

Augmented Reality Integration for Surgical Enhancement in Hepatic Surgery – Review of the Current Literature

David Andraș^{1,2}, Radu Alexandru Ilieș^{3*}, Alexandru Ilie-Ene^{1,2}, Victor Eșanu^{1,2}, Vasile Bințințan^{1,2}, George Dindelegan^{1,2}

¹1st Surgical Clinic, Department of General Surgery, Iuliu Hațieganu University of Medicine and Pharmacy, Cluj-Napoca, Romania

²Emergency County Hospital Cluj, First Surgical Unit, Cluj-Napoca, Romania

³Faculty of Medicine, Iuliu Hațieganu University of Medicine and Pharmacy, Cluj-Napoca, Romania

*Corresponding author:

Radu Alexandru Ilieș, MD
Victor Babeș Street, No 8
Iuliu Hațieganu University of
Medicine and Pharmacy Cluj
Faculty of Medicine
E-mail: iliesradu.14@gmail.com

Abbreviations:

CT: Computed tomography;
MRI: Magnetic resonance imaging;
US: Ultrasound;
ICG: Indocyanine green;
IGS: Image-guided surgery;
AR: Augmented reality;
MILS: Minimally invasive liver surgery;
LUS: Laparoscopic ultrasound;
EM: Electromagnetic;
ICU: Intensive care unit;
ELUS: EM-tracked laparoscopic
ultrasound;
LARN: Laparoscopic AR navigation;
LAH: Laparoscopic anatomical
hepatectomy;
PLC: Primary liver cancer;
IN: Intraoperative navigation;
NIN: Non-intraoperative navigation;
GOALS: Global Operative Assessment
of Laparoscopic Skills Score;
OSATS: Objective Structured
Assessment of Technical Skill.

Rezumat

Integrarea realității augmentate pentru îmbunătățirea intervențiilor chirurgicale hepatice – review al literaturii de specialitate actuale

Context: Anatomia intrahepatică rămâne o provocare în chirurgia hepatică mini-invazivă. Realitatea augmentată (AR), care integrează informațiile digitale cu mediul utilizatorului, poate aduce multiple beneficii în chirurgia hepatică, îmbunătățind poziționarea tumorilor și a vaselor, planificarea rezecțiilor și formarea chirurgilor. Această revizuire subliniază aplicațiile AR în chirurgia hepatică.

Metode: Articolele publicate între 2010-2024 pe PubMed, folosind cuvintele cheie („Realitate Augmentată” ȘI „Chirurgie Hepatică”) SAU („Navigație” ȘI „Chirurgie Hepatică”) au fost analizate. Au fost incluse 32 de articole care evaluează acuratețea, siguranța, timpul operator și impactul asupra formării chirurgilor.

Rezultate: AR în chirurgia ghidată de imagini (IGS) combină reconstrucțiile 3D (de exemplu, CT) cu imagini laparoscopice, îmbunătățind înțelegerea locului chirurgical. AR ajută la planificarea marginilor rezecției, stabilirea limitelor leziunilor și realizarea hemostazei precise. Arhitectura AR îmbunătățește rezultatele oncologice, reduce erorile, crește acuratețea și uneori scurtează timpul operator. De asemenea, AR îmbunătățește procesul de formare a chirurgilor prin accelerarea dobândirii de noi abilități și reducerea curbei de învățare. Totuși, sunt necesare mai multe date pentru standardizarea tehnicilor AR.

Concluzie: AR poate îmbunătăți semnificativ chirurgia hepatică mini-invazivă prin sporirea preciziei, siguranței, eficienței și formării. Deși sunt necesare cercetări suplimentare pentru standardizarea tehnicilor, AR are un potențial mare pentru îmbunătățirea rezultatelor chirurgicale și calității formării.

Cuvinte cheie: realitate augmentată, chirurgie hepatică, navigație chirurgicală, imagistică intraoperatorie

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Abstract

Background: Intrahepatic anatomy remains a challenge in mini-invasive liver surgery. Augmented Reality (AR), which integrates digital information with the user's environment, can benefit liver surgery by improving tumor and vessel positioning, resection planning, and surgical training. This review highlights AR's applications in liver surgery.

Methods: Articles published from 2010-2024 on PubMed using keywords ("Augmented Reality" AND "Liver Surgery") OR ("Navigation" AND "Liver Surgery") were analyzed. 32 articles assessing AR's accuracy, safety, operative time, and training impact were included.

Results: AR in Image-Guided Surgery (IGS) combines 3D reconstructions (e.g., CT scans) with laparoscopic images, enhancing the understanding of the surgical site. AR aids in margin planning, lesion boundary setting, and accurate hemostasis. It improves oncological outcomes, reduces errors, increases accuracy, and sometimes shortens surgery time. AR also enhances surgical training by accelerating skill acquisition and reducing the learning curve. However, more data is needed to standardize AR techniques.

