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Review

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Enhancing liver surgery and transplantation: the role of 3D printing and virtual reality

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Abstract

This review explores the significant advancements in liver surgery and transplantation, particularly focusing on the integration of 3D printing and virtual reality (VR) technologies. The core objective is to enhance preoperative planning, simulation, and intraoperative navigation. The review discusses several studies that underscore the accuracy and utility of 3D printed models derived from medical imaging, which are instrumental in identifying small liver lesions, improving surgical education, and facilitating patient comprehension. Additionally, the role of VR in surgical simulation is examined, highlighting its superiority in tumor identification and its potential in training systems. While clinical outcomes data suggest a need for further randomized trials to establish the impact on surgical efficiency and recovery, the review also touches upon the promising future of augmented reality (AR) for intraoperative guidance and liver segment identification, with prospects of artificial intelligence (AI) integration. The conclusion underscores the importance of continued clinical evidence and technological advancements for wider adoption in liver surgery and transplantation.

Keywords: Liver surgery, transplantation, 3D printing, virtual reality, augmented reality, preoperative planning, surgical simulation, medical education, patient education

INTRODUCTION

Liver surgery and transplantation are both highly complex procedures, requiring extensive knowledge of anatomy and advanced surgical techniques due to the complex and variable vascular supply and biliary drainage of the liver. Precise preoperative planning is critical for achieving optimal outcomes, avoiding complications, and ensuring adequate preservation of the functional liver volume, especially for living donors, which require more precise liver volume and anatomical information preoperatively[1]. Recent advances in 3D printing and virtual reality (VR) simulation show promise for enhancing the understanding of patient-specific anatomy and enabling realistic rehearsal of procedures[1-5]. In this review, we summarize the current applications of these technologies in preoperative evaluation and planning for liver surgery and transplantation.

3D Printing for preoperative planning and simulation

Modern cross-sectional imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) allow detailed visualization of patient anatomy. Several studies have demonstrated the feasibility of using such images to create accurate 3D printed models of the liver vasculature, lesions, and segmental anatomy[3-7].

In an early report, Zein *et al*. described 3D printing liver models for three living liver donors and recipients undergoing liver transplantation. Individual arteries, veins, and biliary radicles were differentially colored, with anatomical accuracy confirmed after explantation[1]. Printed models allowed enhanced the preoperative simulation and intraoperative navigation compared to standard CT/MRI. In the multicenter LIV3DPRINT study, Lopez-Lopez *et al*. validated the accuracy of 3D liver models with average errors of only 0.31 mm compared to the original CT/MRI scans[3]. Although the study did not demonstrate improvements in surgical outcomes, it highlighted the significant utility of these models for educational purposes, enhancing the understanding of complex hepatic anatomy, and aiding in precise surgical planning. This underscores the importance of 3D printing technology in medical training and preoperative preparation, despite the need for further evidence on clinical outcomes.

Joo *et al*. evaluated personalized 3D models for detecting small liver lesions < 10 mm[4]. Of 98 focal lesions (mean 11.5 mm) identified on MRI, printed models enabled the detection of 99.0% compared to 82.7% by conventional review, showing particular value for diminutive metastases and subcentimeter hepatocellular carcinoma. Multiple studies have concluded that 3D models improve spatial comprehension, facilitating planning for complex surgical anatomy for hepatectomy[3,4].

Applications in surgical education

3D printed models allow trainees to visualize and manipulate anatomical structures with high fidelity, offering a hands-on approach to understanding complex surgical anatomy. Valls-Esteve *et al*. devised an economical 3D printing workflow to fabricate low-cost surgical simulators from patient scans, which trainees used to practice complex resections prior to operating[5]. Surveyed residents reported enhanced procedural understanding and rated 3D models as excellent educational tools. These 3D models provide unparalleled visualization of subsurface tumors and vascular anatomy not otherwise visible, offering analytic training opportunities that are superior to animal labs or virtual simulators alone[5].

