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Leveraging augmented reality for dynamic guidance in 3-dimensional laparoscopic and robotic liver surgery: a prospective case series study

Moon Young Oh[1,*], Kyung Chul Yoon[1,*], Hyoun-Joong Kong[2,*], Taesoo Jang[2], Yeonjin Choi[2], Junki Kim[2], Jae-Yoon Kim[3], YoungRok Choi[3], Young Jun Chai[1,4]

[1]Department of Surgery, Seoul Metropolitan Government-Seoul National University Boramae Medical Center, Seoul National University College of Medicine, Seoul, Korea
[2]Department of Transdisciplinary Medicine, Institute of Convergence Medicine with Innovative Technology, Seoul National University Hospital, Seoul, Korea
[3]Department of Surgery, Seoul National University Hospital, Seoul National University College of Medicine, Seoul, Korea
[4]Transdisciplinary Department of Medicine and Advanced Technology, Seoul National University Hospital, Seoul, Korea

Purpose: Accurate anatomical knowledge and precise visualization are critical during liver surgery. We developed augmented reality (AR) software that overlays digital 3-dimensional (3D) models onto laparoscopic or robotic views, providing real-time visual aids for surgical navigation during 3D laparoscopic and robotic liver surgeries. This study assesses the accuracy of manual registration and the subjective perception of this AR software by the operator.
Methods: Ten consecutive patients undergoing 3D laparoscopic or robotic liver surgery from December 2023 to February 2024 were selected for application of the AR software during surgery. Manual registration accuracy was quantified post-registration using the Dice similarity coefficient (DSC) to compare the stereoscopic and virtual liver images. A 6-question operator survey, using a 5-point Likert scale, was administered after each surgery to evaluate the software's helpfulness in clinical settings.
Results: Seven males and 3 females (mean age, 62.4 ± 6.4 years) underwent liver surgery (3D laparoscopic, 5; robotic, 5). Surgical procedures included 4 right hemihepatectomies, 1 extended left hemihepatectomy, 1 left lateral sectionectomy, and 4 segmentectomies. The mean tumor size was 4.4 ± 2.2 cm (range, 1.0–7.5 cm). The mean DSC was 0.912 ± 0.052 (range, 0.879–0.954). The operator rated registration alignment favorably before (mean score, 3.9 ± 1.1) and after mobilization (mean score, 4.1 ± 1.2). The software was reported as very helpful overall (mean score, 4.2 ± 0.8), and in locating blood vessels (4.2 ± 0.6) and tumors (4.3 ± 0.7).
Conclusion: Clinical application of the AR software during 3D laparoscopic and robotic liver surgery is feasible, with favorable registration accuracy and high operator perception of helpfulness.
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Key Words: Augmented reality, Laparoscopy, Liver surgery, Robotic surgical procedures, Software

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Corresponding Author: Young Jun Chai
Department of Surgery, Seoul Metropolitan Government-Seoul National University Boramae Medical Center, Seoul National University College of Medicine, 20 Boramae-ro 5-gil, Dongjak-gu, Seoul 07061, Korea
Tel: +82-2-870-3294, **Fax:** +82-2-870-3863, **E-mail:** kevinjoon@naver.com, **ORCID:** https://orcid.org/0000-0001-8830-3433
Co-Corresponding Author: YoungRok Choi
Department of Surgery, Seoul National University Hospital, Seoul National University College of Medicine, 101 Daehak-ro, Jongno-gu, Seoul 03080, Korea
Tel: +82-2-2072-0069, **Fax:** +82-2-766-3975, **E-mail:** choiyoungrok@gmail.com, **ORCID:** https://orcid.org/0000-0003-2408-7086

*Moon Young Oh, Kyung Chul Yoon, and Hyoun-Joong Kong contributed equally to this work as co-first authors.