Conclusion: AR can significantly enhance mini-invasive liver surgery by improving precision, safety, efficiency, and training. While further research is necessary to standardize techniques, AR holds great potential for improving surgical outcomes and training quality.

Keywords: augmented reality, hepatic surgery, surgical navigation, intraoperative imaging

Introduction

General Overview of Modern Liver Surgery

Modern hepatic surgery faces challenges due to the limited accuracy in determining the position of intrahepatic structures, which often relies heavily on the surgical team's experience. Precise localization of liver vasculature is essential to minimize blood loss and prevent ischemic complications, yet no standardized algorithm exists to validate surgical techniques. Preoperative imaging, such as CT or MRI, provides critical information about tumors and intrahepatic structures, but intraoperative imaging, such as ultrasound or indocyanine green (ICG)-guided systems, offers real-time vessel localization. However, these methods require additional hardware and attention to multiple screens, complicating workflow (1,2).

Surgical resection is the main treatment for hepatic tumors, offering superior survival outcomes, but fewer than 50% of patients are eligible due to strict guidelines. A thorough understanding of Couinaud and Bismuth's segmental hepatic anatomy is crucial for procedures like tumor resections and living donor transplants. Recent advances in 3D visualization technologies have significantly improved spatial understanding, surgical planning, and precision, overcoming the limitations of traditional 2D imaging (3).

Current Limitations of Minimally Invasive Liver Surgery

The complexity of liver anatomy complicates intraoperative recognition. Each arterial and venous branch of the portal pedicle must be identified during surgery to prevent excessive bleeding. Minimally Invasive Liver Surgery (MILS), which includes laparoscopic and robotic procedures, is evolving with innovative techniques that are less invasive while integrating intraoperative imaging (1). However, MILS has drawbacks, such as instrument rigidity, limiting mobility and the operating field, and poor exposure in case of bleeding. In robotic surgery, the lack of tactile sensation (haptic feedback) can confuse the surgeon, potentially causing tissue damage. Additionally, these interventions may take longer due to slow, careful movements needed to protect the parenchyma and vascular structures (2,4).

What is Augmented Reality and How Can it Change Liver Surgery?

Augmented Reality (AR) integrates digital information with the user's environment, creating superimposed images that offer a new perspective (4). In surgery, AR systems like Laparoscopic and Robotic Augmented Reality Navigation enhance the localization of vessels and tumors, aiding complex procedures (1,4). These systems simplify liver anatomy, assist in preoperative planning,

visualize vessels during transection, and project virtual liver images onto the skin surface (1,5).

This technology might be life-changing for training in MILS, simplifying the whole process. It may reduce the learning curve in liver surgery, while still maintaining the same results in new skill acquisition (4). AR systems in surgery integrate engineering and medical technologies, using specialized software to overlay images on a single screen. Key steps involve hand-eye calibration with an optical tracking system, point-based registration to align CT/MRI scans with the liver's position on the surgical table, and re-projecting 3D volumes into single-plane images using algorithms for precise alignment (6,7). AR addresses challenges faced by surgeons who rely on distant screens for pre-operative data by directly overlaying imaging onto laparoscopic views, enhancing precision in various surgical fields, including hepatobiliary and gynecological procedures (8).

Mini-invasive AR systems involve superposition of laparoscopic camera images with the one obtained using imaging techniques, such as CT/MRI scan or even ultrasonography. One version of this system requires interconnection of four main components in echo-guided surgery with Augmented Reality (which can be called echo-augmented surgery): a standard laparoscopic system, a LUS scanner, an EM generator (EM tracking system) and a laptop computer that ensures fusion of the images (8).

Preoperative imaging and 3D rendering are used to assess liver parenchymal anatomy and variations, allowing the surgical team to identify

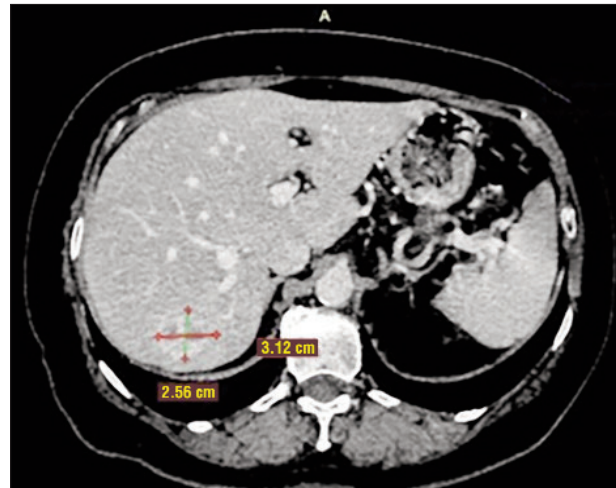


Figure 1. Axial contrast-enhanced CT scan of the abdomen showing a round, hypodense hepatic lesion located in segment VII. The lesion measures approximately 3.12 × 2.56 cm and demonstrates contrast enhancement characteristics suggestive of a metastatic deposit.

