Current Status and Prospects of Three-dimensional Visualization in Precision Liver Resection

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Abstract: Three-dimensional (3D) reconstruction technology, as a vital component of digital medicine, has emerged as a powerful tool in the field of hepatic surgery, particularly in the context of precision liver resection. This review examines the current applications and future prospects of 3D reconstruction technology in hepatic surgery, with a focus on its clinical progress in preoperative assessment, vascular protection, surgical planning, and intraoperative navigation. By accurately calculating liver volume, evaluating liver function reserves, and optimizing surgical strategies, 3D reconstruction significantly enhances the safety and efficacy of liver resection. In terms of vascular protection, 3D reconstruction enables precise localization of tumors relative to vascular structures and identification of vascular variations, thereby reducing intraoperative bleeding risks. For surgical planning, the integration of 3D reconstruction with virtual reality (VR) and augmented reality (AR) technologies allows for the creation of virtual surgical scenarios, optimization of surgical pathways, and reduction of operative time. In intraoperative navigation, 3D reconstruction combined with laparoscopic ultrasound, indocyanine green (ICG) fluorescence imaging, 3D printing, and mixed reality (MR) technologies has enabled real-time navigation, thereby improving surgical precision. Despite these advancements, 3D reconstruction technology still faces challenges, including high costs, time-consuming processes, data quality limitations, and suboptimal reconstruction of intrahepatic bile ducts. Looking ahead, the incorporation of artificial intelligence and big data into 3D reconstruction is expected to further refine preoperative planning and intraoperative navigation, driving the field of hepatic surgery toward greater intelligence and precision.

Keywords: Liver Surgery; Three-dimensional Reconstruction Techniques; Precision Liver Resection; Preoperative Planning; Intraoperative Navigation; Personalized Treatment

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1 Introduction

Liver surgery is an important tool in the treatment of liver diseases, and its complexity and high-risk nature place extreme demands on surgeons. Liver anatomy is the theoretical basis of hepatic resection, and the development of liver segmentation plays a key role in this. 1654, Glisson first proposed the concept of hepatic vascular anatomy, defining the Glisson's sheath and liver segments. 1954, Couinaud proposed the classic eight-segmented

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approach to the liver, which is still widely used. 2010, Fasel discovered the complexity of portal vein branching by CT scanning, and proposed the "1-2-20 liver segments". In 2010, Fasel discovered the complexity of portal vein branches by CT scanning and proposed the concept of "1-2-20 liver segments", which further emphasized the simplicity of the eight-segment method. However, there are differences in liver segmentation methods in different regions: Goldsmith's segmentation method is often used in the United States, Couinaud's method is commonly used in Asia and Europe, and China uses five lobes and four segments or Couinaud's method according to the intrahepatic blood vessels and fissures [1]. These differences reflect the complexity and individualized characteristics of liver anatomy, and pose challenges for precision hepatectomy.

With the continuous progress of medical technology, the concept of hepatic resection has gradually evolved from the traditional eight-segment hepatic resection to anatomical hepatic resection, portal vein basin resection, and ultimately into the era of personalized precision hepatic resection. Precision hepatectomy combines digital medicine technology with preoperative assessment, surgical planning, minimally invasive operation and postoperative management, aiming to maximize the preservation of liver function and ensure the safety and efficacy of the operation. Among them, liver 3D reconstruction technology plays an important role [2]. First applied by Hashimoto et al. in 1990 to the reconstruction of liver blood vessels and tumors, 3D reconstruction technology constructs a three-dimensional model of the liver from CT or MRI data, which is able to visually display liver morphology and lesion characteristics [3]. Compared with traditional two-dimensional images, 3D reconstruction technology has higher precision, which can help surgeons make more accurate diagnosis and individualized treatment. In addition, 3D reconstruction technology can be used to calculate liver volume, simulate hepatic resection in combination with virtual reality technology, optimize surgical plans, and enhance the spatial imagination of doctors.

However, despite the significant progress in the application of 3D reconstruction technology in liver surgery, many challenges remain. For example, the 3D reconstruction process is time-consuming and costly, and problems such as data quality issues and poor intrahepatic bile duct reconstruction still need to be addressed. In addition, the problem of maintaining real-time accuracy due to intraoperative liver deformation is also a bottleneck of the current technology. Therefore, an in-depth discussion of the current status and prospects of the application of 3D reconstruction technology in liver surgery is of great significance in promoting the development of liver surgery in the direction of precision and intelligence. The aim of this review is to summarize the progress of the application of 3D reconstruction technology in preoperative assessment, vascular protection, surgical planning and intraoperative navigation of liver cancer, and to discuss the challenges and future development direction.