INTRODUCTION

The liver, a complex structure with highly variable intraparenchymal architecture, is susceptible to both primary and metastatic cancers [1], which are often treated by liver resection, frequently via a laparoscopic approach and some via a robotic approach. Liver surgery requires an in-depth understanding of the patient's unique vascular and tumoral anatomy, and precise visualization during surgery to achieve successful outcomes [2]. Many liver lesions are located within the parenchyma, making them invisible in the laparoscopic or robotic view. Conventional imaging methods like ultrasound, CT, and MRI generally only provide limited 2-dimensional (2D) information [3]. Furthermore, laparoscopic and robotic surgeries afford no tactile feedback [4,5] which presents additional significant challenges to the surgeon. Augmented reality (AR) technology, which overlays digital 3-dimensional (3D) transparent models of organs and lesions [6] onto laparoscopic or robotic views, offers a promising solution [7] for enhancing surgical planning and providing intraoperative guidance [8]. This technology offers real-time visual guidance for surgical navigation, enabling more precise tissue resection and overcoming the limitations of traditional 2D visualization techniques [9]. AR software has been reported to contribute to safer surgical procedures while maintaining oncological outcomes and ensuring patient safety [6].

The application of AR in laparoscopic or robotic liver surgery is an expanding field, and several software systems have been developed and refined, reporting favorable outcomes [10,11]. One study detailed their clinical experiences in the field and indicated good feasibility with minimal disruption to intraoperative workflow [11]. However, the authors cautioned that improving registration accuracy is imperative and that non-rigid registration algorithms are required. There is a lack of studies that focus on reporting registration accuracy or operator satisfaction with registration accuracy when applying AR in laparoscopic or robotic liver surgery.

We previously developed a software system that superimposes an AR model of the thyroid and its surrounding anatomical structures (constructed from preoperative images) onto the laparoscopic or robotic view during robotic thyroidectomies [12,13]. We demonstrated its favorable manual registration accuracy. Based on our previous successful experiences, we developed an AR software system using virtual 3D liver models reconstructed from preoperative imaging data to assist surgeons in visualizing subsurface liver anatomy during surgery. In this study, we applied our AR software when performing live 3D laparoscopic or robotic liver surgeries and evaluated its registration accuracy. We also collected feedback from operators about their experiences using the technology during the surgical procedures.

METHODS

Three-dimensional liver segmentation and virtual liver model reconstruction

We segmented the liver using "TotalSegmentator," an artificial intelligence-based extension of the open-source 3D segmentation software 3D Slicer (version 5.2.0). Using this software, we processed Digital Imaging and Communications in Medicine (DICOM) files from the portal phase images of triple-phase dynamic liver CT scans, dividing the liver into 3 components: the liver outline, blood vessels, and tumors. We fine-tuned the threshold values to effectively segment blood vessels with diameters of at least 3 mm. To ensure clinically relevant segmentation, we fine-tuned the threshold values to effectively identify and segment blood vessels with diameters of at least 3 mm. This threshold was selected based on clinical practice, where vessels with diameters of 3 mm or larger are generally considered significant in the context of liver surgery [14]. These vessels are large enough to potentially impact surgical planning and execution, particularly in relation to the risk of bleeding and the need for precise resection margins. This threshold was optimized to reduce processing time and minimize unnecessary artifacts and distortions during the 3D reconstruction process [15]. Tumor segmentation was achieved by manually selecting regions of interest.

We used 3D model editing software (Maya 2022, Autodesk Inc.) to reduce noise artifacts and optimize the segmented liver images. We then reconstructed the liver outline into a virtual 3D model composed of a mesh with 3,000 polygon faces, allowing for clear visualization of blood vessels and tumors. The virtual liver model had a joint system that enabled manipulation from all angles, and full rotation with separate articulation for the left, middle, and right thirds of the virtual organ.