stereoscopic relationships between intrahepatic structures and tumors, and to calculate volumes for resection plans (3). To develop the augmented reality (AR) system used during the hepato-biliary surgical intervention, our clinical team followed a structured workflow based on preoperative imaging and advanced 3D reconstruction technologies. First, a contrast-enhanced computed tomography (CT) scan was performed (*Fig. 1*). Using this imaging data, 3D volume-rendered reconstructions were generated to visualize the lesion's spatial relationships within the liver from both axial and coronal perspectives (*Fig. 2 A, B*). These reconstructions

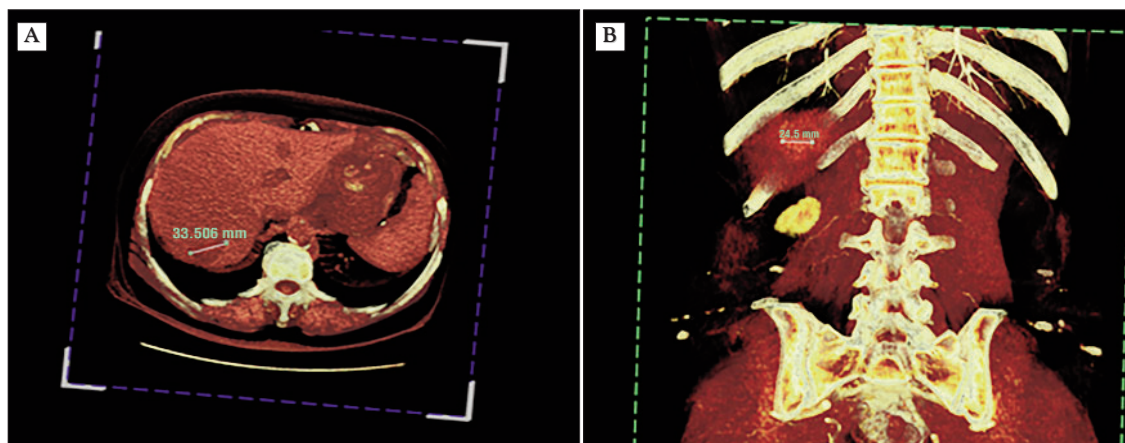


Figure 2. 3D volume-rendered reconstructions from preoperative contrast-enhanced CT imaging: (A) Axial view of the liver with volumetric rendering, highlighting a 33.5 mm lesion located in segment VII of the liver. The tumor appears hypodense and well-circumscribed, consistent with metastatic disease; (B) Coronal 3D reconstruction displaying the spatial relationship between the hepatic lesion and surrounding anatomical structures. The lesion, measuring approximately 24.5 mm in this plane, is positioned in proximity to the posterior ribs and vertebral column.

were then processed with CarnaLife® Holo software to create an interactive 3D model that included the tumor, liver parenchyma, hepatic venous system, and arterial branches (*Fig. 3*). This model was uploaded into the Microsoft HoloLens 2 headset, allowing for intraoperative visualization and navigation. During surgery, the 3D holographic projection was superimposed onto the operative field, enhancing the surgeon's spatial awareness and aiding in precise resection planning (*Fig. 4 A, B*). This process reflects our clinic's practical experience in integrating AR technology into complex hepatic procedures.

Intraoperative ultrasound in robotic surgery enhances tumor identification, guides parenchymal resection, and clarifies spatial relationships (1). US-guided robotic surgery, similar to laparoscopic US-guided AR systems, shows promise in surgical and oncological contexts (5). However, the high cost of this technology remains a disadvantage in new-era Image-Guided Surgery (IGS) (9).

All AR systems have some degree of misalignment between the overlay and the visible anatomy, so the surgeon must remain responsible for interpreting potential errors. To support this, we implemented advanced visualization algorithms

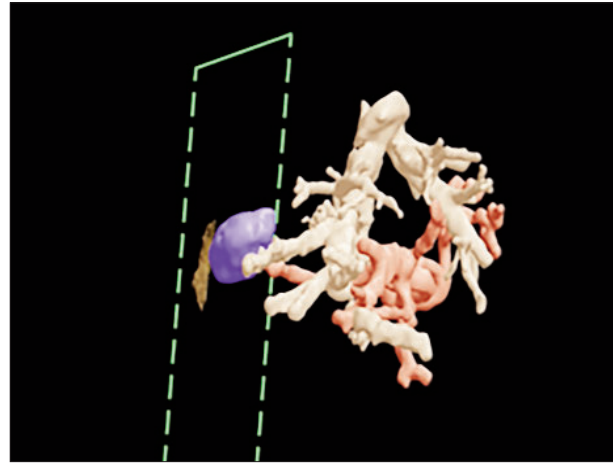


Figure 3. 3D reconstruction generated from the preoperative CT scan using CarnaLife® Holo software. The tumor (blue), liver parenchyma (brown), hepatic venous system (beige), and hepatic arterial branches (pink) are visualized in spatial relationship, highlighting the anatomical complexity. This model was used intraoperatively with the Microsoft HoloLens 2 headset to aid in precise surgical navigation and margin planning.

and included a projected 2D liver outline to help assess overlay accuracy (10).