2 Progress in the Clinical Application of 3D Reconstruction

2.1 Assessment of Liver Volume

Studies have shown that a normal liver can tolerate resection by 70%, but the amount of resection tolerated decreases in the presence of liver parenchymal damage. Post-hepatic resection liver failure (PHLF) is the most serious complication, and Wu Wenming's study showed that the incidence of postoperative liver failure in patients with cirrhosis and hepatocellular carcinoma was 15.19% [4]. Preoperative assessment of liver reserve function is essential to minimize the occurrence of PHLF. Commonly used assessment methods include biochemical tests, comprehensive scoring systems (e.g., Child-Pugh, MELD, ALBI), dynamic liver function tests (e.g., ICG metabolism assay, nuclide tests), and imaging, although each has its own advantages and disadvantages, and there is no comprehensive and accurate assessment method [5, 6].

The standardized liver volume concept was initially used to evaluate living donors for liver transplantation, reflecting the metabolic requirements of the liver and liver function. The main calculation formulas applicable to Chinese patients are the Hong Kong Sheung Tat formula and the West China Hospital formula, and are significantly correlated with body weight. In 1979, Heymsfield [7] et al. assessed liver volume using CT images, and in 2001, Wigmore et al. validated this method for use in liver resection and found that preoperatively assessed resection volume significantly correlated with actual resection volume.

The determination of a safe minimum residual liver volume is influenced by a variety of factors [8], such as hepatic sclerosis, steatosis, serum bilirubin level, intraoperative blood loss, hepatic blood flow occlusion time, and hepatic venous return, so it cannot be solely relied on standardized delineation. Three-dimensional liver reconstruction technology can accurately simulate liver resection, quantify the ratio of resection volume to residual liver volume, assess surgical feasibility and safety, and optimize surgical protocols by the ratio of functional liver volume to standard liver volume. Studies have shown that the 3D reconstruction technique can shorten surgical time, reduce intraoperative bleeding and blood transfusion, decrease the rate of liver failure, and prolong survival. The study by Liu Yu et al. confirmed the advantages of this technique, especially in the case of larger tumors, deeper locations, severe cirrhosis, or proximity to large blood vessels [9, 10]. In contrast, for cases with small tumors and superficial location, a simple assessment method is sufficient.

2.2 Vascular Protection

Intraoperative uncontrolled bleeding in hepatic resection is the main reason for intermediate openings and is closely related to postoperative recovery, emphasizing the importance of intraoperative vascular protection. The hepatic vasculature is complex and variable, and studies have shown that there are individualized differences in hepatic segmentation, which may not fully comply with the Couinaud segmentation criteria. For example, Xie Yu et al. found that about 30% of the right posterior lobe could not be completely divided into segment VII and VI. Three-dimensional reconstruction technology can accurately locate liver tumors and their relationship with adjacent vasculature by rotating and zooming, providing intuitive anatomical information about the vasculature. The 3D reconstruction analysis of 1,665 primary liver cancer patients conducted by Fang Chihua's team showed that there are many variations of the hepatic artery, hepatic vein and portal vein, some of which are favorable for surgery, while others increase the risk of surgery. For example, when the left branch of the portal vein originates from the right anterior branch, right hemihepatectomy will lead to serious consequences; if the main trunk of the portal vein sends out the right posterior branch, and then divides into right anterior and left branches upward (type II variation), then resection of the right anterior and left branches will lead to serious consequences [11]. If the main portal vein trunk emanates first from the right posterior branch and divides upward into the right anterior and left branches (type II variant), it is easier to resect the right posterior lobe. The control of hepatic venous flow is an important factor in the success of liver surgery, and hepatic venous variations are typed to maximize intraoperative preservation of normal liver tissue. The typing of hepatic vein variations in the right posterior inferior hepatic vein, segment IV hepatic vein, and segment VIII hepatic vein is more valuable for decision making in liver surgery. For example, the presence of a relatively large right posterior inferior hepatic vein makes anatomic combined resection of segments VII and VIII possible [12]. However, these variants are very easy to misdiagnose without careful preoperative radiographic review. In response to the requirement of precise anatomical hepatic resection, 3D reconstruction of the liver provides individualized hepatic anatomy and preoperative knowledge of possible vascular variations, which greatly reduces surgical risk.

