo Yang[2], Ji Hyun Kim[2], Baik Hwan Cho[2], and Heecheon You[1]

[1]Department of Industrial and Management Engineering, POSTECH
[2]Department of Surgery, Chonbuk National University Medical School

ABSTRACT

The present study developed a user-centered 3D virtual liver surgery planning system called Dr. Liver, which has clinical applicability and effectiveness to support liver surgery. Use scenarios of Dr. Liver were developed through literature review, benchmarking, and interviews with surgeons. User interfaces of Dr. Liver were designed with various user-friendly features such as hierarchical dropdown menus, hotkey menus provided on the screen, and 3D view indication box and resetting buttons. Novel image processing algorithms were developed and implemented into Dr. Liver for accurate and efficient liver surgery planning. Potential usability problems were identified by a preliminary usability testing at the early development stage and improvements were made for the identified usability problems. A usability testing showed that the improved Dr. Liver achieved higher time efficiency (= 21.8 ± 4.4 min) and overall user satisfaction (= 6.2 ± 0.7) than the previous version (time = 36.6 ± 1.7 min; overall satisfaction = 5.6 ± 0.5). The development and evaluation process of Dr. Liver in this study would help practitioners develop a user-friendly virtual surgery planning system.

Keywords: virtual liver surgery planning system, user-centered system design, usability testing

1. Introduction

A 3D virtual liver surgery (VLS) planning system can provide surgeons with an effective tool for safe and rational surgery. Through 3D reconstruction of the liver, vessels, and tumors from CT images and simulation of virtual liver resection, a 3D VLS planning system helps surgeons find an optimal surgical resection strategy by visualizing and volumetric measurement of the liver, vessels, tumors, remnant, and/or graft (Debarba et al., 2010; Reitinger et al., 2006; Sorantin et al., 2008).

Several 3D VLS planning systems such as LiverAnalyzer™ (MeVis Medical Solutions AG, Germany) and Synapse Vincent™ (FUJIFILM Co., Japan) have been developed, but their user interfaces and image processing algorithms need to be improved for better usability, accuracy, and time efficiency. MeVis provides a distant service by analyzing CT images using LiverAnalyzer which is not for sale and delivers the analysis results within one or two days depending on the selected payment option. However, only 3D analysis results are provided by MeVis without presenting CT images so that surgeons have difficulty in cross-check of the accuracy of analysis results. Synapse Vincent is for sale, but some user interfaces and image processing algorithms such as those for 3D reconstruction of the liver and vessels from CT images are cumbersome to use. For example, the region growing method used by Synapse Vincent for reconstruction of the liver and vessels often extracts adjacent tissues and/or organs along with the liver, which leads to intensive manual editing (> 30 min) to remove parts inaccurately extracted.

The present study developed a user-centered 3D virtual liver surgery planning system commercialized as Dr. Liver™ which provides intuitive and user-friendly interfaces and advanced image processing algorithms to assist surgeons in preoperative planning of liver surgeries within a short time (5 ~ 10 min). The usability of Dr. Liver was systematically evaluated using various performance and preference measures in the study.

2. System Development

2.1 Use Scenario Development

A use scenario consisting of a four-step procedure: (1) liver 3D reconstruction, (2) vessel 3D reconstruction, (3) tumor 3D reconstruction, and (4) surgery planning was developed for Dr. Liver through literature review, benchmarking of existing systems, and interviews with surgeons. Dr. Liver was designed to provide better usability and accuracy and take an entire processing time of 5 to 10 min from liver 3D reconstruction to surgery planning. For each step, detailed sub-steps were determined and 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.

2.2 User Interface

Customized, intuitive, and user-friendly user interfaces were designed for Dr. Liver to provide surgeons with good usability. Based on the use scenario developed for Dr. Liver, a hierarchical user interface with two task levels was designed as illustrated in Figure 1. The design of button size, color, font size, and color is kept consistent for the same hierarchical level. For 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 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. Hotkey menus were provided on the screen of Dr. Liver to reduce the workload of users. 3D view indication box and resetting buttons were provided so that users can easily find their ways in the 3D view.