Image-to-patient registration represents a tech-

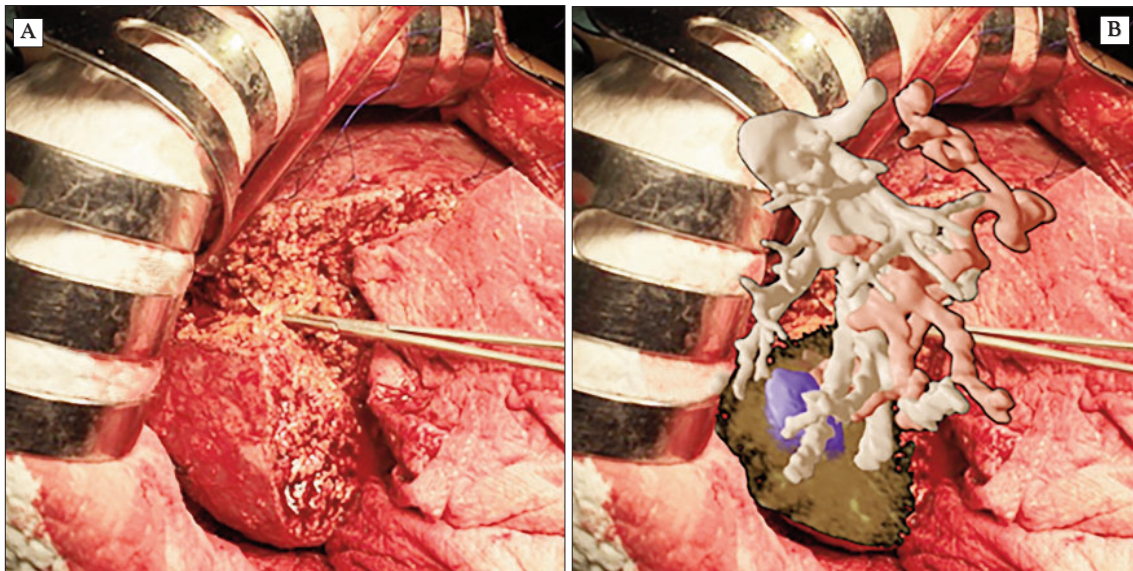


Figure 4. Intraoperative view of hepatic segmentectomy with augmented reality overlay: **(A)** Intraoperative photograph showing the surgical field during resection of the hepatic segment VII. The hepatic parenchyma is being dissected and mobilized under direct vision, aided by intraoperative ultrasonography.; **(B)** The same intraoperative image enhanced with an augmented reality overlay. The 3D reconstruction, generated preoperatively using CarnaLife® Holo software and visualized via Microsoft HoloLens 2, is superimposed on the surgical field. The vasculature and the tumor are shown in their anatomical positions relative to the liver tissue, improving spatial orientation during the resection.

nique that aims to align preoperative volumetric CT/MRI datasets with the configuration of the patient's liver during surgery. Two common methods for this process are available, respectively Point-Based Registration (PBR) and single landmark registration. Both approaches involve matching corresponding positions between coordinate systems (7).

This review aims to highlight the applications and benefits of AR in modern liver surgery, focusing on its role in establishing precise intra-hepatic anatomy. It explores AR's potential to improve accuracy in identifying vessels and tumors, facilitate surgical resection, enhance safety and efficiency, reduce intraoperative errors, shorten operative time, improve oncological outcomes, and additionally, to optimize the training of young surgeons by accelerating skill acquisition and shortening the learning curve. However, the need for standardized techniques and further research is essential to fully integrate AR into routine liver surgery practice.

Materials and Methods

A literature search was conducted using the PubMed database to explore the development and application of augmented reality and navigation systems in liver surgery over the period 2010–2024. The search strategy employed the following keywords: (“Augmented Reality” AND “Liver Surgery”) OR (“Navigation” AND “Liver Surgery”). Filters were applied to include only articles available as Free Full Text or Full Text.

The initial query retrieved a total of 223 articles. Each title and abstract was screened manually to assess relevance. Articles were included if they addressed liver surgery in the context of AR or surgical navigation technologies. Studies not directly related to liver surgery or lacking technological integration were excluded.

Following this screening process, 32 articles were deemed eligible for full analysis. These included a range of study types, such as original research on human subjects, animal model investigations, experimental studies using surgical phantoms, and comprehensive review articles. The diversity in methodology across these studies reflects the progressive evolution of AR and navigation technologies from experimental stages to integration in clinical practice.

