Image-guided liver surgery: intraoperative projection of computed tomography images utilizing tracked ultrasound

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Abstract

Background: Ultrasound (US) is the most commonly used form of image guidance during liver surgery. However, the use of navigation systems that incorporate instrument tracking and three-dimensional visualization of preoperative tomography is increasing. This report describes an initial experience using an image-guidance system with navigated US.

Methods: An image-guidance system was used in a total of 50 open liver procedures to aid in localization and targeting of liver lesions. An optical tracking system was employed to localize surgical instruments. Customized hardware and calibration of the US transducer were required. The results of three procedures are highlighted in order to illustrate specific navigation techniques that proved useful in the broader patient cohort.

Results: Over a 7-month span, the navigation system assisted in completing 21 (42%) of the procedures, and tracked US alone provided additional information required to perform resection or ablation in six procedures (12%). Average registration time during the three illustrative procedures was <1 min. Average set-up time was approximately 5 min per procedure.

Conclusions: The Explorer™ Liver guidance system represents novel technology that continues to evolve. This initial experience indicates that image guidance is valuable in certain procedures, specifically in cases in which difficult anatomy or tumour location or echogenicity limit the usefulness of traditional guidance methods.

Keywords

image-guided surgery, navigated ultrasound, surgical navigation, liver surgery, tracked ultrasound, optical tracking

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Introduction

Image-guided surgical approaches to the management of neoplastic lesions in the liver are becoming more common.1 Intraoperative ultrasound (IOUS) is the primary method of intraoperative guidance. It allows for the localization of tumours and their margins relative to healthy tissue and significant structures such as blood vessels. Intraoperative US, however, produces only two-dimensional (2-D) imaging and does little to enhance understanding of complex three-dimensional (3-D) liver anatomy. In addition, many liver tumours are isoechoic with respect to the surrounding liver, subcentimetre in size, or difficult to visualize as a result of parenchymal changes caused by chemotherapy or steatosis.2-4 These factors make the IOUS identification of tumours and margins of resection and/or ablation difficult. Additionally, thermal ablation treatment can result in difficult visualization of the lesion boundary via IOUS because the treated area is rendered hyperechoic.5 Degradation in the quality of IOUS imaging during ablation treatment impairs the ability of the clinician to assess treatment efficacy in real time. Image-guided surgery (IGS) provides guidance information via the display of tracked surgical instrumentation overlaid on preoperative...
tomograms, such as those provided by computed tomography (CT) or magnetic resonance imaging (MRI), which are 3-D in nature and of high resolution. However, IGS reflects the relative positions of anatomic structures acquired in preoperative scanning and thus does not take into account deformations caused by posture or surgical traction or changes in anatomy since tomographic scan acquisition.

In an ongoing collaboration with Pathfinder Therapeutics, Inc. (Nashville, TN, USA) and as part of a formal clinical trial approved by the institutional review board at Memorial Sloan–Kettering Cancer Center, the authors have assessed the clinical value of an intraoperative navigation system (Explorer™ Liver) that has been cleared by the US Food and Drug Administration. This system combines preoperative imaging, IOUS and real-time instrument tracking to guide liver surgical procedures. Integrating tracked IOUS into IGS systems is a novel technique that combines real-time ultrasonic visualization with preoperative tomographic images and 3-D models. This combination of imaging information enhances the intraoperative assessment of patient anatomy and provides confirmation of guidance system accuracy. This is the first paper describing the specific utility of the Explorer™ Liver system during a series of open liver resection and ablation procedures. Prior iterations of the system described in this paper utilized a laser range scanner and active optical tracking (Optotak Certus; Northern Digital, Inc., Waterloo, ON, Canada). This system was tested in a clinical study, in which its registration accuracy and speed were deemed adequate for surgical navigation. However, the value obtained from surgical navigation was occasionally limited by a system design that prevented a seamless integration into the clinical workflow. This paper describes an experience with an updated system that, in selected procedures, provides valuable guidance information while being unobtrusive to surgical workflow.

Materials and methods
Over a 7-month span, the image guidance system was used in 50 procedures, three of which are described in detail in the present paper in order to illustrate specific navigation techniques that proved useful in the broader patient cohort.

