

Essential updates 2020/2021: Current topics of simulation and navigation in hepatectomy

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Abstract

With the development of three-dimensional (3D) simulation software, preoperative simulation technology is almost completely established. The remaining issue is how to recognize anatomy three-dimensionally. Extended reality is a newly developed technology with several merits for surgical application: no requirement for a sterilized display monitor, better spatial awareness, and the ability to share 3D images among all surgeons. Various technology or devices for intraoperative navigation have also been developed to support the safety and certainty of liver surgery. Consensus recommendations regarding indocyanine green fluorescence were determined in 2021. Extended reality has also been applied to intraoperative navigation, and artificial intelligence (AI) is one of the topics of real-time navigation. AI might overcome the problem of liver deformity with automatic registration. Including the issues described above, this article focuses on recent advances in simulation and navigation in liver surgery from 2020 to 2021.

KEYWORDS

artificial intelligence, extended reality, ICG fluorescence, liver surgery, navigation, simulation

1 | INTRODUCTION

Advances in perioperative care and surgical techniques have significantly improved the outcomes of liver resection during the last three decades. Liver surgery has inherent challenges, including difficult anticipation of complex and variable intrahepatic anatomy and the need for cognitive analysis by the surgeon to integrate preoperative imaging information into the operative field. Therefore, simulation and navigation techniques have been developed in this field.

In preoperative simulation, three-dimensional (3D) simulation technology was developed in Germany in the early 2000s,¹ and immediately thereafter software based on an original algorithm was developed in Japan. The development of intraoperative navigation techniques may also help surgeons to perform liver resections as

planned. Intraoperative navigation began with intraoperative ultrasound (US) in 1980² and progressed to virtual hepatectomy (Hx),³⁻⁷ real-time virtual sonography,⁸⁻¹² and finally indocyanine green (ICG) fluorescence.¹³⁻²⁰ Thus, intraoperative navigation has gradually evolved during the past 40 y.

This biannual review discusses the essential updates to simulation and navigation in Hx that occurred in the 2-y period from 2020 to 2021.

2 | PREOPERATIVE SIMULATION

Preoperative 3D simulation has enabled surgeons to obtain a great deal of information, such as detailed anatomical visualization, the

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precise volume of each segment and each hepatic venous drainage area, and prediction of postoperative liver failure (POLF). As a result, more aggressive and complicated surgeries can be safely performed. We herein summarize the recent refinements of preoperative simulation in liver surgery from 2020 to 2021 (Table 1).

2.1 | Anatomical visualization: 3D printing liver and extended reality

If a 3D liver model including the tumor, each vessel, and the liver parenchyma is created, it is meaningless to display that model on a 2D monitor or printed paper because of the lack of spatial awareness. Therefore, many reports have described the usefulness of 3D printing of liver models for operative planning or medical education.²¹⁻²³ Because 3D printing of the liver results in a model of the patient's own liver, accurate information can be obtained regarding the vessel anatomy, the relationship between the tumor and vessels, and the parenchymal cutting plane. Another advantage of 3D printing is that the operator can freely pick up the patient's own liver. The material used for 3D printing is also being developed in various ways. However, the high cost and complexity of the creation process are undeniable.

Recently, new technologies involving virtual reality (VR), augmented reality (AR), and mixed reality (MR), all of which can be referred to as extended reality (XR), have been developed and applied

to various operative simulations. Head mount displays (HMDs) intrinsically provide the user with an egocentric viewpoint and allow the user to work hands-free without a monitor. Especially in VR, the surgeons can be immersed in the patient's own liver. The merits of the application of XR techniques to surgical support include no need for a sterilized display monitor, better spatial awareness, and the ability to share 3D images among all surgeons.²⁴ XR techniques are applied to preoperative planning or visualization of vessels in liver surgery,²⁵⁻²⁷ and XR images are suitable for clinical presentation because of their sharing function. Huettl et al²⁵ compared 3D printed liver models and VR liver models and concluded that 3D VR liver models enable a better and partially faster anatomical orientation than 3D printed liver models. XR technology is still in its early stages. HMDs should be refined into lighter, simpler, and easier to operate devices.

