Augmented Reality in Ablation of Liver Tumors: A Review of Current Evidence and Future Directions

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Introduction

Liver tumors represent a major global health burden, with hepatocellular carcinoma ranking among the third leading cause of cancer-related mortality[1]. Percutaneous and surgical ablation techniques have emerged as minimally invasive techniques for tumor resection. However, accurate tumor localization and tissue deformities represent significant challenges. Conventional imaging modalities, such as CT and ultrasound, provide crucial guidance but are limited by two-dimensional views. Augmented reality (AR) has emerged as a supplemental imaging modality in surgical navigation of solid liver tumors. By integrating three-dimensional reconstructions, real-time image overlays, and compensating for motion artifact, AR enables surgeons to visualize tumors and surrounding anatomy with greater precision[2]. We evaluated the role of AR as an image-guidance modality in liver tumor ablation, focusing on its accuracy, procedural efficiency, and translation to clinical practice. Additionally, we identified current evidence gaps and technical challenges that need to be addressed.

Methods

A literature review was conducted across PubMed, MEDLINE, and Scopus using combinations of the following search terms: "augmented reality," "liver tumor," "ablation," "radiofrequency ablation," "tumor navigation," and "image-guided surgery." Peer-reviewed preclinical (phantom, animal) and clinical studies evaluating AR in surgical or percutaneous liver tumor ablation were included. Studies that reported outcomes such as targeting accuracy, ablation completeness, and efficiency were also included.

How Augmented Reality Works

AR in liver surgery starts with high-resolution **imaging**, which is typically obtained via contrast-enhanced CT scans. The scans are then processed with software such as *3D Slicer* that is further used to segment the scans allowing for anatomical elements (hepatic vessels and tumors) to be isolated. After **segmentation**, the data is refined in a 3D modeling software to create a more detailed and interactive virtual model. This **virtual 3D model** is built with a polygon mesh and joint system (Fig 1a) that allows independent rotation and manipulation of different sections, enabling precise anatomical alignment intraoperatively[2]. At this point, the model is ready for the operating room. The model is **calibrated** with a stereoscopic laparoscope in the *Matlab* software with a checker-board-based algorithm[2]. This step is necessary to ensure that the laparoscope's properties are matched with the virtual model at which point, the software *Unreal Engine* is used to **register** the model marking its initial appearance on the live laparoscopic video. The software approximates the **3D image overlay intraoperatively** and the surgeon can then further modify the overlay using a sterile handheld controller allowing for **fine-tuned adjustments** and more accurate anatomical alignment correcting for any software inaccuracies.