Preoperative planning
Prior to surgery, preoperative images are analysed by the surgeon. A commercially available software package (Scout™ Liver; Pathfinder Therapeutics, Inc.) is used to generate 3-D surfaces of anatomic structures. Semi-automatic segmentation of the liver, portal and hepatic veins, and relevant tumours requires approximately 15 min of processing time by an experienced user. To aid in intraoperative navigation, identification of salient anatomic features, including the falciform ligament and inferior ridges (segments III, IVb, V and VI), is performed by the experienced user and verified by the practising surgeon. Finally, tumour identification is confirmed preoperatively by the surgeon and images are transferred to the navigation system via USB drive.

Intraoperative set-up
The navigation system set-up requires the presence of one additional person in the operating room (OR) to control the operating interface. Initial set-up takes approximately 5 min and comprises placement of the system, camera carts and cable connections. A passive optical tracking system (Polaris Spectra; Northern Digital, Inc.) is utilized in conjunction with the IGS platform and a set of disposable surgical tools (Fig. 1a, b). Intraoperative US is performed with an Alpha 7 console and T-probe (UST-5713-T; Hitachi Aloka Medical Ltd, Wallingford, CT, USA). Ablations performed during the present study used the Evident™ microwave
Figure 2 (a) Schematic of the rigid body attachment to the Aloka ultrasound (US) transducer. (b) The US adapter and transducer are utilized during a surgical procedure.

Figure 3 Intraoperative display used during surgical navigation. (a) Sagittal orientation of preoperative computed tomography (CT), showing the intraoperative position of the ablation needle (crosshairs). (b) Axial orientation of preoperative CT, showing the intraoperative position of the ablation needle (crosshairs). (c) Cloned Aloka ultrasound (US) image (via S-video), showing the target tumour in the centre. (d) Three-D display of liver, portal (pink) and hepatic (blue) vessels, tumours (brown), and the position of the ablation needle (green) and US transducer (blue). The CT plane reflecting the position and orientation of the US is also shown. The navigation workflow taskbar is displayed on the right.
needle (Covidien, Inc., Boulder, CO, USA), which has a length of 17 cm and an ablation zone of 3.7 cm.

An optically tracked adapter can be attached to the ablation needle via a universal clamp and a tracking calibration is performed via a reference device. Similarly, a calibration procedure is performed for the localizer probe used for registration to ensure accurate instrument tracking and data collection. The tracking accuracy of the tip of the instrument is maintained as long as the tip of the tracked device remains rigid relative to the tracked body. These additional calibration steps add approximately 1–5 min per procedure, but can be performed by the scrub nurse or other support staff while the patient is prepared for the surgical procedure.

Ultrasound calibration

The US probe is calibrated before the procedure using an N-wire calibration phantom with water as a coupling medium as described by Chen et al.8 Specifically, the calibration phantom is a precisely machined, open-ended box with an optically tracked face rigidly attached. The box encloses nine nylon wire fiducials, each strung in an ‘N’ configuration. The locations of these fiducials relative to the tracked face on the phantom are known. The phantom is scanned with the US beam while both the phantom and the US probe are being tracked, and the fiducials are identified in the US image coordinates. This allows for an accurate transformation from the US image to physical space. Bench testing has shown the average US localization error to be about 1 mm.

A calibration must be performed for every model of US transducer to be tracked by the Explorer™ Liver system. Additionally, each model transducer requires a unique clamp that can be reliably attached in the same configuration for every use (Fig. 2a, b). These custom-designed clamps allow for all calibrations to be performed outside the OR, thereby saving critical intraoperative set-up time.

Interface overview

A four-quadrant display allows for simultaneous observation of multiple sources of information, as well as the real-time visualization of up to two optically tracked devices (Fig. 3). Various configurations can be utilized to convey the guidance information once registration has been performed. Axial, sagittal, coronal and oblique views, based on tracked instrument position and orientation, of the preoperative image volume can be displayed. Three-dimensional renderings of the anatomic structures and the US video stream, transferred via S-video interface, can also be displayed. Based on the position and orientation of the US transducer, the IOUS image plane (or corresponding CT or MRI slice) can also be displayed as an overlay on the 3-D models. This can be especially helpful when the target tumours are difficult to localize via IOUS, but are easily visible on preoperative imaging.

