Design and Implementation of a Navigation System for Laparoscopic Tumor Ablation based on Intraoperative US

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Abstract:

Laparoscopic ablation of liver tumors using ultrasound (US) guidance is a challenging task as it depends on the ability to mentally reconstruct the 3D spatial relationships between the tumor and the ablation needle from 2D ultrasound images. In this work we present a simple 2D ultrasound based image-guidance system for laparoscopic liver tumor ablation. The proposed system provides technology for navigation towards a target which is defined directly in the ultrasound images. To evaluate feasibility of the system, first experiments on a plastic torso including an agar ultrasound phantom were conducted. The results of first experiments by an experienced surgeon using three different guiding modalities show, that by using this system the ablation needle can be placed inside a tumor of 1 cm to 2 cm diameter with a success rate of 100% with two of the three used modalities.

Keywords: Image-guided laparoscopic surgery, electromagnetic tracking, ultrasound imaging, navigation

1 Introduction

The laparoscopic access for ablation of liver tumors has the advantage of reduced complications and shorter hospital stays when compared to open surgical approaches. Local ablation represents a valid alternative for treatment of hepatic tumors of limited number and size and within combined treatment strategies of both resection and ablation[1]. For laparoscopic ablation, positioning of the ablation antenna is conventionally done by laparoscopic ultrasound guidance[2]. Ultrasound-based needle guidance requires great experience next to the ability to mentally reconstruct 3D spatial relationships from 2D images [3]. Sipperstein et. al. [2] reported the placement of a needle into a tumor using laparoscopic ultrasound as one of the technically most challenging aspects of the procedure.

To date various navigation systems have been proposed to support needle guidance. Such systems may use mechanical support or mechanical tracking [4], which reduces the freedom of surgical access and intraoperative maneuvering. Other systems, like the CAS-One (CAScination AG, Bern, Switzerland) navigation system, rely on registration of a preoperative image to the surgical scene. Sindram et. al. [3] proposed an approach where the ultrasound, the needle and its trajectory are visualized in real-time in a 3D scene. While this approach allows registration-free targeting, the approach relied on an EM sensor glued to the tip of the needle, which is not applicable in long term clinical routine, and also relied on 3D visualization which may also be suboptimal in a clinical setting.

We propose a simple 2D approach which uses an EM tracked 2D planar ultrasound and an EM tracked ablation tool. This tool can have a tracking sensor attached or can be used together with a tracked needle guidance device. Based on the 6D pose of the image the system calculates the 3D position of a tumor, which is identified by a surgeon on the 2D US image. In order to assist the surgeon during needle placement, the system shows the relative position and orientation of the ablation tool with respect to the target. The needle placement is performed free hand supported by visual information provided by the system. Thus image-guided needle placement is possible without requiring pre-operative planning or registration.

We hypothesize that when using the proposed system, an ablation needle can be placed into a tumor of 1 cm to 2 cm diameter. This is evaluated in an experiment by an experienced surgeon on an agar phantom placed inside a plastic torso. This initial analysis will set the base for further development of the system towards a clinical application in laparoscopic liver surgery.

2 Materials and Methods

The proposed system is based on the CAS-One navigation system, which is equipped with the Aurora (Northern Digital, Ontario, Canada) EM tracking system and the Flex800 (BK Medical, Herlev, Denmark) laparoscopic ultrasound system (LUS). A clamp with an integrated sensor is attached to the LUS to measure its 6D pose. The LUS is calibrated [5] and therefore the system knows the geometric transformation between the 2D US image and the coordinate system of the EM tracking.

2.1 Target Selection & Navigation Workflow

The surgeon first scans the liver using the 2D LUS as in conventional treatments. When the tumor has been identified on the US image the surgeon marks the approximate center by pressing on it in the US image viewer on the touchscreen interface. This causes the image to freeze, and provides commands to move the target horizontally, vertically and orthogonal to the image plane. Additionally, the size of the tumor can be adjusted to simplify the selection of the center. While the surgeon adjusts the target a second live US image is provided with an overlay of the currently defined target, which allows the surgeon to verify the selection (Figure 1 left).