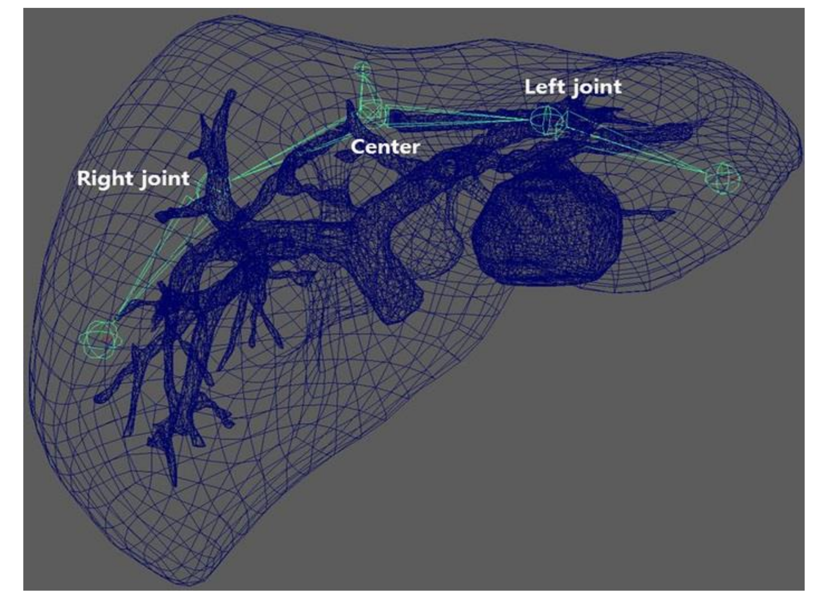

Fig. 1a

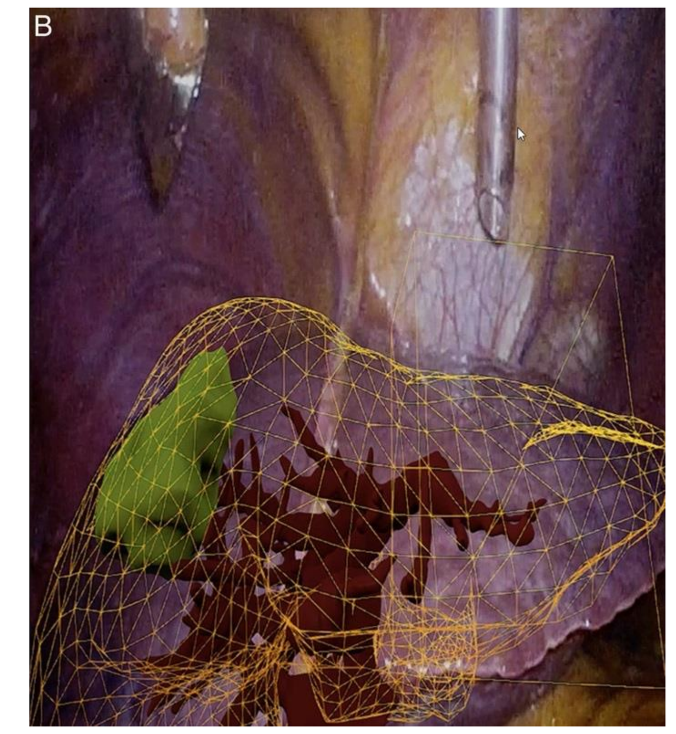

Fig. 1b

Figure 1: (a) 3D model of a liver with several points of manipulation and (b) a similar model superimposed onto a human liver during a surgical procedure in real-time[2].

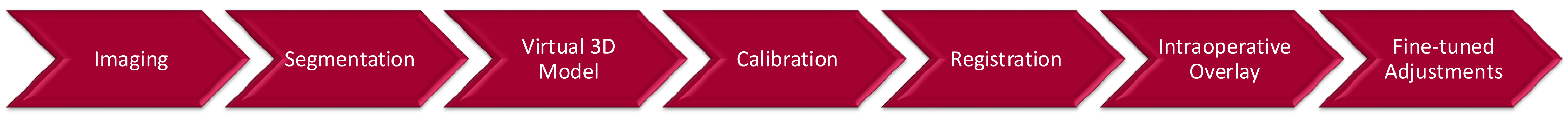

Figure 2: A schematic of the overall steps needed for AR-guided liver tumor ablation as detailed in the above section[2].

Accuracy and Precision

AR-guided navigation for liver tumor resection has demonstrated improvements in both accuracy and precision of intraoperative localization and resection margins. Several preclinical studies including phantom, ex-vivo, and in-vivo animal studies have demonstrating promising findings. One study utilized phantoms – synthetic lab-built liver models – and found that an ultrasound-assisted AR program with a non-rigid iterative closest point (ICP) algorithm was able to maintain high targeting accuracy even under challenging conditions. Their system achieved entry-point errors of ~2-3mm, while on deformed ex-vivo pork liver, errors remained within 3-5mm. This precision was maintained even in cases where areas of the liver surface were not fully scanned, simulating real-world limitations when 100% organ coverage is impractical[3]. In one clinical study, the *Endosight* AR system achieved a mean targeting accuracy of 3.44 mm (range: 2.6 – 4.2mm) with successful ablation of all tumors and >90% 5mm periablational margin in 13 out of 15 cases[4]. Another clinical study utilizing the *Hepataug* AR platform was able to accurately localize liver tumors in the AR group with a 0% conversion rate to open surgery compared to 2.8% in the control group[5].

Clinical Data

Several studies have shown that AR can be safely integrated into liver surgeries. One study of open liver surgeries analyzed 13 patients undergoing AR-navigated resection/ablation and found higher registration accuracy via the left main portal vein branch (LPV) compared to the right main portal vein branch (RPV) (6.2 ± 0.85mm vs 10.41 ± 0.99mm; $p < 0.001$).[6] In one pivotal study, 85 patients with primary liver cancer (PLC) underwent 3D laparoscopic anatomical hepatectomy with AR navigation intraoperatively (n=44) and non-intraoperative navigation (n=41).[7] The AR-navigation group had several statistically significant findings compared to the non-AR navigation group:

- **Lower blood loss (median 200mL vs 300mL; p<0.002)**
- **Less intraoperative blood transfusions (n=5, 10% vs n=19, 42%; p<0.001)**
- **Reduced postoperative hospital stay (median 8 days vs 10 days; p=0.003)**

These perioperative benefits further support intraoperative AR-guided navigation as this modality has the potential to reduce commonly encountered complications of liver tumor resections.

Challenges & Future Directions

Current AR-guided liver interventions face several practical and technical challenges. In one study, surgeons reported the need to alternate between multiple screens, creating cognitive load and workflow inefficiency[4]. Other technical limitations include:

- Organ deformities and respiratory motion
- Workflow complexity and setup time
- Validation and standardization

Future Directions may include immersive mixed or virtual reality (VR) headsets to project real-time overlays directly into the surgeon's field of view, enabling simultaneous viewing of the operative field and the 3D anatomical model. However, additional clinical trials and optimization of the sensors for better registration is still needed to establish safety and efficacy.

Conclusions

AR has demonstrated a high degree of accuracy for liver tumor targeting and promising workflow benefits, yet its clinical integration remains limited. Advances in real-time deformation modeling will be crucial for translating AR from experimental feasibility studies into routine surgical practice. With continued innovation and validation, AR-guided ablation could redefine precision in minimally invasive liver oncology.

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