The combined use of 3D printing and VR technologies has shown significant benefits in neurosurgical preoperative planning, as highlighted by González-López *et al*. (2024) in their study on neuro-oncology[8]. They found that integrating these technologies transforms the paradigm of surgical planning, ensuring safer procedures and enhancing surgical preparedness. The detailed 3D models created from patient scans can be experienced through VR systems for comprehensive preoperative rehearsal, and 3D printed models provide hands-on training opportunities, thereby improving the overall safety and efficiency of neurosurgical procedures. Moreover, the advantages of integrating 3D printing and VR are not limited to neurosurgery.

These technologies are equally applicable and beneficial in liver surgery and transplantation. By creating accurate 3D models of liver anatomy from patient scans, surgeons can plan and rehearse complex procedures in a virtual environment, leading to better understanding and anticipation of potential challenges. This approach can significantly enhance surgical outcomes, improve educational opportunities for trainees, and increase patient safety in hepatic surgeries as well. Moreover, these technologies address some of the limitations of traditional surgical training methods, such as animal labs or cadaveric dissection, by providing a more ethical and logistically feasible alternative[5]. The adoption of 3D printing and VR in surgical education is poised to expand as these technologies become more accessible and affordable. As educational tools, they hold the potential to revolutionize the way surgical skills are taught and acquired, ultimately improving patient outcomes through better-prepared surgeons.

Patient education with 3D models

Structured preoperative education and informed consent discussions are integral in surgery, but conveying complex 3D relationships is difficult with standard imaging for patients. Giehl-Brown *et al.* investigated whether personalized 3D models improved patient education for hepatobiliary procedures[9]. Among 40 subjects randomized to standard *vs.* 3D consent processes, the 3D cohort showed significantly higher satisfaction postoperatively (90% *vs.* 65%, $P = 0.052$). Critically, 94.4% of patients in the 3D model cohort were able to correctly report their complication status compared to just 68.4% of controls, indicating enhanced retention and comprehension.

Limitations of 3D printing

Despite holding immense potential to transform surgical planning in liver surgery, 3D printing has several limitations. For instance, producing accurate anatomical replicas requires considerable modeling expertise and advanced software/hardware, thus limiting widespread adoption[4,5]. Moreover, in addition to costs, multi-day segmentation and printing introduce production delays, which may constrain their utility for urgent cases. Witowski *et al.* noted that static preoperative models cannot reflect intraoperative deformations from pneumoperitoneum or tissue manipulation, necessitating improved biomechanical modeling[10]. Ongoing technological progress will increase the availability and functionality of 3D printing techniques.

VR SURGICAL SIMULATION

Although 3D models enhance spatial comprehension compared to 2D imaging, traditional visualization via specialty software or 3D PDF viewers offers limited interactivity with surgical anatomy. Recent efforts have focused on translating complex 3D data into fully immersive virtual environments using consumer VR headsets. Custom software allows users to dynamically scale, rotate, dissect, and manipulate patient-specific anatomy projected stereoscopically, while rehearsing potential resections[11]. Boedecker *et al.* performed a novel comparison of liver lesion identification between standard PACS, 3D printed models, and VR simulation[12]. Accurately locating tumors was superior in VR and 3D printing cohorts compared to the traditional form of review. Furthermore, the printed models enabled the fastest identification ($P < 0.01$), while VR scored highest for usability, intuitiveness, and depth perception ($P = 0.02$). More than 70% of participants judged VR models as being useful preoperative planning tools with high clinical fidelity. VR holds unique value for allowing unlimited repetitions, improving psychomotor skills, and quantitative motion analysis, which would be impossible *ex vivo*[13].

VR training systems and procedural rehearsal

Immersive 3D environments provide invaluable foundations for elaborate multifaceted simulation systems. Lefor *et al.* developed a virtual reality simulator tailored for robotic liver resection, specifically modeling tissue physics and cautery dissection[14]. Realistic ultrasonic shears approximate fine motor control, procedural kinetics, and pedagogical objectives for robotic training. Validation testing showed significant metric differentiation between novice and experienced surgeons over five domains, including time ($P = 0.004$), economy of motion ($P = 0.043$), and path length ($P = 0.008$). The system demonstrated utility in assessing skill level and progress through graduated complexity scenarios. VR circumvents the limitations of classical animal laboratories and cadaveric training, while generating quantitative performance data that are superior to observational clinical grading systems[14].