In deep and complex liver tumor surgery, the difficulty and risk of surgery is higher due to the involvement of multiple large blood vessels and bile ducts, which requires even more precise preoperative assessment. 3D reconstruction technology can identify the spatial relationship between tumors and important vessels, assess their impact, help select the appropriate resection range, and, combined with preoperative rehearsal, reduce collateral injuries and surgical uncertainty, thus shortening surgical time and improving treatment outcomes.

2.3 Surgical Planning

3D reconstruction-based VR technology can create virtual surgical scenarios and pre-operative interaction with the virtual space via head-mounted devices to help physicians design optimal puncture sites and surgical pathways, thereby improving surgical safety, shortening operative time, enhancing team collaboration, and accelerating the learning process for young physicians [13]. In addition to basic dimensional, angular, and volumetric measurements, 3D reconstruction technology enables advanced analysis based on 2D image data, such as assessment of portal and hepatic vein basins. Currently, many 3D reconstruction software have implemented automated surgical planning techniques, whereby preoperative identification of the rhabdomyolitic portal vein basin by basin analysis is performed with precise planning, and intraoperative navigation with indocyanine green fluorescent staining is combined to accomplish precise resection of the rhabdomyolitic portal vein or Glisson system.

Studies have shown that the Glisson hepatic segmentation system can reach 3 or even 4 levels (subsegmental hepatic segments), and the cone unit corresponding to level 4 is the smallest anatomical unit in current liver surgery techniques. With the aid of 3D reconstruction and basin analysis, precise anatomical hepatic resection is theoretically possible. The complete resection of the portal vein/glisson system of the loaded tumor provides a better oncological benefit, but precise hepatic resection requires maximum preservation of the functionally reserved residual liver volume (FLR), so the role of the hepatic vein should not be ignored during the actual intraoperative operation. Commonly used identification techniques include extrahepatic marking of the hepatic veins, indocyanine green fluorescence-guided visualization of representative hepatic veins at the interface of the isolated liver, and intrahepatic hepatic veins visualized by preoperative three-dimensional reconstruction. It can also be combined with hepatic vein basin analysis techniques to assess areas of hepatic venous return.

Sampogna et al. showed that intraoperative bleeding and operative time were significantly reduced in patients with hepatocellular carcinoma who underwent preoperative VR simulation [14]. Preoperative VR simulation can be used to understand the possible intraoperative risk vessels, to make advance plans, to enhance surgical confidence, to accelerate the growth of young doctors, to enhance the team tacit understanding through repeated simulation and practice of the team to plan the surgical procedure, and to enhance the surgical safety and improve the efficiency of the operation, which will help the patients to benefit from the comprehensive benefits.

2.4 Real-time Intraoperative Navigation

With the rapid development of medical science and technology, three-dimensional reconstruction techniques have demonstrated significant advantages in preoperative evaluation and planning. However, the lack of fixed anatomical landmarks on the surface of the liver, coupled with intraoperative positional changes, abdominal pressure fluctuations, and liver deformations, have resulted in temporal and spatial discrepancies between preoperative 3D reconstructed images and laparoscopic views during actual surgery. More and more physicians are focusing on ways to minimize the impact of these discrepancies. With emerging technologies such as laparoscopic ultrasound (LUS), indocyanine green molecular fluorescence imaging, 3D printing, mixed reality (MR), virtual reality (VR), and augmented reality (AR), the discrepancy between the 3D reconstructed model and the actual operation can be further minimized, which truly realizes real-time intraoperative navigation and ensures real-time and accurate surgery. These technologies show great potential and broad prospects in the application of liver surgery.

2.4.1 Laparoscopic Ultrasonography

Traditional two-dimensional intraoperative navigation relies heavily on laparoscopic ultrasound (LUS), which allows real-time assessment of liver tissue, lesion location, boundaries, and relationship to vasculature, overcoming the lack of haptic feedback in laparoscopic surgery and guiding R0 resection of liver segments. Wang Danpu et al. combined preoperative 3D reconstruction with LUS for anatomical liver resection and found that this method significantly reduced operation time [15], bleeding and hospital stay, and improved radical resection rate and tumor-free survival rate. With the development of technology, ultrasound techniques have gradually evolved to include continuous ultrasound (CEUS) and 3-D ultrasound. Lou Liping et al. used SonoVue ultrasound contrast agent and mixed reality (MR) to further clarify the relationship of the lesion to the hepatic vein and hilum, and to help determine the plane of dissection [16]. Liu Jinqiao et al. used three-dimensional reconstruction and ultrasound in combination for hepatic resection in children [17], significantly reducing intraoperative bleeding and improving surgical safety.

