Design and implementation of an electromagnetic ultrasound-based navigation technique for laparoscopic ablation of liver tumors

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Abstract

Background Efficient laparoscopic ablation of liver tumors relies on precise tumor visualization and accurate positioning of ablation probes. This study evaluates positional accuracy and procedural efficiency of a dynamic navigation technique based on electromagnetic-tracked laparoscopic ultrasound (ELUS) for laparoscopic ablation of liver tumors.

Methods The proposed navigation approach combines intraoperative 2D ELUS-based planning for navigated positioning of ablation probes, with immediate 3D ELUS-based validation of intrahepatic probe position. The environmental influence on electromagnetic-tracking stability was evaluated in the operation room. Accuracy of navigated ablation probe positioning assessed as the target-positioning error (TPE), and procedural efficiency defined as time efforts for target definition/navigated targeting and number of probe repositionings, were evaluated in a laparoscopic model and compared with conventional laparoscopic ultrasound (LUS) guidance.

Results The operation-room environment showed interferences < 1 mm on the EM-tracking system. A total of 60 targeting attempts were conducted by three surgeons, with ten targeting attempts using ELUS and ten using conventional LUS each. Median TPE and time for targeting using ELUS and LUS were 4.2 mm (IQR 2.9–5.3 mm) versus 6 mm (IQR 4.7–7.5 mm), and 39 s (IQR 24–47 s) versus 76 s (IQR 47–121 s), respectively ($p < 0.01$ each). With ELUS, median time for target definition was 48.5 s, with 0 ablation probe repositionings compared to 17 when using LUS. The navigation technique was rated with a mean score of 85.5 on a Standard Usability Scale.

Conclusions The proposed ELUS-based navigation approach allows for accurate and efficient targeting of liver tumors in a laparoscopic model. Focusing on a dynamic and tumor-targeted navigation technique relying on intraoperative imaging, this avoids potential inaccuracies due to organ deformation and yields a user-friendly technique for efficient laparoscopic ablation of liver tumors.

Keywords Ablation techniques · Computer-assisted surgery · Laparoscopy · Ultrasonography · Three-dimensional imaging · Liver neoplasms

Local ablation strategies are increasingly performed for patients with malignant primary and secondary liver neoplasms, representing a locally destructive treatment option for patients with limited disease, or when surgical resection is precluded [1]. Due to its tissue-sparing character, local

ablation can also be applied in repeated treatment sessions in cases with more extensive disease or with recurrence after previous treatments [2]. Furthermore, the combination of local ablation with a minimal invasive treatment access such as laparoscopy allows an optimal reduction of tissue trauma and related patient morbidity, with adequate long-term results [3, 4].

Key aspects of successful ablative therapy are the optimal localization of intrahepatic tumors and the precise placement of ablation probes in the tumor center [5], as inaccurate positioning of ablation probes or repeated targeting attempts can lead to incomplete ablation or seeding of tumor cells with concurrent higher local recurrence

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rates [6]. When relying on conventional laparoscopic ultrasound (LUS), visualizing both the ablation probe and the tumor in the same image plane is challenging, and requires great experience especially when targeting more centrally located liver tumors [7]. In a laparoscopic setting in particular, the often limited instrument access and long targeting trajectories contribute to the complexity of the procedure, especially when targeting lesions in superior or dorsal liver segments. Also, only limited intraoperative feedback regarding technical success of ablation probe positioning is possible when relying on conventional LUS.