Clinical outcomes

While abundant evidence has confirmed the technical accuracy of 3D modeling and immersive realism of VR simulation, few studies have linked these technologies to improvements in concrete perioperative outcomes. Given the multiple concurrent advances in hepatic surgery over the past decade, high-quality randomized controlled trials are essential for determining the impacts on safety, efficiency, complications, recovery, hospitalization duration, and long-term oncologic results[9,10,12-13].

Present clinical data derive primarily from small prospective case series. However, in a 3D planning pilot study for complex oncologic resections, Lyuksemburg *et al.* reported increased concordance between preoperative models and ultimate procedures performed over standard CT/MRI review (92% *vs.* 54% for operating surgeons, 69% vs. 23% for consulting surgeons)[15]. Furthermore, the 3D models enhanced preoperative understanding of respectability and vascular relationships in this initial experience. Experience is accruing, with improvements in planning, operative time, and reproduced margins, portending future randomized evaluations[16].

AUGMENTED REALITY AND IMAGE GUIDANCE

Three-dimensional model fusion with augmented or mixed reality platforms has shown early promise for real-time intraoperative guidance. Indeed, Wang *et al.* employed laparoscopic augmented reality (AR) navigation by the display of 3D anatomy for laparoscopic right hemi-hepatectomy plus total caudate lobectomy for perihilar cholangiocarcinoma[17]. Virtual vessels and tumors overlaid on operative views with AR linked to a better understanding of surgical anatomy. In a randomized AR trial that studied 3D planning models with integrated surgical navigation during both laparoscopic and open hepatectomy, Huber *et al.* found no significant differences in operative time, morbidity, margins achieved, or volumetric accuracy between AR and conventional groups[18]. Though safely implemented, AR failed to improve outcomes over standard techniques in this initial experience, perhaps indicating residual technological limitations[18]. Nonetheless, further efforts accounting for case complexity may unlock lasting clinical gains. In addition, arterial and portal anatomy, especially for transplantation or complex biliary surgery, require detailed information about the bile ducts. However, this anatomical information is usually not available from ordinary CT scans. MRCP is a good tool for obtaining information about the bile ducts, but there is another problem: how to combine the CT angiography, as MRI is not appropriate for abdominal angiography[19-21].

AR navigation for liver segment identification

Beyond localizing lesions and avoiding vascular injury, precise liver segmentation is integral for oncologic resections[22]. Recently, fluorescence imaging with indocyanine green (ICG) has become ubiquitous for identifying tumor-bearing portal segments and facilitating anatomic dissection. Selective puncture of tumor-bearing portal branches (positive staining method) or pedicle ligation with illuminated remnants (negative staining method) enhances intra-operative liver segmentation, but procedures of both positive and negative staining sometimes present technical difficulty in laparoscopy[22,23]. Therefore, AR has shown early promise by compensating through projected portal mapping.

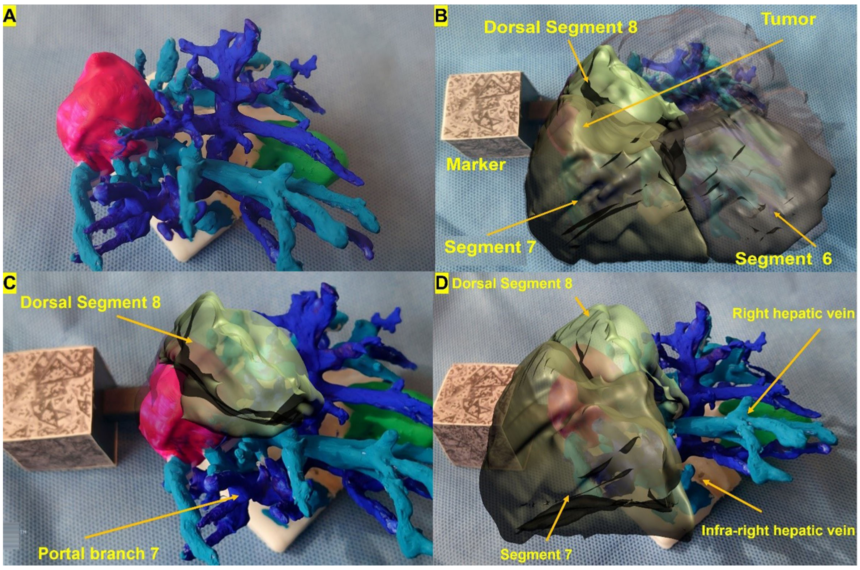

Figure 1. Three-dimensional printing combined with augmented reality. Three-dimensional portal vein, hepatic vein and relationship of liver tumor with intrahepatic anatomy with segmental mapping. (A) Portal vein, hepatic vein, tumor in right liver lobe; (B-D) liver portal segment with augmented reality of segments 6, 7, dorsal segment 8. Image courtesy of Kasai *et al*.[23].