Stereoscopic camera calibration

The stereoscopic laparoscope's cameras were calibrated using a 2.5-cm black-and-white checkerboard pattern. Matlab R2023a (MathWorks) was employed to determine key camera parameters, including focal length, principal point, skew, and distortion, ensuring optimal functionality of the AR system during surgery.

Development of the registration system

Using an AR graphical user interface, we developed a manual registration system to overlay the virtual liver onto the stereoscopic laparoscopic or robotic image. The system had 2 primary modules: (1) an input module for receiving, storing, and duplicating live streaming images from the stereoscopic laparoscope or robotic camera, and (2) a registration module for building the virtual liver model and aligning it with the laparoscopic or robotic images. The overlay module used object visualization, coordinate system alignment, 3D object shading, and opacity adjustment to achieve precise alignment. The system was built using Unreal Engine 5.0.3 (Epic Games), with a stereo registration input system that enabled the overlay of the images onto the Olympus 3D laparoscope (VISERA ELITE II, Olympus Europe SE & Co KG), displayed on a 47-inch passive polarized 3D monitor (LG 47LA6950, LG Electronics). We incorporated Unreal Engine's Spline IK Animation Blueprint Node (Unreal Engine 5.0.3) to enhance the flexibility and accuracy of the model's manipulation, particularly in simulating the liver's natural curvature and movement.

Rigging system and controller

We designed a controller for manual registration using a custom keypad (Razer Tartarus Pros R707-0311, Razer Inc.) (Fig. 1). The controller allowed one-handed manipulation of the virtual liver, with functions for zooming, translation in different directions, and rotation in roll, pitch, and yaw. It also allowed independent manipulation of the left, middle, and right thirds of the liver. To facilitate use, each button on the controller was labeled with a corresponding icon or symbol. The key mapping of the controller was configured using Razer Synapse software (Razer Inc.), with each button labeled with corresponding icons or symbols to facilitate ease of use.

Patient selection and 3-dimensional laparoscopic or robotic liver surgery

Ten patients scheduled for 3D laparoscopic or robotic liver surgery for liver mass excision from December 2023 to February 2024 were selected for application of the AR software during surgery. All patients underwent preoperative triple-phase dynamic liver CT scans. In all 10 cases, surgery was performed by a single experienced surgeon (YC) with 20 years of liver surgery experience. Approval for the study was obtained from the Institutional Review Board (IRB) of Seoul National University Hospital (No. 2312-004-1487) and conducted in accordance with the Declaration of Helsinki. Individual written informed consent was obtained from the patients. Patients were informed of the risks associated with the application of new technology in surgery. However, both our research team and the IRB determined that the use of the AR system posed a minimal risk, as it serves as an additional reference tool, providing supplementary information without altering the established surgical process, such as checking CT or MRI scans to predict the location of tumors or anatomical structures. Additionally, manual registration was conducted on a separate monitor, ensuring that the primary laparoscopic or robotic monitor remained unchanged and did not interfere with the surgical procedure.

Fig. 1. Controller. The controller designed for allowing one-handed manipulation of the virtual liver using a custom wireless keypad, with functions for zooming, translation in different directions, and rotation in roll, pitch, and yaw.

Application of the augmented reality software onto real-time laparoscopic or robotic image

A serial digital interface (SDI) image signal 1:2 splitter (NEXT-SDI0102SP, EZ-Net Ubiquitous) was connected to the recording storage of the Olympus 3D laparoscope (VISERA ELITE II) to duplicate the input video while maintaining the image signal between the laparoscope and the monitor. The video was streamed to the laptop computer via an SDI-to-HDMI converter (NEXT 122SDHC, EZ-Net Ubiquitous). During surgery, the virtual liver model was superimposed on the Olympus 3D laparoscopic view or robotic view in real-time using the visualization software, Unreal Engine 5.0.3. The system was implemented on a laptop equipped with an 11th Gen Intel Core i7-11800H CPU @ 2.30 GHz, 34 GB RAM, and an NVIDIA GeForce RTX 3080 Laptop GPU, which efficiently handled real-time 3D rendering and AR overlay processing. The image was then displayed on a 3D monitor (LG 47LA6950).