Intraoperative registration

Registrations are conducted at the surgeon’s discretion, usually immediately prior to resection or ablation. When the surgeon is ready to utilize navigation, the liver is prepared so that movement is minimized, usually by the placement of surgical sponges. Apnoeic periods may also be employed to minimize liver movement as a result of respiration. Tracking adapters are placed on the relevant surgical instruments. The registration is performed with the aid of salient anatomic features. Surface and feature points can be acquired with a localizer probe or a tracked surgical instrument. After the registration has been performed, anatomic landmarks (e.g. round ligament, falciform ligament, superficial lesions) are identified with the localizing device and tracking accuracy can be observed via the Explorer™ Liver software interface.

Results

Between June 2011 and January 2012, the navigation system assisted in the completion of 21 of 50 (42%) surgical procedures. Additionally, tracked US alone provided information necessary to
perform resection or ablation in six procedures (12%). The following procedures illustrate in detail the various ways in which the guidance system was utilized as an adjunct to traditional guidance methods during open liver surgery. Three patients were evaluated with the Explorer™ Liver IGS system with navigated IOUS. Standard B-mode US images (the reference standard technique) were concurrently used with the Explorer™ Liver system. A total of seven registrations were performed for all three patients, with an average duration of <1 min (Table 1). Re-registration is required when the organ’s position is altered or its morphology is significantly deformed because registration accuracy can be compromised when the intraoperative presentation of the organ changes substantially from that reflected in the preoperative imaging. The navigation system is particularly useful when tumours, visible in preoperative tomograms, are difficult to detect with IOUS alone.

**Figure 5** Patient 1. Final placement of the ablation needle after the second pass. The hyperechoic area created by the initial ablation can be seen in the ultrasound image (c).

**Patient 1**

The first patient was a 65-year-old man with multiple bilobar colorectal cancer metastases. The patient had received neoadjuvant chemotherapy, with significant regression of the liver disease. The preoperative plan included a right hepatectomy combined with ablation of disease in the left liver. In the OR, standard B-mode IOUS was used to scan the liver and locate the tumour that was visible on the preoperative CT scan. It was difficult to localize the tumour with standard IOUS and therefore navigated US was used to aid in tumour localization. The navigated US projected both the standard B-mode US view and the analogous CT scan slice. The tumour was visualized on the CT plane projected by the navigation system onto the 3-D model, thus confirming that the US transducer was in the correct position to assist with visualization of the tumour. Once detected, microwave ablation was performed. A single microwave ablation needle was
The Explorer™ Liver system and IOUS were utilized in tandem to ensure a thorough examination of the relevant area had been conducted, mark, to confirm that the proper area was being examined. Once the IGS system was utilized, using the middle hepatic vein as a landmark, to navigate IOUS in conjunction with the IOUS did not reveal any tumour-like structures. A registration was performed and navigated US was used to re-investigate the area. The CT plane was observed until it intersected with the preoperatively segmented subcentimetre lesion, at which point the US image was consulted. By sweeping the CT plane across the segmented lesion, the surgeon was ultimately able to localize the tumour in the B-mode US image. The tumour was diagnosed as a cyst in view of its ultrasonographic properties (Fig. 8). In summary, by pinpointing the precise area of concern to the surgeon, navigated US enabled the surgeon to identify the lesion on the US image.

**Patient 2**

The second patient was a 54-year-old man with multiple bilobar colorectal cancer metastases treated with neoadjuvant therapy. The patient had demonstrated a good response to initial therapy, with significant regression of the liver disease. The preoperative plan included a complete treatment of the liver disease with a combination of resection and ablation, and placement of a hepatic artery infusion pump. The patient had known disease in the left liver prior to neoadjuvant treatment, but the disease was difficult to visualize on preoperative imaging as a result of chemotherapy-induced steatosis. Similarly, initial examination of segment IVa with IOUS did not reveal any tumour-like structures. A registration was performed and navigated IOUS in conjunction with the IGS system was utilized, using the middle hepatic vein as a landmark, to confirm that the proper area was being examined. Once a thorough examination of the relevant area had been conducted, the Explorer™ Liver system and IOUS were utilized in tandem to guide and confirm placement of a microwave ablation needle (Fig. 7). Postoperative imaging demonstrated no residual viable hypervascular tissue in the peritumoral location.