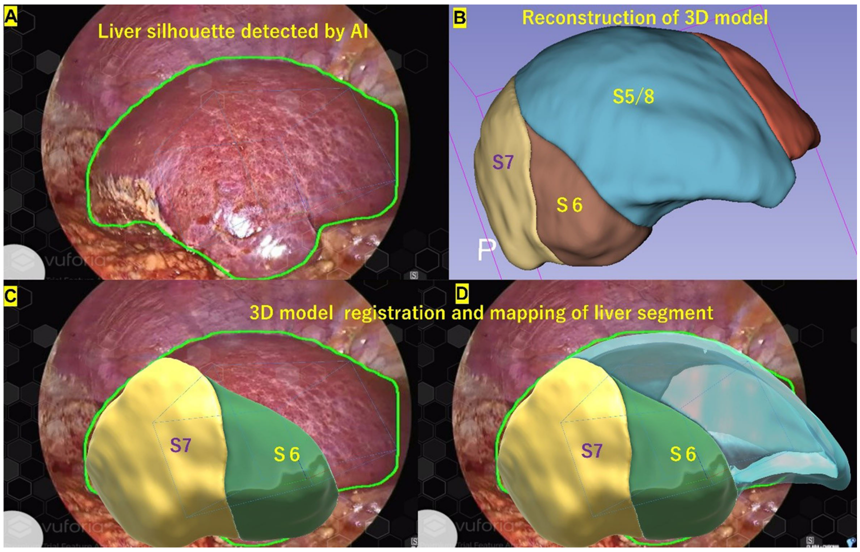

Figure 2. Laparoscopic segmental mapping with augmented reality with artificial intelligence. This figure shows the pipeline of our AI-assisted AR navigation system, illustrating the process from training the AI on liver images to displaying 3D models in augmented reality. (A) Liver silhouette induced by AI; (B) three-dimensional models of liver; (C and D) superimposition of 3D models in laparoscopic surgical videos. Image courtesy of Kasai *et al*.[24]. AI: Artificial intelligence; AR: augmented reality.

Kasai *et al*. devised a hybrid strategy consolidating 3D prints, AR projection, and real-time fluorescence for superimposed visible navigation[24] [Figure 1]. In further evolution, the incorporation of artificial intelligence (AI) markedly improved auto-registration accuracy over algorithms without AI[25] [Figure 2]. Furthermore, AI-based algorithms, such as those developed by Qin *et al*., significantly enhance the realism and accuracy of 3D models used in surgical simulations[26]. AI-assisted AR navigation systems are expected to advance alongside maturing imaging and graphics modalities, potentially matching the stability of expensive robotic platforms.

CONCLUSION

In summary, 3D printing and VR environments offer invaluable assistance for tackling the intricacies of liver surgery and transplantation. Early adopters have demonstrated enhanced anatomical appreciation, innovative educational opportunities, and improved outcomes from immersive preoperative simulation. However, despite technological maturation, continued quantitative clinical evidence is necessary before widespread adoption. Ultimately, realizing lasting benefits depends upon overcoming the financial and logistical barriers impeding dissemination into everyday practice. Further progress awaits definitive randomized data coupled with commercial development, which has the potential to expand access outside of specialized centers.

DECLARATIONS

Authors' contributions

Conceptualization, drafting of the manuscript, editing of the manuscript, technical support, administrative support: Kasai M

Editing of manuscript, administrative support: Aihara T, Yamanaka N

Availability of data and materials

Not applicable.

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Conflicts of interest

Kasai M is a Junior Editorial Board member of the journal *Artificial Intelligence Surgery*, while other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

None.

Consent for publication

Not applicable.

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