2.4.2 Indocyanine Green Fluorescent Staining and Visualisation Technique

Laparoscopic ultrasound provides real-time intraoperative navigation, but navigation is limited and experienced surgeons can still get "lost" during liver resection. Indocyanine green (ICG) is a fluorescent dye that was approved by the FDA in the 1950s and is widely used in human studies because of its stable fluorescent properties [18]. ICG is absorbed by the liver and excreted through the biliary tract after injection, is not affected by renal metabolism, and is non-toxic to humans. The maximum penetration depth of excited near-infrared fluorescence is about 10 mm, which is suitable for precise localization of subperitoneal liver tumors, and can identify more than 99% of malignant lesions located in the superficial layer of the liver [19]. The effect of "forward staining" or "backstaining" of ICG is helpful for fluorescent labeling and precise resection of liver tumors under laparoscopy. The "positive staining" or "reverse staining" effect of ICG is helpful for laparoscopic fluorescent labeling and precise resection of liver tumors [20]. Du Bo et al. showed that laparoscopic hepatectomy with CEUS and ICG fluorescence staining can reduce the difficulty of surgery and postoperative liver function impairment compared with conventional methods [21].

2.4.3 3D Printing Technology

The use of 3D printing in liver cancer surgery was first reported in 2013 by Zeijn et al [22]. The main advantage of 3D printed models is that they can be brought directly into the operating room and compared with the real liver during surgery, thus adjusting the optimal anatomical position for identifying intrahepatic ductal structures [23]. For complex liver surgeries requiring revascularization, the greatest advantage of 3D printing is the ability to visualize critical areas in three dimensions, predict the length of resection required for vascular infiltration, and develop a reconstruction plan accordingly [24].

2.4.4 Augmented Reality

Augmented reality (AR) is an advanced technology that combines computer-generated virtual images with the real world. Users are able to accurately align themselves with the real environment based on preoperatively reconstructed 3D models. The core of the AR surgical navigation system consists of two main technologies: tracking and display. Tracking technologies include mechanical, optical, ultrasound, electromagnetic, and hybrid tracking, while display technologies cover video, stereoscopic, and projection displays.

Among the many tracking technologies, optical trackers are the most widely used, and despite its problems in distortion and calibration, its millimeter-level high accuracy is still advantageous. Other tracking technologies can suffer significant degradation in accuracy due to the operating environment. Therefore, hybrid tracking methods combining multiple techniques are considered to be an important development direction in the future, which can not only make up for their respective shortcomings, but also achieve faster speed and higher computational accuracy while supporting multi-target recognition [25]. For example, Ma et al. developed a novel 3D AR navigation system that combines optical and electromagnetic tracking techniques to identify and correct any deviations in time during long bone stem fracture surgeries using intramedullary nails [26], thereby reducing the risk of screw placement errors, shortening the surgical time, and improving surgical safety.

AR surgical navigation systems enhance the surgical field of view by increasing the virtual transparency of the patient's lesion and surrounding tissues. Video display technology is currently the most commonly used display method, which has the advantage of high image quality and precise positional overlays. However, it also results in the need for the surgeon to frequently switch between the monitor and the surgical site, which can lead to incoherence and visual fatigue. Projection display technology, on the other hand, uses a projector to project the reconstructed image directly into the surgical field of view, which reduces the need to carry equipment and improves surgeon productivity, although it requires the tracking and alignment of multiple anatomical structures, and the projected image is two-dimensional, which may affect depth perception. Stereoscopic display technology focuses more on improving immersion and hand-eye coordination, using a translucent screen or head-mounted display (HMD) to show a three-dimensional scene in real time, enhancing the safety and accuracy of surgery, but prolonged wear may lead to visual fatigue. HMD is a translucent screen shrinkage and micro-computer integrated in the helmet of the lightweight smart devices, the more popular Hololens is the representative product of this technology. HMD is a lightweight smart device that integrates a semi-transparent screen and a miniature computer into a helmet.

AR surgical navigation technology has been applied in neurosurgery, orthopedics, urology and thoracic cardiothoracic surgery, assisting surgeons in pre-operative planning and intra-operative anatomical visualization, thereby improving surgical efficiency and safety [27]. BriceGayet's team uses augmented reality technology to fuse virtual images and intraoperative images into one augmented reality image, which is displayed on a newly added display screen to achieve real-time intraoperative navigation [28].

