Published in final edited form as:

J Gastrointest Surg. 2016 June ; 20(6): 1265–1269. doi:10.1007/s11605-016-3101-7.

Current Evidence in Image-Guided Liver Surgery

Amber L. Simpson and T. Peter Kingham

Hepatopancreatobiliary Service, Department of Surgery, Memorial Sloan Kettering Cancer Center

Background

Image-guided surgery has become the standard of care in neurosurgery [1,2] with the first systems reported in the mid 1990s. Studies support improved accuracy and reduced OR times. These outcomes have led to lower morbidity and shortened inpatient hospital stays [3,4]. Herline *et al.* described the first use of image guidance for liver surgery in 1999 [5]. The paradigm of image-guided surgery is largely unchanged since these early systems: a sensor is used to track the position and orientation of the surgeon's tool. The anatomy of interest is mapped to high-resolution preoperative images using a process called registration. Registration and tool tracking enable the surgeon to see the surgical tool superimposed on the preoperative patient image on a navigational display, as the instrument is manipulated (Fig. 1). This review will describe the state of image guided liver surgery and discuss future applications for MIS liver surgery.

Rationale

Partial hepatectomy has emerged as the most effective and the only potentially curative therapy for many primary and secondary hepatic tumors [6][7]. This procedure can be technically challenging due to the distribution of tumors within complex vasculature and the need to maintain an adequate remnant liver volume with intact vascular inflow and outflow and biliary drainage. Ablation with microwave or radiofrequency devices is often combined with resection to adequately treat all visible disease in patients with liver tumors, or used in place of resection in select circumstances. Recent evidence supports the use of ablation instead of resection for treatment of small hepatocellular carcinomas [8]. In order to achieve an adequate tumor resection or ablation, with good oncologic outcomes and without injury to and needless sacrifice of adjacent normal hepatic parenchyma, the surgeon must have precise knowledge of the tumor location relative to the surrounding major vascular and biliary structures. With these factors in mind, image-guided liver surgery aims to enhance the precision of resection and ablation, while preserving uninvolved parenchyma and vascular structures.

CME questions for this article available to SSAT members at <http://ssat.com/jogscme/>

Disclosure Information: **Authors:** Amber L. Simpson, M.D., has nothing to disclose. T. Peter Kingham, M.D. has nothing to disclose.

Editors-in-Chief: Jeffrey B. Matthews, M.D., has nothing to disclose; Charles Yeo, M.D., has nothing to disclose. **CME Overseers:**

Arbiter: Jeffrey B. Matthews, M.D., has nothing to disclose; Vice-Arbiter: Ranjan Sudan, M.D., has nothing to disclose; Question

Reviewers: I. Michael Leitman, M.D. has nothing to disclose; Abdulrahim Alawashez, M.D., has nothing to disclose

Currently, in resection and ablative therapies, hepatic tumors are localized using a combination of preoperative imaging studies (computerized tomography (CT) and/or magnetic resonance imaging (MRI)) and intra-operative ultrasonography (US). Preoperative tomograms provide high-resolution, 3D views of the tumor and surrounding anatomy. However, these images are static, do not take into account changes in the position of the tumor that can occur between the time the scans were completed and the time of surgery and are also of limited utility during the parenchymal transection phase of the procedure due to organ manipulation. Intra-operative ultrasound is therefore used to provide valuable information regarding tumor location, which guides both resections and ablations. These images, however, are 2D, and this modality is more challenging once the resection begins. In patients treated with chemotherapy and in patients with abnormal liver parenchyma (steatosis or fibrosis/cirrhosis), US can fail to identify tumors seen on preoperative imaging; this has become an increasingly common problem in patients with hepatic colorectal metastases treated with preoperative chemotherapy [9]. In addition, US does not reliably distinguish between ablated and normal tissue [10], further complicating the localization task in patients undergoing multiple ablations. The rationale for image guidance in the liver is to improve localization by mapping the intraoperative organ state to the high-resolution preoperative image.