Once the target has been defined appropriately, the navigation state begins. During navigation, the surgeon is provided with a cross hair viewer which allows the alignment of the needle guidance device to the tumor. Additionally the predicted lateral error and the depth to the target are visualized. The predicted needle trajectory is also projected onto the ultrasound image, allowing the surgeon to verify that the trajectory will not interfere with important anatomical structures. This second part of the software is shown on the right screenshot in Figure 1. The overlay of the defined target on the US image allows the surgeon to detect displacement of the tumor and reacquire the target if necessary.

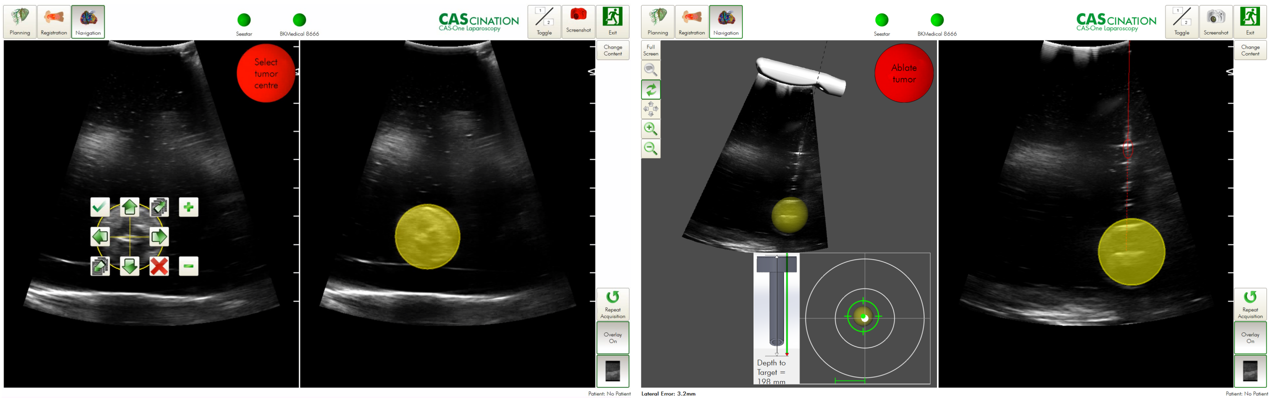

Fig. 1: The selection of the tumor center on the left and the navigation using the cross hair viewer on the right. The red line overlay shows the predicted needle trajectory and the yellow circle the defined target.

2.2 Tracked needle and needle guides

During navigation, the ablation needle has to be accurately placed into the target. After the entry point is chosen and the needle is touching the skin the surgeon has three degrees of freedom to control: two rotational axes and the depth to the tumor. This control is supported by information from the tracked instruments, which can be used interchangeably. In Figure 2 these instruments are shown and explained in the subsequent paragraphs.

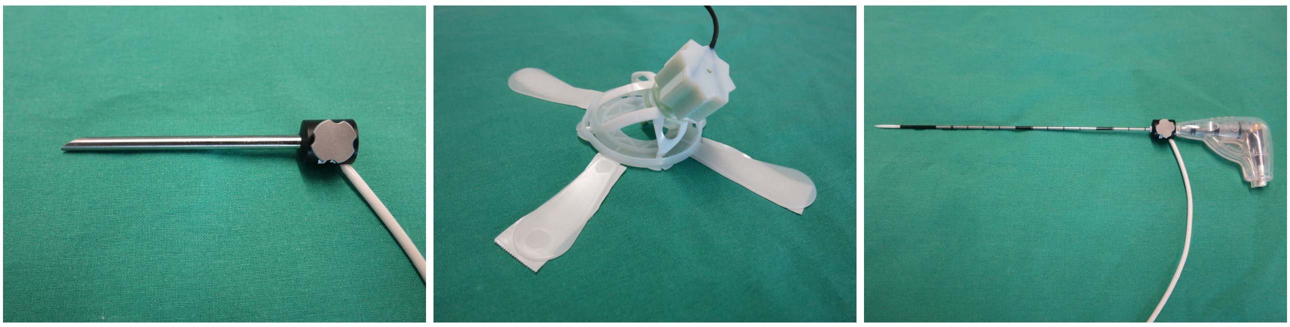

Fig. 2: The three tracked instruments from left to right: trocar, seestar and tracked ablation needle.

