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Ultrasound-Based Navigation System Incorporating Preoperative Planning for Liver Surgery

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Abstract. An overview of the current status of the development of our navigation system for resection of liver tumours is given. The system is based on intraoperative 3D ultrasound volumes for image-guided navigation of surgical instruments. It is also possible to perform a virtual 3D planning of the tumour resection and to non-rigidly register these preoperative models to the intraoperative ultrasound volume.

Keywords: image-guided surgery; navigation system; 3D ultrasound; liver surgery; surgery planning; non-rigid registration

1. Introduction

Computer assisted planning for oncological liver resections based on computed tomography (CT) or magnetic resonance imaging (MRI) can be an important aid for operability decisions and visualization of individual three-dimensional (3D) patient anatomy. Several groups have developed systems for liver surgery planning in the last couple of years [1-3]. Nevertheless it's an unsolved problem to transmit this planning to the patient in the operating room (OR). A number of commercial 3D navigation systems for image-guided surgery are available for bony structures, e.g. in neurosurgery or orthopedics. The advantage of bony structures is that they do not change their shape between preoperative acquisition of image data and the patient in situ. Thus it is possible to register preoperative images rigidly to the physical patient space. In liver surgery usually the liver deforms significantly between preoperative imaging and the patient in the OR. Therefore an intraoperative imaging modality is needed. In contrast to intraoperative MR, 3D ultrasound is cheaper and easier to integrate in the OR. In [4] a requirement analysis for a ultrasound-based navigation system for liver surgery has been made. A navigation system for neurosurgery based on 3D ultrasound is the SonoWand

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System by Mison [5]. Because fast and precise automatic algorithms for non-rigid intraoperative registration of 3D ultrasound data are still under development, Lindseth et al. [6] suggested for the SonoWand system only to rigidly register preoperative data, trust on ultrasound navigation and use the preoperative data as an orientation aid. Applications in abdominal interventions which use preoperative image data to augment navigated intraoperative ultrasound scans are laparoscopy [7,8] for better orientation and thermal ablation of liver lesions [9,10] for precise placement of preplanned applicator positions.
The liver vessels are used for rigid registration of CR/MR scans to 3D B-mode ultrasound in [10,11], because they can be well identified in all modalities. Non-rigid image-based algorithms for registration of two ultrasound volumes are described in [12]. These approaches are usually too time-consuming for intraoperative use. For fast intraoperative non-rigid registration we combined the Iterative Closest Point (ICP) algorithm and multilevel B-Splines, as in [13] In contrast to Xie et al. the correspondence determination is not based on surface similarity but on vessel center line points in both modalities.
The aim of our work is to develop an integrated liver surgery navigation system consisting of a planning module, 3D ultrasound based navigation and intraoperative registration of preoperative models and planning.

2. Methods

2.1 Preoperative Planning

In oncological liver surgery the aim is to completely resect one or several lesions with a security margin and to resect as little healthy parenchyma as possible. In most cases however also healthy parenchyma has to be resected if its blood supply and drainage would be disrupted by the surgery. The purpose of a planning system is to compute anatomical resection proposals based on the vascular territories as shown in Fig. 1 a) and b) [14]. A prerequisite of the planning process is the segmentation of vessels, liver parenchyma and tumor from contrast-enhanced CT or MR images. The use of CT images allows to segment the vessels with a region growing algorithm. The tumor is segmented with interactive tools. An automated segmentation of the parenchyma is not trivial even in contrast-enhanced CT, because the contrast is not sufficient at all parts of the liver boundary. Therefore we developed in cooperation with the Zuse Institute Berlin a method based on a 3D deformable model approach using a-priori statistical information about the shape of the liver [15].

a) b) c) d)

Fig. 1. (a) Portal veins devided into to be resected (light grey) and remaining vessels (dark grey) resulting from tumor location (white). (b) Resulting vascular territories of liver parenchyma. (c) Position sensor fixed to 3D ultrasound probe. (d) Navigation system in the OR consisting of ultrasound device, Polaris camera, computer and monitor.