To address these issues, image-guided surgery (IGS) systems have been introduced, and recent reports suggest enhanced intraoperative tumor localization and precise positioning of ablation probes [8]. While most studies report benefits when applying stereotactic image-guidance systems in open liver surgery [8–10], Earliest studies reporting the use of navigation technology in laparoscopic settings show promising results [11–13]. Nevertheless, the application of navigation technology in a clinical routine remains challenging, mainly due to the additional procedural efforts related to the setup and training for an intraoperative use of these systems [14]. Furthermore, most commercially available systems are based on intraoperative registration of preoperative image data to the intraoperative liver position, visualizing the spatial relationships between the surgical tools and the patient anatomy [15]. However, this registration process can lead to substantial inaccuracies due to organ deformation during intraoperative tissue manipulation, especially when relying on surface registration points. To address these challenges, electromagnetic (EM)-tracking technology has been integrated for use in soft tissue navigation [16]. A major advantage is the possibility of tracking flexible and bending instruments such as the LUS, which is precluded when using optical tracking dependent on a direct line-of-sight. First works report the benefits of navigated LUS using EM-tracking technology [17–19]; however, differences in the measurement of technical success (i.e., tumor hit rate or registration accuracy) allow for only limited knowledge about the exact position of the ablation probe in a quantitative and reproducible and comparable manner.

In order to (i) improve precision in laparoscopic positioning of ablation probes using dynamic intraoperative tracking of surgical instruments and (ii) allow for intraoperative evaluation of technical success using 3D ultrasound [20], we introduce a navigation approach based on intraoperative electromagnetic laparoscopic ultrasound (ELUS). In this study, we evaluated stability of the EM tracking in the operation-room environment, and evaluated positional accuracy and procedural efficiency of the proposed technique compared with the conventional LUS guidance, in a laparoscopic model.

Materials and methods

System overview

A commercially available navigation system for use in liver surgery (CAS-One, CAScination AG, Switzerland) was extended with electromagnetic technology for instrument tracking, using a table-top field generator (FG) for generation of a magnetic working space (Aurora, Northern Digital, Canada). This generates a magnetic field inducing a current into small coils (i.e., EM sensor) [16], from which the 6D pose (position and rotation) is calculated. A LUS with a flexible tip (FlexFocus 800 with 8666-RF probe, BK Medical, Denmark) was used for intraoperative imaging and was supplied with EM technology by developing a laparoscopic ultrasound tracker (LUT) consisting of stainless steel (Fig. 1A). The adapter is dimensioned to fit through a standard 15 mm trocar when mounted onto the probe. The sensor-to-image transformation is calibrated preoperatively in a laboratory environment using an EM-tracked Z-fiducials phantom [21].

As an ablation probe with embedded EM sensor in the tip is currently not available, we developed a tracked probe guide (TBG) where an EM sensor (Pointershell, Fiagon GmbH, Germany) can be reproducibly attached to a trocar (Fig. 1B). The axis of the cannula and its entry point are calibrated preoperatively in a laboratory environment.

Navigation and validation workflow

The workflow of the proposed technique consists of three separate stages: (i) acquisition of the tumor target, (ii) navigated positioning of the ablation probe and (iii) validation of target positioning error (TPE) (Fig. 2).

In a first step, the intrahepatic tumor is localized using the ELUS, and the chosen location is selected on the touchscreen. Precise adjustment of the selected location and the size of the preferred target can be performed in three dimensions using additional commands (Fig. 2A).

For precise alignment of the TBG and navigated positioning of the ablation probe, a crosshair viewer provides a graphical visualization of the lateral alignment with respect to the tumor, next to an additional numerical indication of the lateral and longitudinal distances (Fig. 2B). An overlay of the predicted probe trajectory allows for verification of the safety of the trajectory (i.e., important anatomical structures within the targeting trajectory). During the navigated positioning of the ablation probe, the overlay of the tumor on the US image is monitored to detect an eventual displacement of the tumor target, with need for reacquisition of the tumor location in that case (Fig. 2C).