Trocar

The trocar, (Figure 2 left) consists of the commercially available Pointershell®(Fiagon GmbH, Berlin, Germany) which is mounted on a canula, serving as access through the abdominal wall and providing guidance of the needle to reduce bending. This device is best used two handed, with one hand holding the position of the trocar and the other hand inserting the needle. The device is precalibrated by the manufacturer and provides 6D pose information without intraoperative calibration.

Seestar

The seestar (Figure 2 center, Apriomed AB, Uppsala, Sweden) is used in Interventional Radiology for needle guidance. The top part of the seestar can be fastened and loosened, which allows the surgeon to align the seestar to a specific direction and therefore reducing two degrees of freedom. In contrast to the trocar the seestar can be used one handed by aligning and fixing the device first and then inserting the needle. In order to track the seestar a 3D printed adapter with an integrated 6D EM sensor was developed. The adapter was precalibrated by digitizing the canula with a tracked rigid needle and therefore no intraoperative calibration is needed.

Tracked needle

As a sensor glued to the tip of a needle is not a suitable clinical solution, we introduced a different approach where the Pointershell®, which is also used for the trocar, is attached to an ablation needle, as shown on the right in Figure 2. To get a firm connection, an adapter was built to adjust the inner diameter of the Pointershell®to the outer diameter of the needle. Calibration of the needle tip was performed via pivoting.

2.3 Experiment

To evaluate the developed system an experiment was set up in order to assess the technical success and the time required to navigate a needle into a tumor. Technical success was defined as achieved if the needle is placed inside a spherical tumor with a diameter of 2 cm.

2.3.1 Phantom torso

For the experiments a phantom was built out of a plastic torso, as seen in Figure 3. The torso was opened on the right side to gain access to insert an agar phantom (d). Stones were added to increase the weight and reduce the mobility on the OR table. Then the inside was filled with construction foam.

On the ventral abdominal wall of the phantom, holes were cut for insertion of needles (a), a laparoscope (b) and a laparoscopic ultrasound (c). To mimic the insertion of surgical instruments during laparoscopic liver surgery, holes were placed below the sternum, in a periumbilical location and subcostally on each side. The holes were closed with sponge to provide a skin-like flexible structure.

Fig. 3: The phantom (left) used to mimic a patient in a laparoscopic setting (right). The phantom has insertions for the ablation needle (a), the laparoscope (b), LUS (c). Approximate location of the agar phantom (d).

For simulation of a liver containing intrahepatic tumors, an agar phantom with dimensions of 20 cm × 15 cm × 9 cm was built and grapes of approximately 1 cm to 2 cm diameter were inserted into the gel at a depth of ca. 7 cm to 8 cm. This agar block was then inserted into the torso on the right side.

2.3.2 Experimental workflow

The experiment with the following steps was then performed by an experienced surgeon (Figure 3 right) without prior training on the system:

1. Scanning the agar phantom using the laparoscopic ultrasound to find a tumor
2. Selecting the center of the tumor
3. Inserting of the needle into the tumor
4. Visually validating whether the tumor is hit using the laparoscopic ultrasound and deciding whether the targeting was a "hit" or "no hit"

These steps were repeated five times on different targets with each of the three devices. The time for each targeting was measured from step 2 to step 4, which represented the actual navigation time.

3 Results

In the experiments the technical success was measured as "hit" or "no hit". With the seestar and the trocar all five targeting attempts (5/5) were successful. With the tracked needle only one attempt was successful (1/5). After the experiment it was found that the problem was a miscalibration of the needle which was not detected during the experiment.

The time measurements for the placement of the needle (after selection of the initial target on the US image) yielded a mean time of 60 seconds within a range from 30 seconds to 180 seconds for the placement of the needle, after selection of the initial target on the US image. As shown in Figure 4, with all three modalities the first attempt required the more time than the others. The subsequent attempts took less time, however fluctiations remained.