Application of IGLS

With respect to surgical navigation for liver surgery, several groups have reported on preoperative planning and virtual resection [11–14], image overlays [15], and intraoperative rigid/non-rigid registration strategies [16,17], but few systems are in routine clinical use. There are two FDA approved systems. Explorer (Pathfinder Therapeutics Inc.) was the first FDA-approved system for image-guided liver surgery (Fig. 2). The system uses liver surface data acquired from a tracked probe to register to the preoperative model derived from CT/MRI. We reported our initial experiences with navigated RFA using Explorer, but the treatment population best suited to the technology remains to be determined [18,19]. We have now used the device in hundreds of patients. Studies have shown that the system can create accurate three dimensional models and predict accurate resection planes and remnant volumes [20], and can aid in difficult ablations [18]. Interim analysis of 18 patients in our prospective clinical trial for localizing small sonographically occult colorectal liver metastases, suggests that patients with heavily treated livers can benefit from the Explorer system [21] but evaluation of the full cohort is needed (Fig. 3).

In May 2015, CAScination (Bern, Switzerland) received FDA approval for the CAS-One system developed at the University of Bern. The system is based on tracked US to CT registration using semi-automatically extracted vessel features [22]. Integration with the da Vinci Si System (Intuitive Surgical Inc., Sunnyvale, CA), qualitatively suggests improved visualization in a pilot study of two patients [23]. A case report of a patient with a complex hydatid cyst with biliary tree communication showed the promise of the system [24]. Limited data suggest slight reduction in incomplete (R1) resections [25] and benefit to a few individual patients [26] with guidance. To date, both the Explorer and CAS-One systems have been used primarily to demonstrate clinical utility, accuracy, and feasibility. As with neuronavigation systems, no randomized controlled clinical trials have been performed to

assess the true impact on patient outcomes because determining relevant endpoints, which yield a sufficient number of patients, is difficult [27].

Technical Considerations

Currently, there is no perfect solution to technical issues that continue to challenge adoption of image-guided liver surgery. Line of sight issues in the operating room workflow limit both the CAS-One and Explorer systems because optical tracking cameras require direct sight of the infrared emitting markers placed on tracked tools. Efforts are being made by both groups to move to electromagnetic (EM) tracking, but there are issues with EM technology as well. EM tracking relies on a field generator, typically placed under the patient, to produce a low-intensity EM field. Sensors in the tool emit electrical signals dependent on the distance and angle of the sensor to the field generator. EM tracking is sensitive to interference with metallic objects: the operating table, LCD displays, lights, C-arms, operating microscopes, and surgical instruments placed near the field generator affect the accuracy [28–30]. EM tracking accuracy varies unintuitively over the working volume of the sensors [31].

Addressing organ shape change from the preoperative image to the intraoperative state is a technical hurdle that has hindered adoption. Current systems do not address this deformation [32–34], which compromises registration (and therefore localization) accuracy [35], fundamental to surgical navigation. Intraoperative motion and respiration effects further confound localization, with organ translation ranging from 10 to 75 mm during respiration [36]. Miga et al. describe high resolution intraoperatively acquired surface data provided by laser range scanning to drive mathematical models of deformation [37]. Fig. 4 depicts the OR workflow with this approach and the resulting 3D surface of the liver. Studies report more accurate registration [38] with some intraoperative validation [39], but the system has not been used to guide treatment. Laser range scanning is a source of rich 3D data but requires 30 seconds for acquisition so some authors have turned to US as a real-time data source for non-rigid correction [40–42]. US registration is hindered by lack of surface detail for non-rigid matching. In addition, a liver with segments resected can be more difficult to register as surface features commonly used for registration are missing.

Toward Minimally Invasive Use

Minimally invasive (MI) liver surgery has been slow to gain widespread practice due to the complexity of liver anatomy because many of the visual cues of open surgery are missing. In addition, MI liver ablations are technically more challenging than open ablations due to difficulties with laparoscopic ultrasound and ensuring accurate placement of the ablation probe. Thus, MI liver surgery is the optimal technique for application of image guidance. Similar to open systems, existing laparoscopic image guidance systems are prototypes, not used for routine clinical evaluation. For example, LapAssistent is a system developed for laparoscopic RFA with electromagnetically tracked US with some reports on the feasibility [43,44,44,45]. The University of North Carolina at Chapel Hill has developed a similar prototype system with some work on technical feasibility [46]. Like many of the prototype systems, this system relies on the Aurora electromagnetic tracking system (Northern Digital, Waterloo, ON, Canada) for position sensing. Other prototype systems exist [16,47] but none

have been evaluated with respect to improvements in patient outcomes. We evaluated the Explorer system for laparoscopic use demonstrating that the pneumoperitoneum does not change the model created by the system [19]. Additional reports have described laparoscopic image guided ablations with the Explorer system [48]. As improvements to intraoperative registration improve in image guidance systems, it is possible that complex liver resections will be performed with fewer difficulties while remaining oriented and ensuring adequate margins.