The installation and setup of the AR system required approximately 40 minutes, broken down as follows: 25 minutes for 3D reconstruction, 5 minutes for skeleton rigging, 5 minutes for applying the rigged model to the system, and 5 minutes for intraoperative setup. Notably, the intraoperative setup was performed concurrently with patient anesthesia and surgical preparation, ensuring minimal impact on the overall surgical duration. The total setup time varied depending on the complexity of the DICOM cases and the specific surgical environment. Once the intraoperative setup is initially configured, no additional setup time is required for subsequent uses.

Manual registration during live surgery

Prior to application of the AR software during live surgery, the surgeon received brief instructions about how to operate the controller and perform manual registration. During surgical setup, the controller was encased in aseptic vinyl, allowing the operator to manually register the virtual liver model within the sterile surgical field without the need for an assistant (Fig. 2). During surgery, the operator was seated in front of a monitor while wearing 3D glasses and used the controller with their dominant hand. The operator had the option to use either standard 3D glasses (LG CINEMA 3D glasses AG-F310, LG Electronics) or clip-on 3D glasses (Lightweight circular micro polarizer 3D glasses [clip-on] BKM-31G, Sony Korea) that could be attached to their regular spectacles. A virtual representation of the liver was superimposed onto the laparoscopic or robotic monitor, and the surgeon manually aligned the virtual liver model and laparoscopic or robotic images by adjusting the position, rotation, scale, and deformation of the virtual liver until the surgeon determined that satisfactory alignment was achieved. An assistant screen-captured monitor images during the procedure for documentation.

Outcomes

Manual registration accuracy was assessed using the Dice similarity coefficient (DSC), to measure the similarity between the virtual liver and the laparoscopic or robotic image after registration. To clarify, the 3D laparoscopic image is constructed from two 2D lenses (right and left) of the stereoscopic camera. The virtual liver model, or AR model, is essentially a 2D image designed to be perceived as a 3D model. Therefore, the DSC value was calculated by comparing two 2D images: one 2D laparoscopic image from the right lens of the stereoscopic camera and the 2D image of the AR model. This method allowed for a precise assessment of the alignment accuracy between the AR model and the actual laparoscopic or robotic view. The DSC was calculated using the following formula: $DSC = 2 \times |A \cap B| / |A| + |B|$. The DSC value ranges from 0 to 1, where 0 indicates no overlap between the predicted segmentation and the actual image, and 1 indicates perfect overlap, meaning the predicted segmentation exactly matches the actual image [16,17]. Post-registration, the superimposed image was visually compared with the laparoscopic or robotic image to assess alignment accuracy.

The surgeon's subjective experience using the AR software during live procedures was investigated after each surgery. The surgeon completed a questionnaire, with 6 questions, evaluating (a) satisfaction with achieved alignment, (b) helpfulness locating blood vessels and tumor during surgery, (c) ease of operation, and (d) overall helpfulness, each rated on a five-point scale (1, not at all; 2, slightly; 3, moderately; 4, very; 5, strongly) (Fig. 3).

RESULTS

Case patients

The study included 10 patients (7 males, 3 females) who underwent 3D laparoscopic or robotic liver surgery, with a mean age of 62.4 ± 6.4 years. The tumors ranged in size from 1.0 cm to 7.5 cm, with an average of 4.4 ± 2.2 cm. Surgical procedures included five 3D laparoscopic approaches and 5 robotic approaches, with 4 right hemihepatectomies, 1 extended left hemihepatectomy, 1 left lateral sectionectomy,

Fig. 2. Intraoperative use of the controller. (A) The controller was encased in aseptic vinyl for use within the sterile surgical field. (B) The operator used his dominant hand to use the controller for manual registration.