Fig. 1 **A** The laparoscopic ultrasound tracker, consisting of two parts of stainless steel adapted with a screw nut, with an integrated EM sensor. **B** The tracked probe guide attached to a cannula which was used as trocar for insertion of the ablation probe

For intraoperative validation of TPE, the position of the tip of the ablation probe relative to the previously selected tumor target is acquired. To this end, a compounded 3D US scan is obtained by freehand scanning of the tumor, the positioned ablation probe and the surrounding area, using a pixel-based method with linear interpolation of missing voxels for compounding [22, 23]. In addition, a visual feedback of the bounding box and filling stage is provided to guide complete scanning of the volume of interest (Fig. 2D). Once the true location of the ablation probe is manually confirmed on the image, the IGS system computes the Euclidean TPE with respect to the planned trajectory.

Experimental design

Evaluation of EM-tracking stability in the operating room

Due to the sensitivity of EM tracking to distortions in the electromagnetic field and thus the crucial importance of assessing the system in the target clinical environment [16, 24], we analyzed the influences of electronic devices (endoscope, ultrasound probe, ablation, and cautery devices), the standard OR, and anesthesia equipment as well as the IGS system itself on the EM-tracking system. To this end, three EM sensors were attached in a fixed position on the FG, and the distances between their EM-tracking positions were measured. First, a measurement was performed without any equipment in the proximity to the FG, representing the baseline measurement. Subsequently, the measurement was performed after placing each device or equipment item separately at its expected position in a laparoscopic setup. The effect of each device was then calculated as the difference in the measurements with the device with respect to the baseline measurement.

Evaluation of positional accuracy and procedural efficiency

The proposed navigation approach was evaluated in an ex vivo analysis, using navigated (ELUS) and conventional (LUS) image guidance for positioning of ablation probes, in a virtual OR. The laparoscopic model consisted of a plastic torso (Fig. 3A) with insertions on the ventral abdominal wall for insertion of laparoscopic instruments, which were closed with sponge to provide a skin-like structure. The laparoscopic torso was positioned in a French position, with the LUS, the laparoscopy screens and the IGS positioned according to the standard setup at our hospital and the FG placed on top of the OR table (Fig. 3B).

A liver phantom containing intrahepatic hypoechoic tumors was applied (parenchyma: 1.5% agar and 1% corn starch, spherical tumors: 1.5% agar without corn starch), with several 2 cm tumors randomly placed at 3–5 cm distance from the surface.

Experiments were performed by three surgeons with experience in LUS-guided ablation of liver tumors. The experimental workflow consisted of the following steps:

1. Localization of a tumor using ELUS
2. Selection of the target point in the tumor center
3. Navigated positioning of the ablation probe
4. Acquisition of a 3D US scan of the tumor and the inserted ablation probe
5. Measurement of the resulting TPE on the 3D US scan

This workflow was applied for ten tumors using conventional LUS guidance and for ten tumors using the navigated ELUS approach, by all three surgeons. Up to five repositionings of the ablation probe were allowed in order to hit the tumor, however, once the probe was positioned inside the

Fig. 2 **A** Precise selection of the tumor target on an intraoperative ELUS image. **B** Crosshair viewer showing the alignment of the tracked probe guide and the lateral error and the depth to the target.

C The overlay of the selected tumor (yellow) and the predicted probe trajectory (red) on the live US image. **D** Visualization of the filling state in 3D during acquisition of the 3D US scan

tumor, no repositioning or correction of the probe trajectory were allowed. To achieve probe trajectories of different lengths, directions, and angles relative to the surface of our liver model, the entry point was varied between each targeting attempt. Each surgeon was briefly introduced into the workflow and was granted one practice round using ELUS for ablation probe positioning.

The TPE for each targeting attempt was assessed as the Euclidean distance (straight line distance) between the center of the tumor and the tip of the ablation probe in the 3D US image, as shown in Fig. 4. Time for acquisition of the tumor target included step 2, time for navigated positioning of the ablation probe included step 3 of the above described workflow.