2.3 Liver 3D Reconstruction Module

Figure 1. Hierarchical user interfaces of Dr. Liver

The liver is reconstructed from abdominal CT images by our proposed hybrid semi-automatic method (Yang et al., 2014) consisting of five steps: (1) denoising of CT images by an anisotropic diffusion filter (Perona & Malik, 1990), (2) selection of multiple seed points (3) formation of initial liver regions by a customized fast-marching level-set method (Sethian, 1996), (4) liver reconstruction based on the initial liver regions by a threshold-based level-set method (Hsu et al., 2010; Lefohn et al., 2003), and (5) surface smoothing of the reconstructed liver. An interactive editing function is provided for editing the reconstructed liver if necessary. The use scenario and user interface of liver reconstruction module were customized and simplified as shown in Figure 2.

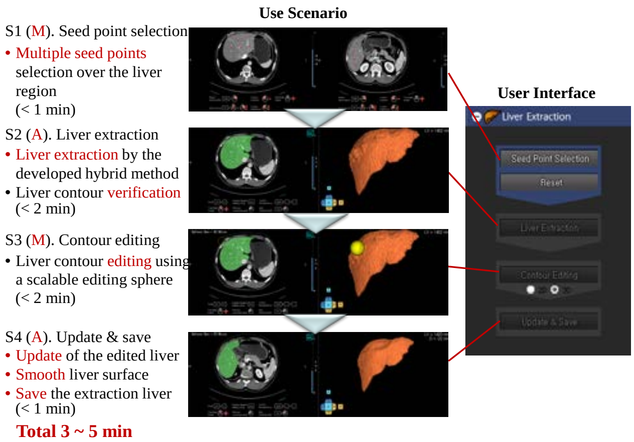

Figure 2. Use scenario and user interface for liver extraction

2.4 Vessel 3D Reconstruction Module

Liver vessels including hepatic artery (HA), portal vein (PV), and hepatic vein (HV) are reconstructed from CT images by an efficient semi-automatic vessel extraction method consisting of five steps: (1) denoising and masking of CT images with the reconstructed liver regions, (2) selection of multiple seed points, (3) automatic identification of multiple threshold intervals, (4) vessel extraction based on multiple threshold intervals by a region growing method, implemented in ITK (Ibanez et al., 2005), and (5) selection of an appropriate extraction result. Same as liver reconstruction, an interactive editing function is provided for editing the reconstructed vessel if necessary.

2.5 Tumor 3D Reconstruction Module

The tumor is reconstructed from CT images by the same method as liver reconstruction (Figure 3).

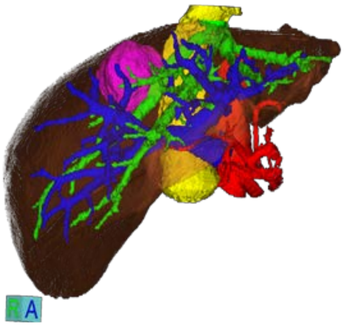

Figure 3. Reconstructed liver, vessels (green: hepatic vein, blue: portal vein, red: hepatic artery), and tumor (purple)

2.6 Surgery Planning Module

The liver is virtually resected by a resection sphere according to the vessel structures and spatial relationship between the tumor and vessels. The 2D and 3D views are synchronized in real time so that surgeons can check the resection results immediately. The volume information of the liver, vessels, tumors, remnant, and/or graft is provided on the screen to support surgery planning. The left figure in Figure 4 showed a surgery planning result of graft resection for living donor liver transplantation, the right figure in Figure 4 a surgery planning result of tumor resection.

3. Usability Testing

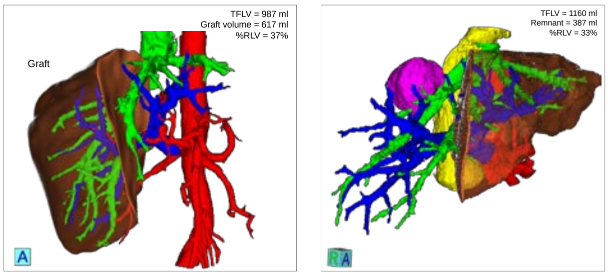

Figure 4. Surgery planning results (left: graft resection for living donor liver transplantation, right: tumor resection)

3.1 Participants

Eight male medical doctors (aged from 30s to 60s) from three different medical centers were participated in the usability testing of Dr. Liver. All the participants were experienced in liver anatomy and liver surgery.