2.2 | Volumetry: Portal perfusion and venous drainage

Preoperative volumetry is essential to ensuring safe hepatic resection by estimating the volume of both the portal perfusion and venous drainage area. In 2020–2021, Saito et al²⁸ proposed Hx based on a hybrid concept of the portal perfusion of the anterior segment and venous drainage area of the superior right hepatic vein. The perfusion area of the anterior segment crossed over the superior right

TABLE 1 Preoperative simulation in liver surgery

Author	Year	Category	Article type/Patients' number	Information
Ozer ²¹	2021	Anatomical visualization	A case study (n = 5) Questionnaire (n = 22)	3D printing porta-celiac vascular model Surgical plan for resident trainees in Hx
Kuroda ²²	2020	Anatomical visualization	A case study (n = 5) Comparison of surgical outcomes (n = 212)	3D printing liver model Vessel's simulation in donor Hx of LDLT
Larghi ²⁴ Laureiro ²³	2020	Anatomical visualization	A case study (n = 1)	3D printing liver model Surgical plan in hilar cholangiocarcinoma
Huettl ²⁵	2021	Anatomical visualization	A case study (n = 20) Questionnaire (n = 20)	VR liver Preoperative visualization of vessels in Hx
Boedecker ²⁶	2021	Anatomical visualization	A case study (n = 1)	VR (immersive into liver) Surgical plan/Clinical presentation in Hx
Pelani ²⁷	2020	Anatomical visualization	A case study (n = 1) Questionnaire (n = 28)	MR liver Preoperative visualization of vessels in Hx
Saito ²⁸	2020	Volumetry	Retrospective single-center study (n = 66)	Hx based on hybrid concept of portal perfusion and venous drainage area
Li ²⁹	2021	Volumetry	Retrospective single-center study (n = 102)	Simulation of portal or venous associated remnant liver ischemia or congestion
Procopio ³⁰	2021	Prediction of POLF	Retrospective single-center study (n = 30)	Volumetry using 3D simulation
Araki ³²	2020	Prediction of POLF	Retrospective single-center study (n = 155)	SI in remnant liver with ROB-MRI
Notake ³³	2021	Prediction of POLF	Retrospective single-center study (n = 67)	SI in remnant liver with ROB-MRI

Abbreviations: EOB-MRI, ethoxybenzyl-magnetic; Hx, hepatectomy; LDLT, living-donor liver transplantation; MR, mixed reality; SI, signal intensity; VR, virtual reality.

hepatic vein in one-fourth of the patients in the study. The authors considered that less invasive Hx based on a hybrid concept might be an alternative to right Hx. Li et al²⁹ preoperatively simulated portal or hepatic vein-associated remnant liver ischemia or congestion, and it led to postoperative complications.

2.3 | Prediction of POLF

Aside from 3D reconstruction or simulation software, also simple liver function simulation is also critical in liver surgery. Preoperative volumetry can estimate the remnant liver volume and predict POLF.³⁰ Gadolinium ethoxybenzyl diethylenetriamine pentaacetic acid (Gd-EOB-DTPA)-enhanced magnetic resonance imaging (EOB-MRI) can also be used to evaluate liver functional reserve.³¹ Functional remnant liver volumetry with signal intensity in EOB-MRI can precisely predict POLF of Hx involving more than one segment.³² EOB-MRI is also useful for predicting POLF after major Hx for biliary malignancy.³³ In terms of a “one-stop shop” of preoperative simulation, EOB-MRI may be the most useful modality for detecting tumors, simulating vessel anatomy, and estimating remnant functional reserve.

3 | INTRAOPERATIVE NAVIGATION

Navigation in liver surgery began in 1985 when Makuuchi et al² performed anatomical resection with dye staining using intraoperative US. Various medical devices have been developed to support the safety and certainty of liver surgery with recent advances in medical engineering technology.