Fig. 3 **A** Laparoscopic torso, with insertions used for introduction of ablation probes (*a*), the endoscope (*b*), and the ELUS (*c*). **B** Overview of experimental setup

Fig. 4 **A** Oblique slice of the compounded 3D US image along the trajectory of the probe (dashed) inside the tumor (dotted). From these images, the TPE with respect to the tumor center was calculated. **B** The oblique slices inside the 3D US volume

After completion of the experiment, each surgeon filled out a Standard Usability Scale (SUS) questionnaire [25], rating the navigation system on a scale of 0–100 (“not usable at all”—“theoretical maximum”) [26]. In addition, each surgeon was asked to rate the statements “I felt confident when using LUS/ELUS for positioning of the ablation probe,” and “I found it difficult to reach to the target using LUS/ELUS” on a scale from 1 to 5 (“strongly disagree”—“strongly agree”).

Statistical analysis

Descriptive statistics were used to report environmental influences on the EM-tracking accuracy, positional accuracy, and procedural times. The Kruskal–Wallis test was applied to analyze between-group differences of the applied approach (LUS vs. ELUS) and of different users on TPE and time for navigated probe positioning. The Chi-square test was applied to analyze differences in the

number of ablation probe repositionings for LUS versus ELUS. All analyses were performed using the software R (R Foundation for Statistical Computing, Austria), and significance levels were set at $p = 0.05$.

Results

EM-tracking stability in the operating room

The assessment of the effect of different devices in the OR environment on the EM-tracking accuracy with respect to the baseline-tracking accuracy yielded interferences < 1 mm for all devices. The most-accentuated effect was observed for the LUS (median 0.29 mm) and the laparoscopic endoscope (median 0.39 mm). All other devices showed a median effect on the EM-tracking system of 0.1 mm or less (Fig. 5).

Fig. 5 Effects of different devices from the OR environment on EM-tracking accuracy with respect to the baseline measurements (dotted line). Median and ranges are shown

Table 1 Main procedural outcomes

	User 1		User 2		User 3		Overall	
	LUS	ELUS	LUS	ELUS	LUS	ELUS	LUS	ELUS
Number of targeting attempts (n)	10	10	10	10	10	10	30	30
TPE (mm)	5	4.35	6.6	3.35	6.55	5	6	4.2
Time for target selection (s)	–	29.5	–	59	–	59	–	48.5
Time for navigation (s)	78.5	23.5	97.5	59.5	69	50.5	75.5	39
Number of ablation probe repositionings (n)	1	0	1	0	3	0	1.5	0

Data are grouped by user and by the applied targeting approach (LUS vs. ELUS), and presented as medians

Positional accuracy and procedural efficiency

A total of 60 targeting attempts were performed by three surgeons, with 30 measurements using LUS, and 30 measurements using ELUS for targeting. Main procedural outcomes are summarized in Table 1.

Median TPE when using conventional LUS was 6 mm (IQR 4.7–7.5 mm) and with navigated ELUS 4.2 mm (IQR 2.9–4.3 mm, $p < 0.01$) (Fig. 6). In contrast, no significant difference in targeting accuracy was shown between all three surgeons ($p = 0.32$). In 17 out of 30 targeting attempts (56%), up to 5 repositionings of the ablation probe were required to hit the tumor when using conventional LUS, versus 0 repositionings required when using navigated ELUS ($p < 0.01$) (Fig. 7). The length of the ablation probe trajectories ranged between 15 and 25 cm.

Median time for acquisition of the tumor target when using navigated ELUS was 48.5 s. Median time for positioning of the ablation probe was 76 s (IQR 47–121 s) when using conventional LUS and 39 s (IQR 25–57 s) when using navigated ELUS ($p < 0.01$) (Fig. 6). No significant

Fig. 6 Positional accuracy and procedural efficiency when using ELUS versus LUS. Left: Target positioning error. Right: time for positioning of the ablation probe. Median and IQR intervals are shown

Fig. 7 Total number of repositionings required for positioning of the ablation probe using ELUS versus LUS. Different colors indicate the numbers of required repositionings (0–5)

differences in targeting times were shown between all three surgeons ($p=0.27$).