Currently, AR navigation systems in clinical applications still face challenges such as alignment accuracy and soft tissue deformation, which affect navigation accuracy. To address these issues, researchers have proposed solutions such as secondary alignment and real-time tracking. Kingham et al. used a laser ranging scanner aligned with a preoperative 3D model [29], which was successfully applied to open hepatectomy, but lacked direct visual support under laparoscopy, which is expected to be improved by a probe-aligned navigation system. Teatini et al. investigated intraoperative imaging to improve navigation accuracy [30], which significantly reduced errors compared to traditional alignment techniques. techniques, significantly reducing errors. Pelanis et al. [31] proposed a real-time alignment scheme based on a robotic C-arm capable of updating the liver position and overlaying augmented reality laparoscopically to provide high accuracy within 5 mm. However, the stability and effectiveness of this system still need to be clinically validated.

2.4.5 Multi-modal Image Fusion

Yang Jian et al. constructed a three-dimensional model of the liver through image fusion technology to achieve accurate preoperative planning, and combined indocyanine green (ICG) molecular fluorescence imaging with augmented reality navigation to accurately display hepatobiliary cholangiocarcinoma foci and their relationship with blood vessels, perform individualized liver segmentation and resection volume prediction, optimize hepatic resection surgical strategies, and enhance surgical safety through multimodal imaging technology. Haisu Tao et al. Successfully realized laparoscopic S8 resection by using self-developed augmented reality navigation technology and preoperative 3D reconstruction, combined with intraoperative ultrasound and virtual hepatic segmentation projection to accurately identify the hepatic resection plane and reduce bleeding. Peng Zhang et al. improved the identification of hepatic resection margins and tumor boundaries through 3D reconstruction and intraoperative fluorescence imaging, while ZhiMing Zhao et al. applied 3D reconstruction and real-time image fusion navigation in complex hepatic encapsulation surgery, which improved surgical safety. With the development of digital intelligent technology, the application of 3D reconstruction, fluorescence guidance and multimodal image navigation in hepatic surgery has been expanding, which promotes the precision and intelligence of hepatobiliary and pancreatic surgery. In the future, the development of hepatobiliary and pancreatic intelligent surgical systems with image fusion, intelligent planning and automatic navigation functions, and the solution of technical problems such as non-rigid alignment, will bring new opportunities for hepatobiliary and pancreatic surgery.

3 Existing Problems

With the advancement of digital intelligence in the medical field, 3D visualization technology has shown remarkable potential in the diagnosis and treatment of liver cancer. However, 3D liver reconstruction technology still faces some challenges: (1) high cost and time-consuming, the reconstruction process usually takes more than 4 hours and costs more than $2,000; (2) data quality issues, such as CT/MRI raw data and image conversion errors, may affect the reconstruction accuracy; (3) poor bile duct reconstruction, especially undilated intrahepatic bile ducts; and (4) complexity of evaluation, the liver volume and postoperative liver function The relationship between liver volume and the risk of postoperative liver failure is nonlinear and requires more metrics for comprehensive evaluation. Despite the improvement of volume measurement and margin accuracy, intraoperative navigation still faces difficulties, as breathing, heartbeat and other factors lead to liver deformation, which is difficult to meet the needs of existing alignment techniques [32]. In the future, the accuracy can be improved by increasing the number of marker points and improving the software with intraoperative modeling. In addition, the problem of hierarchical occlusion in intraoperative navigation still needs to be solved, and research should focus on optimizing image processing technology, imaging equipment, and visualization system [33-35].

4 Conclusion

With the development of the surgical field towards precise anatomy and personalization, 3D reconstruction techniques show great potential and are expected to be continuously improved with the advancement of digital medicine, providing a new impetus for surgical treatment. The core of precise anatomical hepatectomy includes preoperative assessment, planning, intraoperative operation, and postoperative management, in which 3D visualization technology, especially in the preoperative planning and residual liver volume assessment of laparoscopic hepatectomy, has been more maturely applied. Studies have shown that this technique can improve lesion resectability and reduce the risk of postoperative hepatic failure, but most studies are retrospective and lack a control group, so evidence of its benefit to patients is still limited and more large-scale randomized controlled studies are needed to validate it. As technology and data analysis capabilities improve, 3D reconstruction will combine artificial intelligence and big data to further optimize preoperative planning, real-time navigation, and improve surgical precision and safety, thereby improving patient outcomes and quality of life.

Consent for Publication

Consent for publication was obtained from all authors.

Conflict of Competing Interest

The authors declared that there is no conflict of interest.

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