Questions (Scale: 1, not at all; 2, slightly; 3, moderately; 4, very; 5, strongly)
1. Was the achieved alignment favorable before mobilization (after trocar and camera insertion)?
2. Was the achieved alignment favorable after mobilization (just before starting liver resection)?
3. Was the AR software helpful in locating the blood vessels during surgery?
4. Was the AR software helpful in locating the tumor during surgery?
5. Was controller operation easy?
6. Overall, was the AR software helpful?

Fig. 3. Operator questionnaire. This questionnaire was translated from the Korean language. AR, augmented reality.

and 4 segmentectomies. There was 1 case of conversion to open surgery (case 3), during which manual registration was performed in an open setting using the laparoscopic camera. The mean total operation time was 168.5 ± 71.6 minutes. The mean estimated blood loss was 232.0 ± 189.5 mL. The final diagnoses were 7 hepatocellular carcinomas, 1 intrahepatic cholangiocarcinoma, 1 liver metastasis from a pancreatic neuroendocrine tumor, and 1 hepatocellular adenoma. There were no immediate postoperative complications in any of the 10 patients, who are currently being routinely followed up in the outpatient department. Patient characteristics are shown in Table 1.

Table 1. Patient characteristics

Characteristic	Data
No. of patients	10
Sex	
Male	7 (70)
Female	3 (30)
Age (yr)	62.4 ± 6.4
Tumor size (cm) in greatest length	4.4 ± 2.2 (1.0–7.5)
Tumor location	
S2	1 (10)
S3	1 (10)
S2/3	1 (10)
S4/S8	1 (10)
S5	1 (10)
S5/S6	1 (10)
S7	1 (10)
S7/S8	1 (10)
S8	2 (20)
Operation approach	
3D Laparoscopic	5 (50)
Robot-assisted	5 (50)
Operation extent	
Right hemihepatectomy	4 (40)
Extended left hemihepatectomy	1 (10)
Left lateral sectionectomy	1 (10)
Sectionectomy	
S3	1 (10)
S4	1 (10)
S5	1 (10)
S7/8	1 (10)
Diagnosis	
Hepatocellular carcinoma	7 (70)
Intrahepatic cholangiocarcinoma	1 (10)
Liver metastasis from pancreatic neuroendocrine tumor	1 (10)
Hepatocellular adenoma	1 (10)

Values are presented as number only, number (%), or mean ± standard deviation (range).
3D, 3-dimensional.

Registration accuracy

The mean DSC values for each case are shown in Table 1. The total mean DSC value for the 10 cases was 0.912 ± 0.052, with a range of 0.879 to 0.954 (Table 2). Case 4 is a representative case (Fig. 4). The patient underwent laparoscopic left lateral sectionectomy for a hepatocellular adenoma tumor measuring 6.9 cm in length, located in segment 3 of the liver. The mean registration accuracy was 0.883 and the registration output showed good alignment between the virtual liver and the laparoscopic image. Captured images after the manual registration of each case are shown in Supplementary Figs. 1–10.

Operator questionnaire

The results of the operator experience questionnaire are summarized in Table 3. The achieved alignment was rated as very favorable both before mobilization (after trocar and camera insertion) with a mean score of 3.9 ± 1.1, and after mobilization (just before starting liver resection) with a mean score of 4.1 ± 1.2. The AR software was found to be very helpful in locating

Table 2. Registration accuracy

Case No.	No. of images	Dice similarity coefficient
1	3	0.952 ± 0.039
2	2	0.954 ± 0.032
3	2	0.919 ± 0.028
4	1	0.883
5	1	0.912
6	4	0.879 ± 0.079
7	2	0.913 ± 0.029
8	2	0.854 ± 0.063
9	2	0.939 ± 0.030
10	1	0.913
Total	22	0.912 ± 0.052

Values are presented as number only, mean ± standard deviation, or mean only.