2.2 Ultrasound Navigation System

In contrast to freehand 3D ultrasound systems, where the volume is compounded from manually moved and tracked 2D ultrasound data, we use the 3D ultrasound device Voluson 730D from Kretztechnik/GE. This system is based on a 3D probe containing a 2D ultrasound transducer, which is mechanically swept by a motor. The advantage of this system is that it is fast and can easily be applied in the OR. Intraoperatively a 3D ultrasound scan consisting of simultaneous BMode and Powerdoppler (PD) acquisition is performed in a few seconds. The position of a passive tracker attached to the ultrasound probe (see Fig. 1c) is measured during the acquisition by a Polaris tracking system. The data are digitally transferred in high quality to the navigation system via a DICOM interface and not via the video output. Afterwards tracked surgical instruments can be navigated in relation to the 3D ultrasound data (see Fig. 1d).

An important prerequisite for ultrasound navigation is the calibration of the 3D probe. In this context calibration means to compute the rigid transformation between the position sensor of the Polaris and the local coordinate system of probe. Our calibration procedure is based on a commercial 3D ultrasound phantom (CIRS, model 055) and is described in more detail in [16].

2.3 Non-rigid Intraoperative Registration Based on Vessel Centre Lines

Before surgery the vessels are segmented from preoperative CT/MR by a region growing algorithm and manual post-processing to assure the segmentation of as many vessels as possible. Next the centre lines of the vessels are automatically extracted by a skeletonization algorithm. The intraoperative pre-processing starts with a reformatting of the 3D US data to Cartesian coordinates, because the original imaging geometry is special. After this reformatting the centre lines of the vessels are extracted from the Powerdoppler US volume like they were extracted from the preoperative data.

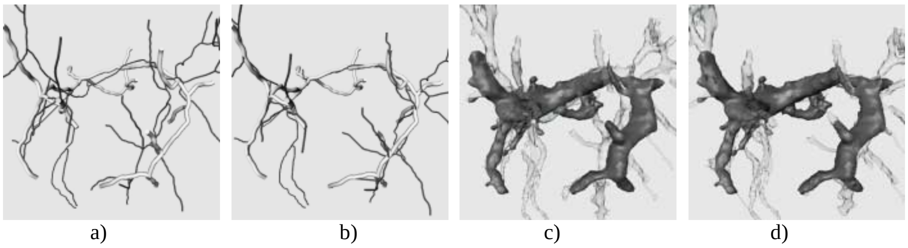


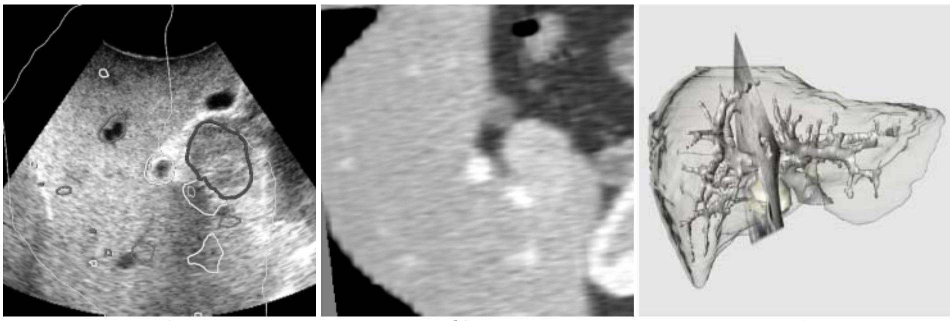
Fig. 2. (a) Rigidly and (b) non-rigidly registered portal vein center lines from CT (thin and dark) and 3D US (thick and bright). (c) Rigidly and (d) non-rigidly registered vessel surfaces from CT data (transparent) to 3D US (opaque).