Future Directions

Current navigational technologies provide intraoperative guidance for a single reference point in time; once the liver is disturbed, either through patient respiration or surgical manipulation, registration must be repeated or else accuracy is lost. An ideal system would provide real-time localization feedback to the surgeon as new data are continually incorporated into the display so that information is immediate and decisions are informed with minimal impact on surgical workflow. It is conceivable for current systems to evolve so that high definition imaging models guide liver resections and ablations in both open and minimally invasive operations to improve the speed, accuracy, and outcomes of liver surgery.

References

1. Kondziolka D, Lunsford LD. Intraoperative navigation during resection of brain metastases. *Neurosurg Clin N Am.* 1996; 7(2):267–277. PMID: 8726440. [PubMed: 8726440]
2. Korinith MC, Delonge C, Hütter BO, Gilsbach JM. Prognostic factors for patients with microscopically resected brain metastases. *Onkologie.* 2002; 25(5):420–425. PMID: 12415195. [PubMed: 12415195]
3. Paleologos TS, Wadley JP, Kitchen ND, Thomas DG. Clinical utility and cost-effectiveness of interactive image-guided craniotomy: clinical comparison between conventional and image-guided meningioma surgery. *Neurosurgery.* Jul; 2000 47(1):40–7. discussion 47–8. PMID: 10917345. [PubMed: 10917345]
4. Jensen R, Garber S. Image guidance for brain metastases resection. *Surg Neurol Int.* 2012; 3(3):111. PMID: 22826814. [PubMed: 23087827]
5. Herline AJ, Stefansic JD, Debelak JP, Hartmann SL, Pinson CW, Galloway RL, Chapman WC. Image-guided surgery: preliminary feasibility studies of frameless stereotactic liver surgery. *Arch Surg.* 1999; 134(6):644–649. discussion 649–650. PMID: 10367875. [PubMed: 10367875]
6. Rosen CB. Management of Hepatic Metastases. *Cancer Control.* 1998; 5(3 Suppl 1):30–31. [PubMed: 10762479]
7. Sardi A, Akbarov A, Conaway G. Management of primary and metastatic tumors to the liver. *Oncol (willist Park).* 1996; 10(6):911–25. discussion 926, 929–30.
8. Shibata T, Niinobu T, Ogata N, Takami M. Microwave coagulation therapy for multiple hepatic metastases from colorectal carcinoma. *Cancer.* 2000; 89(2):276–284. [PubMed: 10918156]
9. Vledder MG Van, Torbenson MS., Pawlik, TM.; Boctor, EM.; Hamper, UM.; Olino, K.; Choti, MA. The Effect of Steatosis on Echogenicity of Colorectal Liver Metastases on Intraoperative Ultrasonography. 2010; 145(7):661–667.
10. Bilchick, AJ.; Krasny, RM.; Allegra, D. Radiofrequency ablation for liver tumors.. In: Jarnagin, WR., editor. *Blumgart's Surg Liver, Biliary Tract, Pancreas.* 5th ed.. Elsevier; 2012.
11. Lang H, Radtke A, Liu C, Fruhauf NR, Peitgen HO, Broelsch CE. Extended left hepatectomy--modified operation planning based on three-dimensional visualization of liver anatomy. *Langenbecks Arch Surg.* 2004; 389(4):306–310. [PubMed: 14704797]
12. Lang H, Radtke A, Hindennach M, Schroeder T, Fruhauf NR, Malago M, Bourquain H, Peitgen HO, Oldhafer KJ, Broelsch CE. Impact of virtual tumor resection and computer-assisted risk