The selected literature highlights various aspects of AR use in liver surgery, including technical feasibility, surgical accuracy, intraoperative

orientation, and potential to improve outcomes. Review articles within the selection offered valuable insights into the current state of the field, as well as future challenges and opportunities. Overall, the analysis provides a comprehensive overview of the role and development of AR and navigation systems as innovative tools in modern hepatobiliary surgery.

Results

For our review, we used an integrated approach, categorizing each study into multiple sections based on the utility of AR systems in liver surgery. Each article was organized in a table according to its main outcomes. *Table 1* presents a structured overview by domain and subsection, outlining the reported benefits of AR technologies. *Table 1* represents each article by domain and subsection, outlining the benefits of AR systems in liver surgery. These include improved oncological outcomes, increased safety and accuracy, reduced operative time, enhanced visualization, data integration, and enhanced surgical training. This method provides a clear overview of AR's transformative potential in modern hepatic surgery.

Accuracy, Safety, Oncological Outcomes and Enhanced Visualization

Teatini et al. assessed the accuracy of point-based registration (PBR) for AR in laparoscopic liver resection. The PBR algorithm was tested to link CT/MRI coordinates with the patient's position on the surgical table across three scenarios: machined phantom, patient-specific phantom, and in vivo (with surgeon-annotated landmarks). The target registration error averaged 6.9 mm for the machined phantom, 7.9 mm for the patient-specific phantom, and 13.4 mm in vivo. The study concluded that AR's accuracy is highly sensitive to target sampling, with larger volumes increasing registration errors (7).

A dynamic EM-tracked laparoscopic ultrasound (ELUS) navigation system for liver tumor ablation is described in a study described by Paolucci et al. When compared to conventional laparoscopic ultrasound, ELUS provided more accurate positioning (target position error of 4.2 mm vs. 6 mm) and faster targeting (39 s vs. 76 s). ELUS also eliminated probe repositioning. This system was found useful, providing a more precise and efficient approach for performing laparoscopic hepatic tumor ablation. (9)

Table 1. The full list of articles which are used for this review and their conclusion towards the benefits of using AR system in hepatic surgery.

No.	Author, Article	Superior oncological outcomes	Increasing safety and accuracy	Better view of anatomical structures	Less operative time	Upgrading training in surgery
1	Ahmed et al.		✓	✓	✓	
2	Balci et al.			✓		
3	Banz et al.		✓	✓		✓
4	Bijlstra et al.		✓	✓		
5	Correia et al.	✓	✓		✓	
6	Freudenthal et al.		✓	✓		✓
7	Gavaghan et al.		✓	✓		
8	Giannone et al.	✓		✓		✓
9	Golse et al.		✓	✓	✓	
10	Huber et al.			✓		
11	Ivashchenko et al.		✓	✓		
12	Kasai et al.		✓	✓		✓
13	Kleemann et al.		✓			
14	Kratzke et al.		✓	✓	✓	✓
15	Kuroda et al.	✓		✓		
16	Lau et al.	✓	✓	✓		✓
17	Luo et al.		✓	✓		
18	Paolucci et al.	✓	✓	✓		
19	Ramalhinho et al.		✓	✓		✓
20	Ratti et al.	✓	✓	✓		✓
21	Ribeiro et al.		✓	✓		
22	Robu et al.		✓			
23	Saito et al.			✓		
24	Smit et al.		✓	✓	✓	
25	Soler et al.				✓	
26	Teatini et al. (1)		✓	✓		
27	Teatini et al. (2)		✓			
28	Thompson et al.		✓	✓		
29	Van den Bosch et al.		✓		✓	
30	Wang et al.	✓	✓	✓	✓	✓
31	Wild et al.			✓	✓	✓
32	Zhang et al.		✓	✓		✓

One study analyzed a cohort of 65 patients who underwent image-guided liver surgery, divided into three groups - resection (38 cases), ablation (11 cases), and combined resection and ablation (16 cases). Over time, as the accuracy of the AR system improved from 8.4 ± 4.4 mm in phase I to 4.5 ± 3.6 mm in phase III, which resulted in an expansion of image guidance. It was further applied for performing atypical liver resections and even combined procedures, leading to replacement of formal resections ($p < 0.0001$). These results state that an improved accuracy enables various applications, improving the treatment of previously challenging cases (such as multiple, small, bilobar, lesions). (11)

A prospective randomized-controlled pilot trial evaluated computer-assisted 3D navigation in liver surgery on 16 patients with 20 tumors. Eight

tumors were resected with the navigation system, while the others underwent standard surgery. No significant differences were found between groups regarding resection margin, operative time, complications, hospital stay, or resection volume ratios. Although the navigation system was feasible, its accuracy did not surpass that of conventional methods (12).