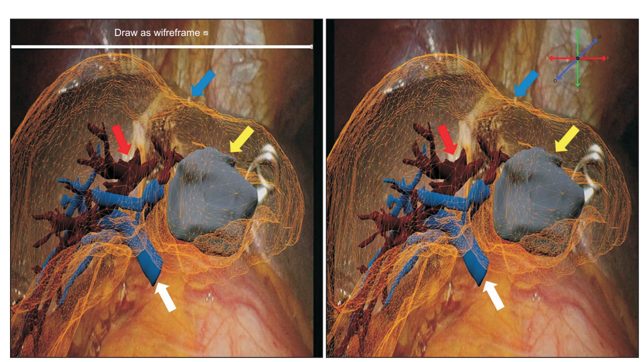

Fig. 4. Representative case (Case 4). Registration of the virtual liver onto the laparoscopic image of the liver after mobilization. The virtual liver consists of the tumor (yellow arrow), portal veins (white arrow), hepatic veins (red arrow), and the mesh outline of the liver (blue arrow).

Table 3. Operator questionnaire scores (n = 10)

Questions	Score
1. Was the achieved alignment favorable before mobilization (after trocar and camera insertion)?	3.9 ± 1.1
2. Was the achieved alignment favorable after mobilization (just before starting liver resection)?	4.1 ± 1.2
3. Was the AR software helpful in locating the blood vessels during surgery?	4.2 ± 0.6
4. Was the AR software helpful in locating the tumor during surgery?	4.3 ± 0.7
5. Was controller operation easy?	3.8 ± 0.6
6. Overall, was the AR software helpful?	4.2 ± 0.8

Values are presented as mean ± standard deviation.
AR, augmented reality.
Scale: 1, not at all; 2, slightly; 3, moderately; 4, very; 5, strongly.
This questionnaire was translated from the Korean language.

the blood vessels (mean score, 4.2 ± 0.6), and tumors (mean score, 4.3 ± 0.7). The AR software was reported to be very helpful overall (mean score, 4.2 ± 0.8).

DISCUSSION

Our AR system was successfully applied during 10 live 3D laparoscopic or robotic liver resections, and favorable manual registration accuracy between the virtual liver model and the actual laparoscopic or robotic image was demonstrated. Manual registration accuracy was assessed using the DSC, a straightforward statistical validation metric that evaluates the reliability or reproducibility of image segmentation by measuring spatial overlap [17]. In clinical practice, the interpretation of the DSC value varies depending on the specific application and context. Previous studies suggest that a DSC value greater than 0.7 denotes good agreement [18]. The mean DSC value of 0.912 ± 0.052 across our cases indicates a strong overlap between the predicted and actual structures. Moreover, the alignment between the virtual liver model and the laparoscopic or robotic view was perceived by the operator as very favorable both before and after liver mobilization. Overall, the AR system was seen as very helpful by the operator, particularly for locating blood vessels and tumors.

Aligning the 3D model with the laparoscopic or robotic view of the liver has some remaining challenges due to liver deformations caused by gravity, pneumoperitoneum, and surgical movement, which are not yet accurately represented in the AR superimposed images [19]. In particular, in the presence of pneumoperitoneum, gravity causes both lobes of the liver to bend around the middle hepatic vein. Consequently, there is a tendency for inaccurate alignment at the end of segment 4, as seen in Supplementary Fig. 6. Therefore, further refinements capable of reflecting these physical changes during surgery are necessary. Additionally, the entire liver surface is not always visible within the laparoscopic or robotic field of view which complicates accurate alignment and registration between the 3D structure and the real-time laparoscopic or robotic image during surgery. Discrepancies can also arise due to variations in the distances in the 3D model and the actual distances within the laparoscopic liver. Furthermore, rapid movements of the laparoscopic or robotic camera may cause the AR system's responsiveness to lag, potentially leading to misalignment and reduced accuracy during manual registration. Indeed, the laparoscopic or robotic view of the liver constantly changes as the camera moves. Automatic registration and automatic visual tracking remain significant challenges [20]. Currently, our AR software requires manual registration of the virtual liver onto the laparoscopic or robotic view, necessitating manual adjustments every time the camera angle or position changes. We anticipate that future technological advancements will address this issue, enabling automatic registration and visual tracking, thereby reducing the need for continuous manual adjustments. Despite these limitations, the operator questionnaire indicated that the AR alignment was perceived very favorably by the operator, both before and after mobilization, and was considered helpful overall, particularly in locating blood vessels and tumors.