The first step of the registration procedure is a coarse rigid registration of the centre lines via 3-4 manually selected paired landmarks near the main branching of the portal vein. The second step consists of an automatic ICP-like rigid registration. In the third step non-rigid transformations modelled by multilevel B-Splines are incorporated into the ICP-like registration. In contrast to the standard ICP algorithm in each iteration corresponding vessel centre line points of reference and model data are determined instead of corresponding points between surfaces. Because of the branching topology of vessels the nearest point of a model point to the reference centre lines is often not an anatomical corresponding point. Thus we search for the closest vessel segment with a similar direction. A vessel segment is to be defined as a part of the centre line between two branching points.

2.4 Intraoperative Visualization

We implemented different intraoperative visualization techniques. For direct US navigation two ultrasound image planes, a top view and a perpendicular slice are shown. The planes can be dynamically chosen according to the position of the tip of the surgical instrument or can be frozen and the instrument is shown in relation to the planes. Optionally structures (e.g. vessels) from neighboring slices can be projected into the current slice, such that structures of risk can be earlier identified during an intervention. In addition the tip of the instrument and the maximum circumference of the tumor can be projected in the current slice.

The registered preoperative models of vessels, tumour, liver surface and resection plan can be rendered as different coloured intersection lines into the ultrasound planes. In addition the current position of the surgical instrument and one or both ultrasound planes in relation to the preoperative models are visualized in an extra viewer. It is also possible to show corresponding CT/MR slices to the ultrasound planes.



a) b) c)

Fig. 3. Intraoperative visualization possibilities. (a) US slice with different coloured intersection lines of preoperatively modelled tumour (dark and thick), portal veins (bright), hepatic veins (dark)
and liver surface (bright and thin). (b) Corresponding CT slice. (c) Overview image showing portal veins, tumor, liver surface and location of US slice.

3. Results

In order to measure the accuracy of the direct ultrasound navigation an expert surgeon tried to resect a silicon sphere (radius 15mm) from a chicken breast with a safety margin of 15 mm. An accuracy of 3.2 mm (n=9, standard deviation: 2.1) with navigation aid compared to 5 mm (n=5, standard deviation 2.9) accuracy without navigation aid was reached.

We tested the handling and the principle function of the direct ultrasound navigation system on three patients in the OR. After optimizing the configuration of Polaris camera and 3D ultrasound probe in relation to the patient on the operating table reasonable locations of a navigated pointer to ultrasound data of the liver could be achieved. A more systematic and quantitative investigation is planned as a next step.

The automatic non rigid registration procedure without interactive segmentation of Powerdoppler-US data and manual pre-registration is possible in 1-2 minutes. The whole registration process lasts less than 15 minutes and can be significantly accelerated by an improved intraoperative segmentation step, which seems possible.

Correctness and accuracy determination of non-rigid registration algorithms is a non-trivial task. On the one hand we evaluated the correct assignment of pre- and intraoperative portal vein center lines and on the other hand we measured the deviations of structures which have not been involved in the correspondence determination, like hepatic veins, tumor boundary and liver surface. Vessel center line segments were manually assigned and these assignments were compared with the assignments of the algorithm. We observed only two wrong assignments. In Fig. 2 a) and b) rigidly and non-rigidly registered portal vein center lines of one patient are shown. A RMS difference of 5.6, 5.7 and 3.4 mm has been computed between rigidly and non-rigidly registered center line points of three patients. The resulting portal vein surfaces match well for all three patients as can be seen for one patient in Fig. 2 c) and d). Intersections of the preoperative models with the ultrasound data are shown in Fig. 3. By inspection of these intersections for all three patients we observed 6 to 9 mm maximal deviation for the vessels, 12 bis 15 mm for the tumor and 16 to 20 mm for the liver surface.

4. Discussion and Conclusion

We implemented all necessary components of an ultrasound based navigation system for liver surgery. The components work properly but have to be streamlined for the intraoperative use and detailed accuracy evaluations have to be preformed. The use of portal vein centre lines as features for a non-rigid registration approach worked well. The registration procedure will be further accelerated and robustness will be improved. A possibility to improve the accuracy for structures lying further away from vessels is to incorporate the liver surface into the registration process. Some parts of the liver surface can be identified in the ultrasound images yet other parts can be determined better by a range scanner. We will explore both possibilities.

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