Artificial Intelligence-assisted AR system for laparoscopic liver surgery which is able to integrate preoperative 3D models with real-time surgical images is presented in a study by Kasai et al. AI-driven silhouette detection can precisely identify the liver boundaries, while the AR system overlays the portal liver segments onto the laparoscopic images. The AI approach demonstrated to have better accuracy, reporting mean error of 14.5 mm, compared to 31.2 mm for the conventional

method (13).

Kratzke et al. evaluated a simulated AR model using the Emprint SXTTM navigation system, showing significantly improved ablation outcomes compared to standard ultrasound. Under-ablation was reduced by 16.3% and over-ablation by 14.0% (both $P < 0.001$). Operative time decreased by 32 seconds, with 1.3 fewer antenna positioning attempts ($P < 0.001$). Novice radiologists benefited most, with greater improvements than experienced ones ($P = 0.018$). The study confirms that AR navigation enhances tumor ablation efficiency (14).

Luo et al provided a study that presents an AR-assisted navigation system created for liver resection which combines preoperative 3D models with laparoscopic images (in real-time). Being tested on porcine livers, this system could accurately overlay anatomical information, such as tumor position and the course of vessels, with errors of reprojection measuring 6.04 ± 1.85 mm (ex vivo) and 8.73 ± 2.43 mm (in vivo) (15).

Ribeiro described and evaluated the accuracy of an AR system called Hepataug, created for laparoscopic liver resection. The errors of tumor prediction were greater when projected on the laparoscope axis (29.4 ± 17.1 mm) compared to the operator port axis (9.2 ± 5.1 mm). Deeper tumors lead to higher errors, but accuracy was not affected by the size of the tumor. AR guidance showed to improve tumor localization, especially for lesions not far from the operator port, potentially avoiding surgical trauma (16).

A study by Smit et al explores a navigation system that makes use of preoperative 3D models, intraoperative ultrasound (US) respectively EM tracking (which are integrated) in order to intraoperatively localize lesions inside the liver. Real-time overlay of US images is enabled by the system, taking into account liver motion. In a total 22 procedures, the system provided an average fiducial registration error of 10.3 mm and an average target registration error of 8.5 mm. Navigation setup required 12.7 minutes. This approach showed improvements during liver surgery by tracking organ movement and integrating preoperative data (17).

Zhang et al. evaluated the safety and efficiency of a laparoscopic AR navigation (LARN) system in laparoscopic anatomical hepatectomy (LAH) for primary liver cancer (PLC). The study included 85 PLC patients, divided into two groups: intraoperative navigation (IN) with 44 patients and non-intraoperative navigation (NIN) with 41 patients. The results showed no significant

differences in preoperative features or complications, but the IN group experienced significantly less operative bleeding, lower blood transfusion rates, reduced postoperative hospital stay, and a lower delta hemoglobin percentage compared to the NIN group. LARN facilitated better identification of anatomical structures, reduced vascular injury, and improved postoperative recovery, showing promising outcomes in liver surgery (18).

Preoperative Planning, Operative Time and Training in Surgery

In their study, Wild et al objectively assessed training in laparoscopy, randomising laparoscopy novices (a total of 60) in two separate groups that underwent two different training programs - group 1 (30 members), using only verbal guidance while training and group 2 (other 30 members) to whom AR navigation was added. Evaluation consisted of performing a laparoscopic cholecystectomy on porcine model and outcome included several parameters such as time needed for training, GOALS (Global Operative Assessment of Laparoscopic Skills Score) score and OSATS (Objective Structured Assessment of Technical Skill) score. They strongly reflect the abilities of the candidates to correctly perform such an intervention and offer a realistic point of view when comparing their acquired skills. The results were in favour of the AR group, as all these parameters were superior compared to the non-AR group (4).

An animal-model study (hepatic wedge resection in a porcine model) evaluated the use of an AR system for real-time integration of laparoscopic ultrasound with laparoscopic video. The AR system showed to improve surgical guidance, obtaining a faster resection of the liver lesions when compared to standard techniques. Both resections had negative margins, being considered successful (8).

Thompson et al conducted a study presenting a method for estimating in vivo errors in AR during laparoscopic surgery, making use of the SmartLiver system. It allows the operators to compare the projected landmarks via live video, achieving accuracies with values around 12 mm. Consistent performance was claimed to remain challenging. Their study represents the first quantitative in vivo evaluation of AR in laparoscopic surgery (10).

Bijlstra et al designed a study that validated the application of an in-house developed software for realizing 3D virtual reality models of the liver, being based on preoperative imaging. Applied on

15 patients, the superposition of these 3D models into the robotic surgery console turned out to be feasible in all these cases, achieving high-quality reconstructions in 14 (93%) patients. Tumor diameters were measured on the 3D models and showed a close match with those from CT and/or MR imaging (19).