Fluorescent navigation using ICG has been clinically applied in various ways for liver navigation surgery. As described above for preoperative simulation, XR techniques have also been applied to intraoperative support systems. Furthermore, artificial intelligence (AI) technology has been introduced to intraoperative navigation. We herein summarize the recent refinements of intraoperative navigation in liver surgery from 2020 to 2021.

3.1 | ICG staining

Indocyanine green emits a fluorescent wavelength and is clearly visualized when irradiated with near-infrared light (760 nm). In total, 73 articles were found in PubMed in 2020–2021 using the search terms “ICG” and “Liver surgery”; articles describing the intraoperative use of ICG were more limited and can be classified into liver area staining or tumor detection. Recently, ICG has also been widely used in laparoscopic surgery (Table 2).

In 2021, consensus recommendations were established for the use of fluorescence imaging with ICG in hepatobiliary surgery.³⁴ Seven recommendations were formulated. In area staining, the consensus states that “ICG is helpful in delineating segmental

boundaries in both open and minimally invasive liver resection (Recommendation Class IIa/IIb).” In tumor imaging, the consensus states that “ICG is helpful to localize subcapsular tumors within 8 mm of the liver surface or cut surface of the liver parenchyma, and may reduce the risk of positive margins (Recommendation Class IIa/IIb).”

The usefulness of positive and negative staining of each segment has been fully reported. In a retrospective single-center study of 120 cases, Lu et al³⁵ reported that ICG staining contributed to a shorter operative time and lower amount of intraoperative blood loss and that it helped to achieve a wide surgical margin. Furthermore, ICG staining was performed in special types of Hx, such as laparoscopic donor Hx,³⁶ robotic Hx,³⁷ and Hx for hepatolithiasis.³⁸ Kubo et al³⁹ used ICG staining for navigation of the venous drainage area of the right hepatic vein. Collaboration with a preoperative 3D simulation modality and intraoperative ICG staining with AR techniques was also introduced in 30 patients undergoing laparoscopic Hx.⁴⁰ This new navigation technology contributed to better surgical outcomes; however, its effect on the long-term prognosis remains unclear. In terms of the technical performance of ICG staining, although negative staining is relatively easy, positive staining is sometimes difficult, depending on the location of the tumors, especially in laparoscopic Hx. Xu et al⁴¹ described their failed cases of positive staining, reporting a success rate of around 50%. Performing positive staining requires the surgeon to be proficient in intraoperative laparoscopic US (LUS), comfortable performing US-guided puncture, and skillful in interpreting the preoperative 3D image simulation. The manipulation of LUS is the most demanding part. Therefore, a new kind of LUS probe should be developed for useful positive staining in the future. Because LUS is difficult, Aoki et al⁴² performed US-guided preoperative positive percutaneous staining immediately before laparoscopic surgery. This was a very simple technique and may be a reasonable way to resolve the technical difficulty of the procedure.

In tumor detection, ICG is useful to identify not only intrahepatic tumors⁴³ but also extrahepatic metastatic tumors such as those in the adrenal gland⁴⁴ or abdominal wall.⁴⁵ Tumor detection with ICG contributes to the safe achievement of surgical margins during liver resection.⁴⁶ Purich et al⁴⁷ performed a systematic review and meta-analysis of the diagnostic test accuracy of ICG. The sensitivity of intraoperative ICG-related imaging for superficial tumors was high; however, the overall sensitivity was low, at 0.75, suggesting that this technique would have to be used in combination with current identification methods such as intraoperative US. Their study also showed that intraoperative ICG fluorescence imaging was able to detect additional malignant hepatic tumors in 11.6% of patients.