The operator also reported through the questionnaire that the AR system was very helpful overall, and very helpful for visualizing both vessels and tumors. Notably, the operator was a surgeon with 20 years of experience performing liver surgeries, adding significant credibility to the positive feedback. Although the operator expressed a positive attitude toward using the AR system, we recognize that acceptance may vary among different surgeons, depending on factors such as familiarity with technology, perceived benefits, and the learning curve associated with the system. The AR technology may be helpful for surgeons, offering additional guidance and confidence during complex procedures. AR technology, which integrates 3D image data into the operating room, represents a promising solution for enhancing surgical planning and intraoperative guidance [8]. AR makes it easier to see the 3D structure of the liver, along with the relative positioning of tumors and blood vessels, allowing for more precise surgical navigation [21]. AR technology can aid surgeons in locating intrahepatic tumors that are otherwise invisible and can help confirm hepatic inflow and outflow during surgery. AR can help improve surgical precision by overlaying 3D virtual models onto laparoscopic or robotic views, allowing surgeons to identify and control feeding arteries or portal veins, thereby reducing the risk of bleeding and minimizing tissue damage during liver resection. This may lead to more precise tumor removal and contribute to safer surgical procedures.

Indeed, AR offers considerable advantages over conventional intraoperative methods like laparoscopic ultrasound. First, AR provides a direct visual overlay onto the laparoscopic or robotic screen, giving surgeons a comprehensive view of the entire liver without limiting the field of exploration [22]. Second, AR operates in real-time, to provide continuous guidance without interrupting the surgical procedure. Moreover, the visual information provided by AR is easily interpreted without specific skills, and the technology is user-independent, and reproducible [23]. Lastly, AR reduces cognitive load when compared to intraoperative ultrasound, which demands the surgeon makes a detailed analysis of preoperative CT scans [24]. When operating in a 2D environment, surgeons must mentally project the tumor's 3D location onto the surgical field based on 2D images and adjust the resection plane accordingly [25]. Maintaining an ultrasound probe perpendicular to the liver surface can also be difficult, especially when excising deeper or posterior tumors [26]. The AR system addresses these challenges by providing clear, 3D-guided visualization to support surgical precision.

A notable advantage of our AR system is that it allows the operator to manually register the virtual liver model from within the surgical field using a handheld controller. This eliminates the need for an assistant to externally manage the software and provides the surgeon with more flexibility and control during surgery [27,28]. The operator perception indicated that the controller operation was moderately easy to control. Prior to surgery, the operator received brief instructions on using the controller and performing manual registration, becoming comfortable with the process in less than 5 minutes. Although manual registration time was not recorded in this study, a previous study showed a mean registration time of 2.4 minutes for 3 separate evaluators, with no clear trend in manual registration time observed across cumulative cases. However, further studies are needed to determine whether a learning curve exists for manual registration time. An additional advantage of our design is the use of 3D glasses, which are commonly used in 3D laparoscopic or robotic surgeries, eliminating the need for a specialized virtual headset, which is often required by other AR technologies [29]. Additionally, the AR software was effectively applied even in the case of conversion to open surgery by utilizing the laparoscopic camera.