Another study realized by Golse et al tested a new AR system (vision-based) designed for intra-operative navigation in liver surgery. The use of preoperative 3D CT segmentations, combined with physics-based elastic models (having the purpose of real-time liver deformation) facilitated the use of AR, being applied with success in five cases. Four of them represented in-vivo hepatectomies ($n = 4$). Their setup was fast (less than 10 minutes) and achieved real-time superposition of virtual liver anatomy onto the surgical field. The remaining one represented an ex vivo experiment ($n = 1$), demonstrating an accuracy with a root mean square error of 7.9 mm for registering internal landmarks (20).

Ivashchenko et al. evaluated an EM navigation system for open liver surgery in 35 patients. The system integrated preoperative 3D liver models from 4D MRI with intraoperative CBCT and EM tracking of the liver surface and instruments, enabling real-time visualization of anatomy and tumor location. Verified using anatomical landmarks, the system had an average accuracy of 4.0 ± 3.0 mm and caused a surgical delay of less than 20 minutes. While effective in lesion localization, further improvements - such as faster intraoperative imaging - are needed to minimize delays (21).

Van den Bosch conducted a study on a novel AR system for CT-guided liver interventions, comparing it to conventional free-hand techniques using a phantom model. AR significantly reduced intervention times for all operators: resident ($p < 0.001$), junior ($p < 0.001$), and senior staff ($p = 0.027$). Accuracy improved by 1 mm for the junior staff member ($p = 0.026$), with no significant changes for the others. Overall, the AR system enhanced procedural speed without compromising accuracy, highlighting its potential to optimize minimally invasive interventions (22).

Discussion

AR and its Oncological Precision in Liver Surgery

The integration of AR into hepatic surgery is potentially redefining the concept of oncological precision by providing enhanced spatial awareness

during complex surgical procedures. Apart from accurately localizing tumors, AR systems offer an in-depth view of tumor geometry in relation to other critical structures, which is vital for preserving sufficient functional liver parenchyma (23,24). The improved accuracy as reported by Banz et al. (with errors decreasing from 8.4 mm to 4.5 mm) highlights a substantial transition in surgical practice (11). This shift offered surgeons the opportunity to replace several standardized resections with more personalized interventions, such as atypical resections which are adapted to the anatomy of the patient and characteristics of the disease. Precise mapping of the margins allows surgeons to confidently realize excision of tumors with minimal loss of functional tissue, which is particularly important for cases with impaired liver function, especially in cases with small residual liver volume.

The role that AR plays in adapting to intra-operative changes, like liver deformation or modifying anatomical landmarks, is also transformative. In the study conducted by Golse et al., elastic models and dynamic updates are used to test this technology's adaptability. It is of critical importance for optimally managing multifocal or bilobar tumors, where precise localization and assessment of surgical margins are inherently more challenging (20). Expanded use of AR for such cases demonstrates its potential to reshape the definition of what is surgically achievable, offering a new hope for patients who might otherwise face non-curative options.

Safety and Reduced Surgical Trauma

AR technologies not only enhance precision but also improve surgical safety by reducing intra-operative trauma and optimizing recovery. They allow detailed visualization of critical structures, minimizing dissection and lowering the risk of complications. Ribeiro's study showed that AR can localize tumors near operator ports, preserving vascular and biliary structures, which helps prevent significant postoperative morbidity. Zhang et al. reported reduced hospital stay, bleeding, and vascular injuries due to AR implementation (a major concern in liver surgery). AR technologies offer safer navigation in high-risk areas compared to conventional techniques (23-25).

AI integration in AR, as shown by Kasai et al., further enhances safety by automating tasks like boundary detection and vascular mapping. This reduces cognitive load and improves decision-making, with AI-assisted AR achieving higher

accuracy (14.5 mm vs. 31.2 mm for conventional methods) (13).

AR also changes how surgeons approach complex cases. In cases with multiple tumors, AR reduces the risk of incomplete resections or excessive tissue sacrifice. Luo et al.'s system, with sub-9 mm reprojection errors, proves AR's potential for guiding precise dissections, even in complex anatomical regions (15).

Preoperative Planning with Augmented Reality

Significant progress can be made in the preoperative planning area if using AR, as ports can be placed more efficiently at the beginning of the intervention. In mini-invasive liver surgery, one conceptual example is placing the optical port at the inferior border of the liver and after this, each port is inserted AR-guided, making use of the re-projection of the organs on the skin surface (26). Moreover, the relationship of these 'organ holograms' projected on the antero-lateral abdominal wall enables the surgical team to plan the whole intervention, before making any incisions (27,28). This not only improves communication between team members, but it is also responsible for reducing the number of errors (caused by miscommunication, decreased level of attention or unawareness) (6).