**Patient 3**

The third patient was a 46-year-old man with synchronous colorectal cancer liver metastasis. A triple-phase CT scan revealed one colorectal liver metastasis in segment VI, as well as two subcentimetre uncharacterized lesions located in segments II and VII, respectively. These two lesions were possibly small cysts but were not able to be characterized on preoperative imaging; clearly, the operative plan would be altered if these lesions were found to represent metastatic disease. In the OR, the lesions in segments II and VI were identified via standard B-mode IOUS. However, the segment VII lesion was not visualized after extensive survey of the organ with standard US. A registration was performed and navigated US was used to re-investigate the area. The CT plane was observed until it intersected with the preoperatively segmented subcentimetre lesion, at which point the US image was consulted. By sweeping the CT plane across the segmented lesion, the surgeon was ultimately able to localize the tumour in the B-mode US image. The tumour was diagnosed as a cyst in view of its ultrasonographic properties (Fig. 8). In summary, by pinpointing the precise area of concern to the surgeon, navigated US enabled the surgeon to identify the lesion on the US image.

**Discussion**

Indications for hepatic resection in both primary and secondary liver cancers are expanding. In addition, minimally invasive approaches to liver surgery using both laparoscopic and robotic platforms have become more common. Mortality rates in liver resection have decreased over the last several decades, even with the expanding indications. However, some aspects of modern liver surgery have become increasingly difficult, particularly as a result of the impact of preoperative chemotherapy in patients with hepatic colorectal metastases. Chemotherapeutic agents at times cause tumours to shrink to subcentimetre size, which makes them difficult to identify in the OR via IOUS. In some patients, these tumours even seem to ‘disappear’ on all imaging modalities. In addition, liver parenchyma is often difficult to evaluate with US in patients who have been treated with chemotherapy prior to liver resection or who have steatosis, an increasingly common comorbidity affecting liver surgery outcomes, for other reasons. Because of these issues, image-guided systems represent an important adjunct to help expand surgical options and overcome some of the many obstacles associated with liver resection.

Imaging in the preoperative setting has improved over recent years. Computed tomography scan technology, utilizing tri-phase contrasted acquisitions, and MRI and magnetic resonance cholangiopancreatography (MRCP), with new contrast agents such as Eovist, have expanded in application, sensitivity and specificity. Preoperative imaging techniques such as CT and
MRI provide excellent visualization of the significant anatomic structures in hepatic surgery, including the portal and hepatic veins, bile ducts, tumours and liver parenchyma. In general, transfer of this information to the OR is conducted via 2-D tomographic image review on intraoperative monitors. Although the intraoperative standard of IOUS provides real-time visualization of anatomic structures, the modality is limited by the 2-D nature of the images. Because of the limitations in evaluating the 3-D shape of subsurface structures in the liver with IOUS techniques and the impractical nature of intraoperative tomographic imaging, combined with the difficulties involved in finding and targeting tumours in patients with treated or steatotic livers, the optimal guidance system will allow for a marriage of IOUS visualization and preoperative 3-D imaging in the form of 3-D anatomic models, MRI and/or CT scans.

A surgical navigation system utilizes a tracking system to localize instruments relative to a frame of reference. There are numerous types of tracking system, including active optical, passive optical and electromagnetic (EM), each of which has its own advantages and disadvantages. Active and passive optical tracking are line-of-sight systems and thus require an unobstructed path between the camera and the tracked instrumentation. Active optical tracking requires that cables be connected to each tracked device, which limits its usability in the OR. Passive optical tracking is wireless but is constrained by the geometric design of tracked instrumentation, as well as by a more limited ability for simultaneous instrument tracking. Passive optical tracking has been shown to have accuracy comparable with that of active tracking. Electromagnetic systems allow for the tracking of non-rigid instruments, such as flexible laparoscopic US transducers, but their utility in the OR has yet to be successfully demonstrated.