- analysis on operation planning and intraoperative strategy in major hepatic resection. *Arch Surg*. 2005; 140(7):629–38. discussion 638. PMID: 16027326. [PubMed: 16027326]
13. Selle D, Preim B, Schenk A, Peitgen HO. Analysis of vasculature for liver surgical planning. *IEEE Trans Med Imaging*. 2002; 21(11):1344–1357. [PubMed: 12575871]
 14. Kaibori M, Chen YW, Matsui K, Ishizaki M, Tsuda T, Nakatake R, Sakaguchi T, Matsushima H, Miyawaki K, Shindo T, Tateyama T, Kwon AH. Novel Liver Visualization and Surgical Simulation System. *J Gastrointest Surg*. 2013
 15. Gavaghan KA, Peterhans M, Oliveira-Santos T, Weber S. A portable image overlay projection device for computer-aided open liver surgery. *IEEE Trans Biomed Eng*. 2011; 58(6):1855–1864. PMID: 21411401. [PubMed: 21411401]
 16. Bao P, Warmath J, Galloway R Jr, Herline A. Ultrasound-to-computer-tomography registration for image-guided laparoscopic liver surgery. *Surg Endosc*. 2005; 19(3):424–429. [PubMed: 15645329]
 17. Penney GP, Blackall JM, Hamady MS, Sabharwal T, Adam A, Hawkes DJ. Registration of freehand 3D ultrasound and magnetic resonance liver images. *Med Image Anal*. 2004; 8(1):81–91. [PubMed: 14644148]
 18. Kingham TP, Scherer MA, Neese BW, Clements LW, Stefansic JD, Jarnagin WR. Image-guided liver surgery: intraoperative projection of computed tomography images utilizing tracked ultrasound. *HPB (Oxford)*. Sep; 2012 14(9):594–603. PMID: 22882196. [PubMed: 22882196]
 19. Kingham TP, Jayaraman S, Clements LW, Scherer MA, Stefansic JD, Jarnagin WR. Evolution of Image-Guided Liver Surgery: Transition from Open to Laparoscopic Procedures. *J Gastrointest Surg*. Jul; 2013 17(7):1274–1282. PMID: 23645420. [PubMed: 23645420]
 20. Simpson AL, Geller DA, Hemming AW, Jarnagin WR, Clements LW, D'Angelica MI, Dumpuri P, Gonen M, Zendejas I, Miga MI, Stefansic JD. Liver planning software accurately predicts postoperative liver volume and measures early regeneration. *J Am Coll Surg*. 2014; 219(2):199–207. [PubMed: 24862883]
 21. Leung U, Simpson AL, Adams LB, Jarnagin WR, Miga MI, Kingham TP. Image guidance improves localization of sonographically occult colorectal liver metastases. 2015; 9415(c):94151L.
 22. Peterhans M, Vom Berg A, Dagon B, Inderbitzin D, Baur C, Candinas D, Weber S. A navigation system for open liver surgery: Design, workflow and first clinical applications. *Int J Med Robot Comput Assist Surg*. 2011; 7(1):7–16. PMID: 21341357.
 23. Buchs NC, Volonte F, Pugin F, Toso C, Fusaglia M, Gavaghan K, Majno PE, Peterhans M, Weber S, Morel P. Augmented environments for the targeting of hepatic lesions during image-guided robotic liver surgery. *J Surg Res*. 2013; 184(2):825–831. PMID: 23684617. [PubMed: 23684617]
 24. Panaro, F.; Habibeh, H.; Pessaux, P.; Navarro, F. *Int J Surg Case Rep*. Vol. 12. Elsevier Ltd; 2015. Navigation liver surgery for complex hydatid cyst with biliary tree communication.; p. 112-116.
 25. Beller S, Hünerbein M, Eulenstein S, Lange T, Schlag PM. Feasibility of navigated resection of liver tumors using multiplanar visualization of intraoperative 3-dimensional ultrasound data. *Ann Surg*. Aug; 2007 246(2):288–94. PMID: 17667508. [PubMed: 17667508]
 26. Oldhafer KJ, Stavrou G a, Prause G, Peitgen HO, Lueth TC, Weber S. How to operate a liver tumor you cannot see. *Langenbeck's Arch Surg*. 2009; 394(3):489–494. PMID: 19280221. [PubMed: 19280221]
 27. Banz, V.; Peterhans, M.; Ribes, D.; Candinas, D.; Weber, S. *Newer Technol Hepatopancreatobiliary Surg - ECAB*. Elsevier; 2014. Intra-operative Image Guidance in Liver Surgery..
 28. Hummel J, Figl M, Birkfellner W, Bax MR, Shahidi R, Maurer CR, Bergmann H. Evaluation of a new electromagnetic tracking system using a standardized assessment protocol. *Phys Med Biol*. 2006; 51(10):N205–N210. PMID: 16675856. [PubMed: 16675856]
 29. Poulin F, Amiot LP. Interference during the use of an electromagnetic tracking system under OR conditions. *J Biomech*. 2002; 35(6):733–737. PMID: 12020992. [PubMed: 12020992]
 30. Birkfellner W, Watzinger F, Wanschitz F, Ewers R, Bergmann H. Calibration of tracking systems in a surgical environment. *IEEE Trans Med Imaging*. 1998; 17(5):737–742. PMID: 9874297. [PubMed: 9874297]
 31. Nafis C, Jensen V, Beauregard L, Anderson P. Method for estimating dynamic EM tracking accuracy of Surgical Navigation Tools. *SPIE Med imaging*. 2006:61410K–61410K–16.