3.2 Test Procedures

The usability test was performed in a secure room for each individual participant, administered by a test monitor. The usability test consisted of three sessions, pre-test, test, and post-test sessions, which lasted about two hours in total. At the pre-test session, paper manual and video demonstrations of Dr. Liver were provided to teach a participant how to use the system. Then usability testing was introduced by reading an orientation script. Exhaustive practice was allowed for a participant to be familiar with the system. After that, an informed consent was obtained.

In the test session, four modules of usability evaluation were conducted in sequence: (1) liver 3D reconstruction, (2) vessel 3D reconstruction, (3) tumor 3D reconstruction, and (4) liver surgery planning. The order of the four modules followed the use scenario of Dr. Liver. During each test module, the performance of a participant was evaluated using various measures including accuracy measures, task completion times, number of mouse clicks, and number of keystrokes. After each module, a questionnaire was provided to survey a participant's subjective usability assessment, likes, dislikes, and open suggestions. A 5-min break was offered after testing of each module.

Lastly, in the post-test session, debriefing was performed to learn more details. Questions raised from observations during the test session such as tasks not completed and critical comments were addressed and discussed.

Table 1. Usability test measures for Dr. Liver*

Modules		Performance Measures						Preference Measures						
		Completion time	Number of mouse clicks	Number of keystrokes	Similarity index	False positive error	False negative error	Usefulness	Ease of use	Learnability	Informa-tiveness	Clarity	Tolerance	Satisfaction
Liver reconstruction		○	○	○	○	○	○	○	○	○	○	○	○	○
Vessel reconstruction	Portal vein	○	○	○				○	○	○	○	○	○	○
	Hepatic artery	○	○	○				○	○	○	○	○	○	○
	Hepatic vein	○	○	○				○	○	○	○	○	○	○
Tumor reconstruction		○	○	○	○	○	○	○	○	○	○	○	○	○
Liver surgery planning		○	○	○				○	○	○	○	○	○	○

* ○: Applied measure

Table 2. Preference assessment questions (selected)

No	Questions	Very Poor	Poor	Slightly Poor	Fair	Slightly Good	Good	Very Good
1	How useful is it for extracting the liver from DICOM images?	①	②	③	④	⑤	⑥	⑦
2	How easy is it to use?	①	②	③	④	⑤	⑥	⑦
3	How easy is it to learn the steps of liver extraction?	①	②	③	④	⑤	⑥	⑦
4	How adequate is the information provided?	①	②	③	④	⑤	⑥	⑦
5	How clear are the step names?	①	②	③	④	⑤	⑥	⑦
6	How adequate is the tolerance to allow you make mistakes?	①	②	③	④	⑤	⑥	⑦
No	Questions	Very Dissatisfied	Dissatisfied	Slightly Dissatisfied	Neutral	Slightly Satisfied	Satisfied	Very Satisfied
7	What is your overall satisfaction with the liver extraction module?	①	②	③	④	⑤	⑥	⑦

3.3 Usability Assessment Measures and Questionnaires

Six performance (task completion time, similarity index, false positive error, false negative error, number of mouse clicks, and number of keystrokes) and seven preference (usefulness, ease of use, learnability, informativeness, clarity, tolerance, and overall satisfaction) measures were incorporated into the usability test. Different sets of performance and preference measures were applied to each test module (see Table 1) by considering the task of each test module. As an example, in Module 1: liver reconstruction, the time to finish liver reconstruction task, number of mouse clicks, and number of keystrokes were automatically measured by Dr. Liver. Similarity index, false positive error and false negative error of the reconstructed liver were measured by comparing to the golden standard (manually reconstructed liver by a radiologist). Seven criteria (usefulness, ease of use, learnability, informativeness, clarity, tolerance, and overall satisfaction) were used to evaluate the participants' preference with Dr. Liver. Based on the evaluation measure matrix table, usability assessment questionnaires were designed for each test module. Table 2 shows sample questions for subjective assessment of Module 1 (liver reconstruction).