Usability analysis

The SUS was scored with a mean of 85.8 out of 100, with scores of 80, 87.5, and 90 by surgeons 1, 2, and 3, respectively. The question whether most people would learn this system quickly received the highest rating (mean 4.6), and

the question whether initial technical support would be needed received the lowest rating (mean of 2.6). Moreover, all three surgeons indicated feeling more confident when using the navigation system for targeting (4.3 vs. 2.0), while finding it more difficult to reach the target when using the conventional LUS approach (1.3 vs. 4.3).

Discussion

In this study, we present a dynamic and user-friendly navigation approach for laparoscopic ablation of liver tumors, based on EM-tracked US. Next to yielding accurate and efficient positioning of ablation probes in the laparoscopic model, this is the first navigation approach introducing the possibility of intraoperative validation of targeting accuracy based on 3D US.

The EM-tracking stability measurements in the OR showed that the proposed approach can be applied in a clinical environment with insignificant interference on the system's tracking accuracy (<1 mm), similar to interferences reported in other studies [17]. While the largest effects observed for the LUS and the endoscope seem logical as these are the only electronic devices located within the actual EM field, the OR table had a negligible effect on tracking stability as it is especially designed for this application and unaffected by metal objects located below the FG. Nevertheless, a real-time monitoring of the EM distortions during the surgery continuously detecting the impairment of the EM tracking would be desirable. With this knowledge about the environmental influence on EM-tracking accuracy, we conducted our ex vivo analysis using the same endoscope, ELUS, and FG.

In contrast to other navigation approaches [12, 13, 17], the proposed technique does not rely on a registration to preoperative imaging, and thus reduces potential inaccuracies due to organ deformation, a frequent limitation of registration-based soft tissue navigation. It rather operates in the available intraoperative imaging space, allowing a very fast acquisition of the tumor target (48 s), with the possibility of an equally fast reacquisition in case of intraoperative tissue deformation. The surgical plan is created after the liver is mobilized and immediately before placement of the ablation probe, increasing surgical freedom and reducing errors resulting from liver manipulation between the planning and the targeting phases of the procedure [11]. This further allows to apply the technique with the patient placed in different positions (e.g., in a left lateral position), making tumors located in the right posterior segments more easily accessible all by using the dynamic navigation technique by directly placing the ELUS on the posterior surface of the liver. This might also allow reducing the lengths of intrahepatic probe trajectories compared with the long intrahepatic courses required when targeting posterior tumors from the anterior liver surface. Furthermore, organ motion compensation was not included in this study due to maximally reduced time for navigated tumor targeting (on average 39 s), which allows targeting during an extended end-expiratory phase assuming a static environment during this period. Alternatively, organ motion can be controlled to a great extent using high-frequency jet ventilation or apnea [27]. We rather focused on a dynamic and efficient intraoperative planning method, which allows the surgeon to adapt the intraoperative plan quickly and easily during the procedure in case of tissue deformation.

Both positional accuracy and procedural efficiency measurements showed superiority when using ELUS compared with conventional LUS guidance in this study. This result is highlighted by the fact that up to five repositionings of the ablation probe were needed when using LUS. Contrarily, ablation probes could be accurately positioned in the first targeting attempt when using ELUS, thus reducing potential tissue damage and bleeding due to multiple probe positionings, and preventing potential seeding of tumor cells [6]. This underlines the potential benefit of ELUS toward not only enhanced positional accuracy, but more importantly improved safety by substantially reducing the amount of required targeting attempts. The differences in accuracy and efficiency when using ELUS versus LUS might have been even more accentuated in this study when including inexperienced surgeons for performing the targeting experiments. However, we deliberately included three surgeons familiar with the use of the LUS, in order to exclude potential confounding due to an inexperienced instrument handling [28]. Furthermore, a trend toward achieving better results in terms of targeting accuracy and

targeting times over time was noticed in two of the three surgeons. Even though the sample size was too small to address this adequately, we expect the learning curve to be steep based on our previous experience with the use of navigation technology in a laparoscopic clinical setting [11].