32. Najmaei N, Mostafavi K, Shahbazi S, Azizian M. Image-guided techniques in renal and hepatic interventions. *Int J Med Robot Comput Assist Surg.* 2013; 9(4):379–395. PMID: 22736549.
33. Peterhans M, Oliveira T, Banz V, Candinas D, Weber S. Computer-assisted liver surgery: clinical applications and technological trends. *Crit Rev Biomed Eng.* 2012; 40(3):199–220. [PubMed: 22694200]
34. Galloway R, Herrell S, Miga M. Image-Guided Abdominal Surgery and Therapy Delivery. *J Healthc Eng.* 2012; 3(2):203–228. [PubMed: 25077012]
35. Heizmann O, Zidowitz S, Bourquain H, Potthast S, Peitgen HO, Oertli D, Kettelhack C. Assessment of intraoperative liver deformation during hepatic resection: prospective clinical study. *World J Surg.* 2010; 34(8):1887–1893. PMID: 20372896. [PubMed: 20372896]
36. Clifford MA, Banovac F, Levy E, Cleary K. Assessment of hepatic motion secondary to respiration for computer assisted interventions. *Comput Aided Surg.* 2002; 7(5):291–299. [PubMed: 12582982]
37. Clements LW, Dumpuri P, Chapman WC, Dawant BM, Galloway RL, Miga MI. Organ surface deformation measurement and analysis in open hepatic surgery: Method and preliminary results from 12 clinical cases. *IEEE Trans Biomed Eng.* 2011; 58(8):2280–2289. PMID: 21521662.
38. Simpson AL, Burgner J, Glisson CL, Herrell SD, Ma B, Pheiffer TS, Webster RJ III, Miga MI. Comparison study of intraoperative surface acquisition methods for surgical navigation. *IEEE Trans Biomed Eng.* 2013; 60(4):1090–1099. 2012/08/30 PMID: 22929367. [PubMed: 22929367]
39. Clements LW, Collins JA, Wu Y, Simpson AL, Jarnagin WR, Miga MI. Validation of model-based deformation correction in image-guided liver surgery via tracked intraoperative ultrasound: preliminary method and results. 2015; 9415:94150T.
40. Chopra SS, Hunerbein M, Eulenstein S, Lange T, Schlag PM, Beller S. Development and validation of a three dimensional ultrasound based navigation system for tumor resection. *Eur J Surg Oncol.* 2008; 34(4):456–461. [PubMed: 17765451]
41. Lange, T.; Papenberg, N.; Heldmann, S.; Modersitzki, J.; Fischer, B.; Lamecker, H.; Schlag, P. *Int J Comput Assist Radiol Surg.* Vol. 4. Springer-Verlag; 2009. 3D ultrasound-CT registration of the liver using combined landmark-intensity information.; p. 79-88.
42. Pheiffer TS, Thompson RC, Rucker DC, Simpson AL, Miga MI. Model-based correction of tissue compression for tracked ultrasound in soft tissue image-guided surgery. *Ultrasound Med Biol.* 2014; 40(4):788–803. PMID: 24412172. [PubMed: 24412172]
43. Hildebrand P, Schlichting S, Martens V, Besirevic a. Kleemann M, Roblick U, Mirow L, Bürk C, Schweikard a. Bruch HP. Prototype of an intraoperative navigation and documentation system for laparoscopic radiofrequency ablation: First experiences. *Eur J Surg Oncol.* 2008; 34(4):418–421. PMID: 17561365. [PubMed: 17561365]
44. Hildebrand P, Kleemann M, Roblick UJ, Mirow L, Bürk C, Bruch H-P. Technical aspects and feasibility of laparoscopic ultrasound navigation in radiofrequency ablation of unresectable hepatic malignancies. *J Laparoendosc Adv Surg Tech A.* 2007; 17(1):53–57. PMID: 17362180. [PubMed: 17362180]
45. Harms J, Feussner H, Baumgartner M, Schneider a. Donhauser M, Wessels G. Three-dimensional navigated laparoscopic ultrasonography: First experiences with a new minimally invasive diagnostic device. *Surg Endosc.* 2001; 15(12):1459–1462. PMID: 11965466. [PubMed: 11965466]
46. Sindram D, McKillop IH, Martinie JB, Iannitti D a. Novel 3-D laparoscopic magnetic ultrasound image guidance for lesion targeting. *Hpb.* 2010; 12(10):709–716. PMID: 21083797. [PubMed: 21083797]
47. Bao P, Sinha TK, Chen CCR, Warmath JR, Galloway RL, Herline AJ. A prototype ultrasound-guided laparoscopic radiofrequency ablation system. *Surg Endosc Other Interv Tech.* 2007; 21:74–79.
48. Hammill CW, Clements LW, Stefansic JD, Wolf RF, Hansen PD, Gerber DA. Evaluation of a Minimally Invasive Image-Guided Surgery System for Hepatic Ablation Procedures. *Surg Innov.* 2013; 21(4):419–426. PMID: 24201739. [PubMed: 24201739]