The use of AR may support the development of surgical checklists (nearly all surgical steps of the intervention are quickly revised). The senior physicians can assess the skills of the juniors and trainees and correct any misunderstanding involving surgical technique (1). Bijlstra's findings regarding the concordance between imaging measurement of tumor dimensions and AR method further reinforce the reliability of an AR system, which addresses a well-known challenge in hepatic surgery: the translation of preoperative imaging into decisions which are made intra-operatively. High-quality reconstructions were reported in 93% of cases, suggesting that AR could eventually fill the gap between planning and execution, potentially reducing the variability which was introduced by human interpretation or any surgical conditions (19).

Training in Mini-invasive Surgery and Augmented Reality

Visual guidance systems could provide better understanding of every action that has to be made, achieving better results and fewer complications.

This device allows the surgeons to combine verbal instructions with visual images that appear on the laparoscopic monitor. AR guidance can potentiate operative skills, minimally invasive basic skills and efficiency during training (22,29). Telestration with AR improves both safety and success rate in mini-invasive surgery. Its implementation is strongly recommended for successful surgical training of every physician who undergoes surgical specialties. The results of the aforementioned study designed by Wild et al suggest that AR technology may play a pivotal role in filling the gap between theoretical knowledge and practical skills (3). As trainees are enabled to visualize the procedure in real-time, AR facilitates an intuitive perception of complex spatial relationships and tissue manipulation, which are crucial for performing successful laparoscopic surgery. This particularly applies in a dynamic field like laparoscopic surgery, with limited tactile feedback. The fact that training using AR systems provided better outcomes in terms of efficiency and performance has promising implications for medical education and achievement of surgical skills. Ultimately, there could be several challenges related to the integration of such AR systems into the pre-existent surgical workflows, including their cost, specialized training, and technology adoption.

Limitations of this Study and Sources of Bias

A major limitation is the absence of a standardized definition of AR, as each study applies different technological criteria. This variability makes comparing outcomes challenging. Additionally, most research relies on animal models, especially porcine ones, which, despite similarities to human anatomy, may not fully reflect the complexities of human liver surgery. Lastly, the diversity in AR implementation methods, including different imaging modalities like ultrasound, MRI, and CT scans, contributes to inconsistencies in results, as each method has its own strengths and limitations.

Future Directions

The potential of Augmented Reality in mini-invasive liver surgery is promising, but several developments are needed for full clinical integration. A key requirement is the creation of a standardized definition and framework for AR in surgery. The current lack of consensus regarding the definition of AR impedes standardization and comparative evaluation. Future research should

focus on establishing a consensus definition that clearly distinguishes AR from technologies like virtual reality (VR) or mixed reality (MR). Standardization will facilitate collaboration, data sharing, and accelerated AR adoption in liver surgery (18).

A promising area for future research is integrating AR with AI and machine learning. AI could enhance AR by automating anatomical segmentation, predicting surgical margins, and offering real-time decision support, improving precision and reducing human error (30,31). Additionally, hardware improvements, such as ergonomic AR headsets and higher-resolution displays, will make AR more practical and user-friendly in surgeries.

AR's potential in surgical education is encouraging, as AR-based programs allow trainees to practice complex procedures in simulated environments before working with patients (1). This can shorten learning curves, improve skill acquisition, and enhance surgical competence. As AR advances, simulations could be tailored to individual learning needs, providing targeted feedback and more challenging scenarios (32,33).

The heterogeneity of AR technologies in current research underscores the need for a comparative analysis of different AR modalities. AR systems use various imaging techniques like ultrasound, CT, MRI, or PET scans, integrating intraoperative visualization with ICG. Each offers distinct advantages in accuracy, resolution, real-time capabilities, and integration into surgical workflows (12,34). Future research should compare these modalities to identify the most effective technologies for tasks like tumor localization, vessel identification, and resection planning. Such studies will guide the development of hybrid systems that combine the strengths of multiple imaging modalities for liver surgery (35).

Conclusions

Overall, AR shows great potential in enhancing mini-invasive liver surgery by improving anatomical identification, optimizing resection planning, and reducing operative time. Integrating AR with imaging techniques like ultrasound, CT, and MRI provides real-time visualizations, enabling safer, more precise surgeries. AR also holds promise for surgical training, offering young surgeons a more efficient skill acquisition path.

However, challenges persist, such as the

unclear definition of AR, reliance on animal models, and variability in the AR technologies used. Future research should focus on standardizing definitions, conducting human-based trials, and developing consensus-driven protocols. Addressing these issues will help AR improve surgical outcomes, reduce errors, and elevate the quality of liver surgery, paving the way for a future where surgery combines human expertise with advanced digital technology.

Authors' Contributions

Radu Ilies - researched of the literature and writing the introduction; Andras David - researched of the literature and writing and formatting the article; Esanu Victor - picture editing, image acquiring, intraoperative support, article formatting; Vasile Bintintan - surgical procedure, intraoperatori technology transfer, manuscript formatting; Dindelegan George - tehnology transfer, manuscript formatting.

Conflicts of Interest

The authors declare no conflicts of interest.

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