3.3 Test Results

Module 1: Liver Reconstruction

The average (S.D.) time (unit: min) to extract the liver was 3.0 (0.5). The average (S.D.) number of mouse clicks was 78 (9). The average (S.D.) of keystrokes was 17 (3).

The average (S.D.) similarity index (unit: %) was 96.8 (0.4). The average (S.D.) false positive error (unit: %) was 2.4 (0.3). The average (S.D.) false negative error (unit: %) was 2.8 (0.3).

Consistently high evaluation scores were given for the usability of the liver extraction module (see Table 3). The average (S.D.) of the assessments of the liver extraction module was 6.3 (0.6).

Module 2: Vessel Reconstruction

The average (S.D.) time (unit: min) to extract portal vein was 1.4 (0.2). The average (S.D.) number of mouse clicks was 21 (5). The average (S.D.) of keystrokes was 10 (3). High evaluation scores were given for the usability of the portal vein extraction module (see Table 3). The average (S.D.) of the assessments of the portal vein extraction module was 6.2 (0.8).

The average (S.D.) time (unit: min) to extract hepatic artery was 2.3 (0.3). The average (S.D.) number of mouse clicks was

Table 3. Average (S.D.s) of preference assessments*

Modules		Preference Measures						
		Usefulness	Ease of use	Learnability	Informa-tiveness	Clarity	Tolerance	Satisfaction
Liver reconstruction		6.4 (0.5)	6.4 (0.5)	6.4 (0.5)	6.4 (0.5)	6.6 (0.5)	5.6 (0.8)	6.3 (0.5)
Vessel reconstruction	Portal vein	6.4 (0.5)	6.1 (0.7)	6.3 (0.8)	6.1 (0.7)	6.6 (0.5)	5.6 (1.3)	6.0 (0.6)
	Hepatic artery	6.0 (0.9)	5.7 (1.0)	6.0 (1.1)	5.8 (1.0)	6.3 (0.5)	5.5 (0.5)	6.0 (0.6)
	Hepatic vein	6.4 (0.5)	6.3 (0.5)	6.4 (0.8)	6.1 (0.7)	6.4 (0.5)	5.7 (1.0)	6.1 (0.4)
Tumor reconstruction		6.0 (0.0)	6.3 (0.5)	6.0 (0.8)	6.0 (0.8)	6.3 (0.5)	6.5 (0.6)	6.3 (0.5)
Liver surgery planning		6.7 (0.5)	6.3 (1.0)	6.3 (0.8)	6.4 (0.5)	6.7 (0.5)	6.0 (0.8)	6.1 (0.7)

* Used a 7-point Likert scale, '1' for very poor or very dissatisfied and '7' for very good or very satisfied

46 (7). The average (S.D.) of keystrokes was 17 (4). The average (S.D.) of the assessments of the hepatic artery extraction module was 6.1 (0.8).

The average (S.D.) time (unit: min) to extract hepatic vein was 1.4 (0.2). The average (S.D.) number of mouse clicks was 19 (7). The average (S.D.) of keystrokes was 5 (2). The average (S.D.) of the assessments of the hepatic vein extraction module was 6.2 (0.7).

Module 3: Tumor Reconstruction

The average (S.D.) time (unit: min) to extract the tumor was 2.9 (0.1). The average (S.D.) number of mouse clicks was 22 (4). The average (S.D.) of keystrokes was 5 (1). The average (S.D.) similarity index (unit: %) was 97.3 (0.8). The average (S.D.) false positive error (unit: %) was 1.9 (0.2). The average (S.D.) false positive error (unit: %) was 2.3 (0.2). The average (S.D.) of the assessments of the tumor extraction module was 6.2 (0.5).

Module 4: Liver Surgery Planning

The average (S.D.) time (unit: min) to plan the liver surgery using a resection sphere was 1.6 (0.2). The average (S.D.) number of mouse clicks was 12 (3). The average (S.D.) of keystrokes was 5 (2). The average (S.D.) of the assessments of the liver surgery planning using resection sphere module was 6.4 (0.7).

4. Recommendations

Recommendations were made for better usability of Dr. Liver as follows based on the usability testing results:

1. Disable synchronization during contour editing due to lag.
2. Provide direct 3D editing function.
3. Show progress bar except time information during processing.
4. Use softer colors for visualization of blood vessels.