3.2 | XR

In XR techniques, VR is useful for preoperative simulation, allowing the surgeon to become immersed in the patient's own liver with

TABLE 2 ICG navigation in liver surgery

Author	Year	Category	Article type/Patients' number	Information
Wang ³⁴	2021	Area staining/Tumor detection	Guideline	Recommendation Class; IIa or IIb Evidence level; II-2 or II-3
Lu ³⁵	2021	Area staining	Retrospective single-center study (n = 120)	Better short-term outcomes and surgical margin
Kim ³⁶	2021	Area staining	Retrospective single-center study (n = 76)	Laparoscopic donor's Hx Demarcating exact midplane
Marino ³⁷	2020	Area staining	Retrospective single-center study (n = 40) Positive (n = 20) and Negative (20) staining	Robotic-assisted Hx
He ³⁸	2020	Area staining	A randomized controlled trial (n = 46)	Hx for hepatolithiasis Better short-term outcomes
Kubo ³⁹	2020	Area staining	Retrospective single-center study (n = 12)	Determining areas of liver congestion of RHV
Zhang ⁴⁰	2020	Area staining	Retrospective single-center study (n = 64)	Collaboration with preoperative 3D simulation and intraoperative ICG
Xu ⁴¹	2020	Area staining	Retrospective single-center study (n = 36)	Technical difficulty in positive staining (Success rate; around 50%)
Aoki ⁴²	2020	Area staining	A case study (n = 14)	Preoperative positive percutaneous staining before laparoscopic surgery
Lim ⁴³	2021	Tumor detection	Retrospective single-center study (n = 32)	Detection of intrahepatic tumors
Yamamura ⁴⁴	2020	Tumor detection	A case study (n = 1)	Detection of extrahepatic tumors
Hayashi ⁴⁵	2021	Tumor detection	A case study (n = 1)	Detection of extrahepatic tumors
Tashiro ⁴⁶	2020	Tumor detection	Retrospective single-center study (n = 125)	Better surgical margin
Purich ⁴⁷	2020	Prediction of POLF	A systematic review and meta-analysis	overall sensitivity; 0.75 Additional tumor detection; 11.6%

Abbreviation: RHV, right hepatic vein.

TABLE 3 XR navigation in liver surgery

Author	Year	Category	Article type/Patients' number	Information
Golse ⁴⁸	2021	AR overlay	A case study (n = 5)	Real-time marker less registration with RGB-D camera
Espinel ⁴⁹	2020	AR overlay	A case study (n = 7)	Laparoscope and liver surface as landmark Average registration error <1.0 cm
Prevost ⁵⁰	2020	AR overlay	A case study (n = 10)	Laparoscope and 4 points as landmark Mean fiducial registration error 14 mm
Bertrand ⁵¹	2020	AR overlay	A case study (n = 17)	"Hepataug system" Safety and feasibility
Pelani ⁵²	2021	AR overlay	A case study (n = 4)	Cone beam CT / Optical tracking system Mean target registration error 3.8 mm
Zhang ⁵³	2020	AR overlay	Retrospective single-center study (n = 85)	AR contributed to less blood loss and shorter hospital stays
Saito ²³	2020	MR hologram	A case study (n = 2)	Last-minute simulation before Glissonian pedicle approach
Saito ⁵⁵	2021	MR hologram	A case study (n = 2)	Anatomy understanding of intrahepatic anatomy especially in B1 origination
Aoki ⁵⁶	2020	MR hologram	A case study (n = 1)	Holography-guided percutaneous puncture in positive staining

Abbreviations: AR, augmented reality; CT, computed tomography; RGB, right green blue.

better spatial awareness. AR or MR techniques should be used with intraoperative navigation tools because surgeons must examine the real operative field in both open and laparoscopic surgery.

In total, 27 articles were found in PubMed in 2020–2021 using the search terms “VR/AR/MR” and “Liver surgery” (Table 3). Most of these reports focused on AR-guided navigation. A preoperatively reconstructed 3D liver model should be overlaid onto the real liver. Unlike for neurosurgery, otolaryngology, and orthopedic surgery, in which rigid structures facilitate a rather unproblematic registration, liver surgery is associated with the problem of deformation of abdominal tissues and organs. This deformation results in a difficult registration procedure, potentially requiring nonrigid registration techniques to achieve sufficient registration accuracy. Therefore, various ways to perform registration of a preoperative 3D liver model have been developed.