On the other hand, there are several potential drawbacks and challenges associated with implementing the AR system in 3D laparoscopic and robotic liver surgery that need to be addressed. These include the limited availability of 3D laparoscopic or robotic equipment in many hospitals, the time-intensive process required for 3D reconstruction of the virtual liver or AR model, the need for specialized AR software, and the use of a customized controller that is not commercially available. Additionally, the potential for AR-induced disorientation or fatigue is a recognized concern with AR technologies [30]. Prolonged viewing of AR displays, especially in 3D mode, can contribute to visual fatigue and ocular discomfort. In our study, we mitigated this issue by limiting the duration of alignment tasks to short periods. However, we acknowledge the need to further reduce visual strain. Future research will need to focus on developing strategies to minimize visual fatigue and enhance user experience and safety during extended use of AR systems in surgical environments.

A limitation of this study is the small sample size, which impacts the generalizability of the findings, as well as the absence of a control group, making it difficult to compare outcomes between surgeries utilizing AR software and those that do not. Additionally, the variability in the complexity of the surgeries performed could influence the results. To address these limitations, future studies will include control groups, larger sample sizes, and stratify cases based on surgical complexity. This will allow for a more nuanced analysis of the user experience and provide more robust conclusions on the impact of AR software on surgical outcomes. Another limitation of this study is that all procedures were conducted by a single, experienced liver surgeon, which may limit the generalizability of the findings to less experienced surgeons. Although AR technology has the potential to provide valuable guidance to less experienced surgeons, further research is needed to confirm its effectiveness in this specific group. Moreover, the study did not fully explore the learning curve associated with the AR software, which could influence the results. Although no clear trend was observed in manual registration accuracy across cumulative cases, the impact of the learning curve on surgical outcomes warrants further investigation. Despite these limitations, the current study provides a basis for the application of our AR in 3D laparoscopic or robotic liver surgeries and opens the door for more extensive research in the field.

In conclusion, the clinical application of our AR software in 10 live 3D laparoscopic or robotic liver surgeries demonstrated favorable registration accuracy and was perceived to be very helpful by the operator. While our system shows potential to improve the precision and efficiency of 3D laparoscopic or robotic liver surgeries, further studies and refinements are necessary to fully assess its effectiveness and applicability in broader clinical settings.

SUPPLEMENTARY MATERIALS

Supplementary Figs. 1–10 can be found via https://doi.org/10.4174/astr.2025.109.1.44.

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Conflict of Interest

Young Jun Chai, serving as an member of the Editorial Board of *Annals of Surgical Treatment and Research*, did not participate in the review process of this article. No other potential conflicts of interest pertinent to this article were reported.

ORCID iD

Moon Young Oh: https://orcid.org/0000-0002-8939-1735
Kyung Chul Yoon: https://orcid.org/0000-0001-5147-6162
Hyoun-Joong Kong: https://orcid.org/0000-0001-5456-4862
Taesoo Jang: https://orcid.org/0009-0009-4272-5062
Yeonjin Choi: https://orcid.org/0009-0005-9732-7820
Junki Kim: https://orcid.org/0000-0001-8446-9954
Jae-Yoon Kim: https://orcid.org/0000-0002-2546-3752
YoungRok Choi: https://orcid.org/0000-0003-2408-7086
Young Jun Chai: https://orcid.org/0000-0001-8830-3433

Author Contribution

Conceptualization, Supervision: HJK, YJC
Data curation: TJ, YC, JYK, YRC
Formal analysis: MYO, TJ, YC, JK
Funding acquisition: YJC
Investigation: MYO, KCY, TJ, YC, JK
Methodology: KCY, HJK, YRC, YJC
Project administration: YRC, YJC
Resources: JYK, YRC
Software: HJK, TJ, YC, JK
Supervision: HJK, YJC
Validation: KCY, YRC, YJC
Visualization: MYO, HJK, TJ, YC, JK
Writing – Original Draft: MYO, KCY, HJK
Writing – Review & Editing: All authors

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