One passive tracking navigation system utilizing a landmark-based registration has been reported for open liver surgery. This
system incorporates navigated US and offers a median registration accuracy of 6.3 mm based on nine clinical cases. Another system provides navigation of tracked surgical instruments within a 3-D US volume. This method allows for rapid response to organ deformation, but demands larger, more costly US probes and increased set-up time. In addition, it presents a significant learning curve for the surgeon. Another method involving the registration of 3-D IIOUS to preoperative CT is less dependent on manual input and does not necessarily require accurate initial alignment. Although this method appears promising, it is unclear whether resulting guidance information would be accurate outside the region of interest contained within the 3-D US image. Multiple re-registrations may be required depending on the location of the acquired 3-D US data used for registration in relation to the anatomic region to be treated. By contrast, the registrations performed within the Explorer™ Liver device incorporate information over the entire anterior surface of the organ and therefore the registrations calculated may be more accurate throughout the entire liver anatomy. Similar navigation systems have been developed for laparoscopic procedures.

The navigation system utilized in this study integrates IIOUS, preoperative tomographic imaging and 3-D anatomic models on a single display in the OR, thus facilitating achievement of the optimal course of therapy in selected patients. Preoperative tomographic imaging assists with providing an enhanced understanding of the anatomic context during the surgical procedure, and navigation based on preoperative imaging is clearly useful in targeting lesions that are not visible or ‘disappear’ sonographically. Standard abdominal imaging protocols are sufficient for image guidance, assuming a maximum slice thickness of 5 mm.

Figure 8 Patient 3. Localization of subcentimetre cyst with navigated ultrasound (US). The cyst is visible in the upper right of the US image (c). The computed tomography slice shown in (a) and (b) reflects the position and orientation of the US transducer and visibly intersects the cyst, as corroborated by the US image.
However, if preoperative images are of poor quality, the value obtained from the guidance system may be diminished. The accuracy of all registrations acquired during the procedures outlined in this paper was deemed adequate for surgical guidance. Although registration error is not explicitly reported by the Explorer™ interface, in cases in which subcentimetre lesions were present, registrations were deemed accurate enough to be utilized for guidance and ultimately resulted in the localizing of the said lesions. Specifically, the standard error values reported for registrations involving surface matching can be misleading because small surface error values do not necessarily correspond to accurate guidance. In order to assess the accuracy of a computed registration, the clinician is prompted with a dialogue (Fig. 9) after the intraoperative surface data have been acquired. The clinician can then accept or reject the registration based on a qualitative assessment of guidance accuracy (i.e., an anatomic structure is identified with the tracked probe and the guidance display is checked to ensure accuracy).

In procedures in which large lesions or other deformations grossly alter the surface anatomy of the liver, additional care must be taken to ensure registration is accurate. The present authors have not yet encountered a situation in which this was not possible.

Although the present experience indicates that surgical workflow is not impeded by the additional time required to perform registration, it is helpful for an additional person to be present in the OR to operate the navigation system rather than to place all of the controls at the surgeon’s fingertips, as described by Peterhans et al.19 If an additional staff member is not available as a resource, a sterile touch screen interface that allows the surgeon and his or her assistant to control the system may be beneficial.

There are some issues inherent to image guidance in liver surgery, one of which concerns the organ’s mobility and capacity for intraoperative deformation. During open liver surgery, the liver is routinely mobilized from adjacent structures and also readjusted to facilitate optimal placement and ergonomics throughout the procedure. Numerous approaches have been developed to account for deformations, but, regardless of the proposed solution, a significant factor in the success of an image-guided liver system is the surgeon’s comprehension of the limitations of whichever approach is utilized. Formal training provided by the manufacturer can significantly accelerate the learning curve, but, anecdotally, surgeons and trainees become facile with the Explorer™ Liver device after using it in five procedures or fewer. The cost of the technology is roughly comparable with that of currently marketed IOUS systems and is therefore not prohibitive.

Another limitation of the system described in this paper is its inability to continuously register to the liver. In the event that the liver is deformed or is moved relative to the tracking camera by surgeon manipulation or patient respiration, a re-registration must take place to realign instrument tracking to the new organ position. Approximately 1 min is required per registration. This re-registration is possible during or after a resection if at least two salient anatomic features can be identified intraoperatively.6,27

Future work will focus on compensation for organ motion and deformation, as well as an approach for navigated laparoscopic US. Overall, a technology that allows for constant updates of the display of surgical instrumentation overlaid on preoperative tomograms shown in conjunction with 3-D anatomic models and real-time navigated IOUS is of considerable value in identifying, ablating and resecting liver tumours.
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Conflicts of interest
MAS, JDS, LWC and BWN are employees of Pathfinder Therapeutics, Inc.

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