5. Discussion

The present study developed a user-centered 3D VLS planning system Dr. Liver to support safe and rational liver surgery. A use scenario, user interfaces, and image processing algorithms were developed and implemented to Dr. Liver to provide good usability and accurate information within an acceptable time to surgeons for preoperative liver surgery planning. 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. Hotkey menus were provided on the screen of Dr.

Liver to reduce the workload of users. 3D view indication box and resetting buttons were provided so that users can easily find their ways in the 3D view. Furthermore, unlike LiverAnalyer, Dr. Liver allows surgeons to inspect and edit the analysis results through the overlaid CT images.

The usability of Dr. Liver was evaluated using a comprehensive set of performance (completion time, similarity index, false positive error, false negative error, number of mouse clicks, and number of keystrokes) and preference (usefulness, ease of use, learnability, informativeness, clarity, tolerance, and overall satisfaction) measures. The usability testing is an analytical and comprehensive way to identify usability problems of Dr. Liver and develop recommendations for improving usability of Dr. Liver in a systematic manner.

This study demonstrated the application of usability testing as an effective tool throughout the development process of a liver surgery planning system Dr. Liver. By applying concepts and techniques of usability testing, the liver surgery planning system Dr. Liver with various user-friendly features was developed, problems of the system were screened, and recommendations on the system for usability improvement were produced in an effective, systematic manner. The high usability of Dr. Liver would contribute to a greater overall consumer satisfaction with Dr. Liver.

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Author listings

Xiaopeng Yang: yxp233@postech.ac.kr

Highest degree: PhD, Industrial Engineering, Pohang University of Science and Technology

Position title: Post-doc, Department of Industrial & Management Engineering, POSTECH
Areas of interest: 3D hand kinematic modeling, Ergonomic product design, Medical image processing

Hee Chul Yu: hcyu@jbnu.ac.kr
Highest degree: MD. PhD, Surgery, Chonbuk National University
Position title: Professor, Department of surgery, Chonbuk National University Medical School
Areas of interest: Hepatobiliary-pancreas Surgery, Organ transplantation-Liver and Kidney, Vascular surgery

Younggeun Choi: sidek@postech.ac.kr
Highest degree: BS, Industrial & Media Design, Handong Global University
Position title: PhD, student, Department of Industrial & Management Engineering, POSTECH
Areas of interest: Digital human modeling & simulation, User-centered product design & development, Anthropometric and biomechanical methods for product development, Universal design, User experience design

Wonsup Lee: mcury@postech.ac.kr
Highest degree: PhD, Industrial Engineering, Pohang University of Science and Technology
Position title: Post-doc, Department of Industrial & Management Engineering, POSTECH
Areas of interest: Ergonomic product design, Product shape design based on 3D scanning, 3D human modeling, Engineering design

Jaedo Yang: hirojawa@jbnu.ac.kr
Highest degree: MD. PhD, Medicine, Chonbuk National University
Position title: Clinical professor in surgery, Department of surgery, Chonbuk National University Medical School
Areas of interest: Ischemic/reperfusion injury in the liver, Liver regeneration, liver transplantation

Ji Hyun Kim: 407kk@jbnu.ac.kr
Highest degree: PhD, Anatomy, Chonbuk National University
Position title: Post-doc, Department of surgery, Chonbuk National University Medical School
Areas of interest: Anatomy, Embryology, Histology

Baik Hwan Cho: chobh@jbnu.ac.kr
Highest degree: MD. PhD, Surgery, Chonnam National University
Position title: Professor, Department of surgery, Chonbuk National University Medical School
Areas of interest: Hepatopancreatobiliary disease, liver transplantation, nutritional support

Heecheon You: hcyou@postech.ac.kr
Highest degree: PhD, Industrial Engineering, Pennsylvania State University
Position title: Associate Professor, Department of Industrial & Management Engineering, POSTECH
Areas of interest: Ergonomic product design & development, User interface design & evaluation, Digital human modeling & simulation, Human performance & workload assessment, Work-related musculoskeletal disorders (WMSDs) prevention, Usability testing