Learning objectives:

1. Understand the history of image guided surgery
2. Understand the limitations of current FDA-approved systems
3. Explain the development of current image guidance systems
4. Provide a vision for future application of next generation image guidance systems
1. The first image-guidance systems were for what type of surgery?
 - a. neurosurgery
 - b. orthopaedics
 - c. maxillofacial
 - d. liver resection
2. True or false: steatosis can effect the echogeneity of tumors in the operating room.
3. True of false: an FDA-approved system incorporates non-rigid registration.
4. All of the following are limitations of optical tracking except:
 - a. line of sight issues
 - b. the use of specialized tools
 - c. sensitive in infrared
5. What is the limitation of CT and MRI scans for intraoperative treatment of liver tumors?
 - a. They provide high-resolution images
 - b. They provide 3-dimensional images
 - c. They are static imaging modalities
 - d. They demonstrate surrounding liver anatomy
6. All of the following are limitations of ultrasound except:
 - a. 2-dimensional images
 - b. Post-chemotherapy US imaging can be limited in the liver
 - c. Imaging steatotic livers is challenging
 - d. US is user dependent
 - e. US is dynamic

7. True or false: There are level 1 data that demonstrate a benefit of image guided liver surgery to standard US guided liver surgery.
8. Which of the following does not interfere with electromagnetic tracking?
 - a. Anesthesia machine
 - b. C-arm
 - c. Lights
 - d. Operating table
 - e. Surgical instruments

Figure 1.

A typical image guidance system: a sensor (camera) tracks the position and orientation of the tool and registration maps points collected with the tool to the preoperative 3D model of the patients.

Figure 2.
Illustration of image-guided liver surgery using the Explorer system.

Figure 3.

Tumor successfully located with guided US: (left) green probe indicates tumor in CT on the image-guidance display and (right) yellow arrow indicates tumor. Tumor was not found using standard US alone.

Figure 4. Laser range scanner positioned over patient in the operating room and a high-resolution 3D surface of the liver acquired intraoperatively using a laser range scanner.