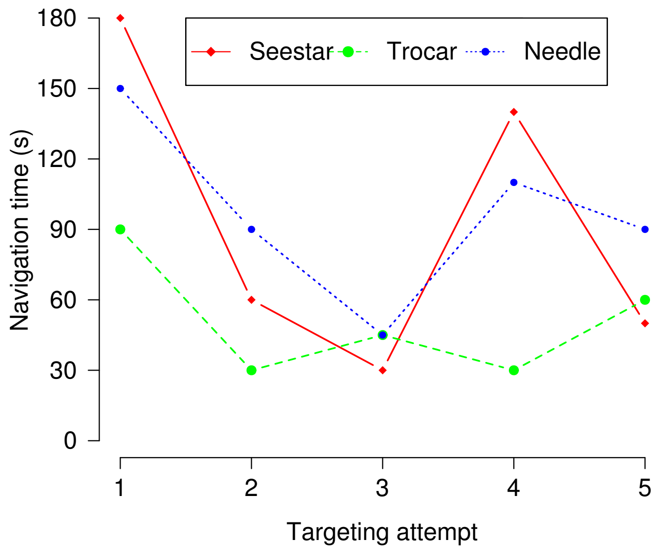

Fig. 4: The navigation time per targeting modality tends to decrease with increasing attempts

3.1 Subjective Feedback

The surgeon rated the navigation using the seestar as the easiest. The possibility of using it one handed allows the surgeon to simultaneously navigate the needle and use the ultrasound to verify the procedure in real time. Using the seestar for guidance, no instruments (eg. the LUS) had to be handed over from the surgeon to the assistant, which was the case with the trocar.

The surgeon found the support from the navigation system in precise targeting of the intrahepatic tumor models to be very useful. The feedback provided by the navigation system was rated to be intuitive. However, by tracking the needle and showing its position on the monitor gave the impression of an accurate placement even though the needle was placed approximately 1 cm away from the tumor due to a unidentified calibration error.

4 Discussion

The results show that this simple method for laparoscopic needle guidance might be a valuable support during surgery. From the subjective feedback of the surgeon and the time required for navigation and targeting of intrahepatic tumors in our experiment we can conclude that the system is easy to use. With the trocar and the seestar a success rate of 100% could be achieved in these first experiments. With the tracked needle the success rate was 20% due to undetected miscalibration of the needle. In laparoscopic surgery intraoperative calibration of the needle tip is a difficult task due to the long and flexible needles. The process of calibration and its validation could be improved with a calibration device which is currently developed for EM tracking.

The major advantage of the presented method is that there is only little additional surgical training necessary in order to use the navigation system due to its supplementation of the conventional method with relevant clinical information. Furthermore, no major interruption of the general surgical workflow is necessary due to insignificant additional time required due to use of the navigation system. Also, time measurements indicate that the time required for navigation is reduced with increasing targeting attempts performed indicating a positive and fast learning curve. No additional preoperative planning nor intraoperative registration is needed. Therefore no registration errors are introduced and no time is needed for this additional tasks in comparison to other navigation systems.

The major drawback of the system is that it is only applicable for tumors visible in the ultrasound image. Therefore vanishing lesions can not be treated, which on the contrary is possible by systems using preoperative images [6].

For future research we aim to develop a validation procedure to get quantitative data on how accurate the needle was placed into a target. Additionally, an intraoperative calibration and validation device for the tracked needle will be provided. If in the future ablation needles with integrated sensor become available, we believe that their use will yield the highest accuracy.

In conclusion we presented a simple method for needle placement in laparoscopic liver tumor ablation, which provides additional information to the conventional procedure while interrupting the intraoperative workflow only minimally. The trocar and the seestar as guidance tools show promising results, whereas the ablation needle could be placed with a success rate of 100%. To improve the accuracy of the tracked needle, an easy and robust intraoperative calibration and validation needs to be provided. Additionally, more experiments with different users of different experience levels are planned.

5 Acknowledgements

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