Golse et al⁴⁸ placed a special camera called the e RGB-D camera in the operation room to perform real-time markerless registration in open liver surgery. In laparoscopic surgery, combination techniques with intraoperative calibration of the laparoscope and various landmarks to define the liver anatomy such as the falciform ligament, edge of the liver, and gall bladder are commonly used.^{49–51} Pelanis et al⁵² performed intraoperative cone-beam computed tomography (CT) and used an optical tracking system in registration. Target registration error and fiducial registration error were evaluated in those reports^{49–52} and ranged from 3.0–14.0 mm. Such an AR overlay navigation system contributed to a reduction in vascular injury and more rapid postoperative recovery.⁵³ Therefore, more refinements of accurate registration should be implemented in the future.

Mixed reality techniques with 3D computer-generated models called holograms have also been introduced intraoperatively with HMDs. Saito et al used a hologram based on preoperative CT immediately before performing the Glissonean pedicle approach in Hx⁵⁴ and a hologram based on intraoperative cholangiography immediately before dissecting the intrahepatic bile duct in biliary surgery.⁵⁵ Operators and assistants can share the same hologram from each angle with HMDs and observe the detailed biliary anatomy around the dissected bile duct (Video S1). A system called a “virtual session” was also recently introduced. Conductor (operator), two assistants and a remote participant, who is not in the operating room, can share the hologram in the metaverse. Conductor explains the operative plan to assistants and the remote participant. We plan to apply this system in the field of remote medical care in the near future (Video S2). Strictly speaking, holograms contribute to “last-minute simulation,” not navigation. However, the hologram might be a new next-generation operation-support tool in terms of spatial awareness, sharing, and simplicity. Aoki et al⁵⁶ also reported holography-guided percutaneous puncture in positive staining with ICG in laparoscopic surgery. As described in the ICG navigation section, positive staining especially in laparoscopic Hx is sometimes difficult, depending on the location of the tumors. This holographic guidance might help the operator to develop a better imagination.

3.3 | AI

Artificial intelligence technology was recently introduced to surgical navigation. AI should provide image recognition, focusing on anatomical structures, image recognition focusing on the surgical procedure itself, and control against incorrect performance of the surgical procedure. AI can already reportedly recognize the surgical process,⁵⁷ surgical instruments such as laparoscopic forceps,⁵⁸ and anatomical landmarks^{59,60} in cholecystectomy or colorectal surgery. AI has also been applied to assessment of surgical skill.⁶¹

Nazir et al⁶² reported a new searching and tagging system that recognizes various anatomical landmarks in laparoscopic liver surgery. Only one article focused on intraoperative navigation with AI in liver surgery from 2020–2021. AI is not yet frequently used in liver surgery, but future technological applications are expected.

To date, AI has only been used for the recognition of anatomical structures based on information of surgical field images. In the future, some suggestions or attention on anatomical structure information that cannot be directly seen in the surgical field are expected. Furthermore, an integrated analysis of real surgical field images and preoperative modalities should be developed for AI navigation surgery.

4 | CONCLUSION

The current status of simulation and navigation in hepatectomy from 2020 to 2021 has been reviewed. Preoperative simulation technology is already almost fully established; the next step is navigation in liver surgery. ICG staining is now widely used for area staining and tumor detection. Some refinements should be developed in terms of positive staining in laparoscopic liver surgery. XR techniques provide amazing new information regarding the liver anatomy, with better spatial awareness; however, the problems of registration and real-time liver deformity remain to be solved. Finally, the development of AI technology is ongoing. The establishment of various simulation and navigation technologies should help surgeons to perform safer liver resection.

DISCLOSURE

Conflict of interest: All authors declare that they have no competing interests.

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