Very few studies analyzed targeting accuracy when applying navigation technology for positioning of ablation probes to date, reporting values between 5 and 10 mm [29]. Compared with the results from these studies, a median targeting accuracy of 4.2 mm (IQR 2.9–4.3 mm) reached in this study seems acceptable and favorable when considering an intended ablation margin of 5–10 mm [30]. A recent study on accuracy and efficacy of laparoscopic navigated ablation of liver tumors reported surface registration accuracies around 8 mm; however, TPE of the ablation probe inside the tumor could not be calculated with the applied navigation technique [11]. When analyzing the improvement on first attempt hit rates with the ELUS-guided approach, our results were similar to the ones reported in a previous study using a similar technique [28].

To reduce the often considerable efforts regarding the setup and user training when introducing novel navigation technology into a clinical routine [14, 31], we deliberately implemented a user-friendly and simple workflow, which can be easily embedded into the surgical procedure and minimizes additional efforts during the surgical procedure itself. To this end, we propose a technique that eliminates a registration process as such and integrates the use of intraoperative imaging. However, an additional effort related to the perioperative setup of the instrumentation (e.g., mounting, positioning of navigation system) is hardly avoidable when introducing novel technology and is known to increase the perioperative complexity in a clinical setting. To address this issue, we designed tracking instruments which are readily usable in the operating theater, with the LUT that can be mounted and dismounted from the LUS at any time. Due to its unique fit, the LUS does not require intraoperative calibration, nor does the TBG, thus, limiting user-induced calibration errors and prolonged calibration time as described in other studies [32]. Nevertheless, we believe that the optimal solution for navigated targeting would be an ablation probe and LUS with an integrated EM sensor into the tip, available for clinical use. The usability analysis in this study yielded an easy use of the proposed navigation approach, which was preferred over the conventional LUS approach. Still, two of the three surgeons stated to prefer initial technical support when using the system in a clinical setting. Ultimately, we believe that the reduction of the complexity of the surgical task itself, when using navigation technology that yields efficient, accurate, and safe tumor targeting, justifies the additional perioperative efforts related to the system setup. Obviously, the time efforts related to perioperative setup as

well as the usability of the proposed devices must be confirmed in a clinical trial.

A possible confounding factor in the methodology of this study might be the rather short distance from the artificial tumors from the surface (3–5 cm), whereas centrally located lesions might be located as deep as 8 cm from the liver capsule. This theoretically does not affect targeting using ELUS, as the trajectory is planned overall from skin incision to target. In contrast, LUS might have been overrated in our setup, which would accentuate the demonstrated benefits of ELUS even more. Importantly, the overall lengths of the trajectories (from skin entry to tumor center) ranged between 15 and 25 cm, showing good correspondence to the range of trajectories expected in a clinical laparoscopic scenario.

A possible limitation of the proposed navigation technique is the limited knowledge regarding potentially relevant anatomic structures along the ablation probe trajectory, as the proposed technique focuses on a directly tumor-targeted approach. Although the probe trajectory can be verified using the overlay of the targeting trajectory on the navigated 2D LUS image, this could be further enhanced by adding intraoperative segmentation of vessel structures or by adding registered preoperative image data (e.g., a 3D model from CT data). Also, the proposed approach focuses on tumors that can be visualized on the LUS image, and is thus not suitable in cases where tumor visibility is altered or for treatment of vanishing lesions after previous chemotherapy [33]. This might be overcome by integrating contrast-enhanced ultrasound, which is readily available in most novel LUS devices [34].

In conclusion, the proposed ELUS-based navigation technique yielded accurate and efficient positionings of ablation probes in a laparoscopic model, compared with conventional LUS guidance. We introduce a dynamic and user-friendly approach for laparoscopic ablation of liver tumors, with the possibility of intraoperative acquisition of target-positioning accuracy and thus quantitative knowledge about technical success.

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Compliance with ethical standards

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