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REVIEW ARTICLE

Intraoperative modification of resection plans for liver surgery

Christian Hansen · Alexander Köhn · Stefan Schlichting · Florian Weiler · Stephan Zidowitz · Markus Kleemann · Heinz-Otto Peitgen

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Abstract

Objective Recent surgical planning software provides valuable tools for evaluating different resection strategies preoperatively. With such virtual resections, predictions and quantitative analyses may be carried out to assess the resection feasibility with respect to tumors and risk structures. In oncologic liver surgery, additional tumors that were not seen in the preoperative images are often found during the intervention using intraoperative ultrasound (IOUS). Due to such findings, the resection strategy must be updated or completely revised.

Materials and methods Therefore, we have developed methods for the intraoperative modification of resection plans. The probe of an ultrasound-based navigation system and alternatively the pointing device *Wiimote* are proposed as intraoperative interaction devices. Fast adaptation of planning information and the communication with both interaction devices is supported by our system, the Intraoperative Planning Assistant (IPA). The IPA has been evaluated in the operation room (OR) during laparoscopic liver interventions on pigs.

Results Our preliminary results confirm that intraoperative modifications of resection plans are both feasible and beneficial for liver surgery. After the intraoperative modification task, updated remaining liver volume and resection volume were displayed and quantified within 10 s.

Conclusion For the first time, surgeons are provided with a system for intraoperative modification of resection plans that offers a crucial decision support, is easy to use and integrates smoothly into the clinical workflow. The new system provides major support for decision making in the OR and thus improves the safety of surgical interventions.

Keywords User interaction · Visualization · Liver surgery · Wiimote · Surgery planning · Ultrasound

Introduction

A serious complication after liver resection is liver failure due to inadequate functional residual liver volume. Clinical studies indicate that depending on the status of the liver (normal, cirrhotic, steatosis) a postoperative residual liver volume of at least 20% is necessary [1]. With recent planning software for oncologic interventions, resection strategies based on individual liver anatomy are evaluated preoperatively and influence important surgical decisions in certain cases [2]. Virtual resection planes can help the surgeon to guide instruments along a predefined resection path when a navigation system is used during surgery [3,4].

In approximately 20% of the patients with liver metastases or primary liver malignancies, additional tumors are found during the intervention using intraoperative ultrasound (IOUS) [5,6]. Although the maximum diameter of these intraoperative findings is smaller than 15 mm in the majority of cases, changes of the resection strategy may be necessary, especially if the new tumors are adjoined to hepatic vessels. In such cases, a tool for the modification of an existing resection plan is essential to adapt and optimize the resection strategy intraoperatively. Conventional interaction devices like mouse or keyboard have only a limited value during surgery. They demand much space and are difficult to sterilize without reducing functionality. To modify resection plans

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C. Hansen (✉) · A. Köhn · F. Weiler · S. Zidowitz · H.-O. Peitgen
MeVis Research GmbH, Center for Medical Image Computing,
Bremen, Germany
e-mail: Christian.Hansen@mevis.de

S. Schlichting · M. Kleemann
Department for Surgery, University Hospital Schleswig-Holstein,
Lübeck, Germany

intraoperatively, surgeons need an intuitive interaction device that can easily be integrated into the surgical workflow.

In this paper we introduce a new application, the *Intraoperative Planning Assistant* (IPA), which includes two novel approaches for intraoperative modification of resection plans. The first approach uses the probe of an ultrasound-based navigation system as an interaction device. After the registration to the preoperative planning data, the current 2D ultrasound plane defined by the surgeon is combined with tracking information from the navigation system. Thus, the ultrasound plane is correlated to the preoperative resection plan and can be directly used as a sculpting tool. A simultaneous visualization of the resection plan (resection plane, remaining liver volume, resection volume) and current ultrasound plane provides visual feedback.

The second approach is based on the pointing device *Wiimote* being the controller for the Wii console from Nintendo [7]. The main feature of the *Wiimote* is its motion sensing capability provided by an accelerometer and optical sensor technology, allowing the user to interact with items on the screen via simple movements and pointing. Since the *Wiimote* is intuitive to use, wireless and sterilizable, we found this device appropriate for intraoperative interaction tasks like the modification of virtual resection planes and basic user interaction, e.g., viewpoint or object selection.

Materials and methods

In this section we briefly report the applied registration technique and the ultrasound-based navigation system since they influence the accuracy of the IPA considerably. Then, we report prior and related results concerning the specification and modification of resection plans for liver surgery. In addition, a new technique for intraoperative modification of resection plans using an ultrasound-based navigation system is presented. Finally, we introduce a novel approach that uses Nintendo's *Wiimote* as an intraoperative user device.

Intraoperative navigation and registration

In our project, we utilize a prototypal ultrasound-based navigation system with electromagnetic tracking for laparoscopic liver surgery [4]. The navigation system consists of a touch screen that is wrapped in a sterile plastic hull, and can be used as an input device for simple interaction tasks during surgery. An important feature of the ultrasound-based navigation system is its service-oriented architecture (SOA), which allows registered computer systems in the OR to grab the current navigation data including the corresponding ultrasound image via a simple network connection. This architecture together with a well defined exchange protocol is the basis for the entire communication between IPA and navigation system.

In order to calculate the relative position of surgical instruments to preoperative planning data, a registration between the intraoperative ultrasound images and the preoperative planning data is crucial. The registration task is performed by the ultrasound-based navigation system and described in [8]. It requires the definition of a small set of corresponding markers in both the preoperative radiological data (before surgery) and the intraoperative ultrasound images (during surgery). For this purpose, intrahepatic anatomic landmarks like vessel branchings can be used. The intraoperative landmarks are acquired using a respiratory gating technique that permits the approximation of a motionless liver during the respiratory cycle [9]. We chose the end-exhalation plateau as time point for acquisition, because it is the longest phase where nearly no motion occurs. Afterwards, the registration is computed, solely based on the alignment of the landmarks using thin plate splines. As a result of this procedure the registration is only valid on the same point in the respiratory cycle and only as long as no further mobilization or repositioning of the patient occurs. Another critical point is the accuracy of the tracking system [10] and the calibration of the ultrasound probe to the tracking system. The root mean square error of both, calibration and tracking, sums up to a landmark localization error of approximately 4 mm neglecting the minimal liver movement.

Resection planning for liver surgery

We previously presented a planning system that proposes resection plans for oncologic liver surgery based on risk analysis and vascular territories [11] including methods for the specification and modification of virtual resections [12]. Based on security margins around each tumor, the segmented liver and vessels (portal vein, hepatic vein, hepatic artery, and biliary duct), as well as the liver parenchyma at risk are determined automatically. In a second step, a virtual resection plane is specified and adapted semi-automatically using manipulators controlled by a 2D input device like mouse or keyboard. Other groups presented methods for the specification of resection plans that follow the same paradigm [13,14] or presented methods utilizing VR technology [15]. However, none of these approaches is designed for the use in the sterile area of an OR.

Two basic interaction approaches for the specification of virtual resections were developed by our group. For the first method the resection is marked by drawing in a few slices of the volume dataset (Fig. 1a). Thus, a resection can be specified as precisely as desired, but is limited to axial slices which might not be appropriate for complex resections. To minimize the interaction time the approach considers interpolation methods to reduce the number of required slices.

For the second method the user draws one or more lines onto the virtual 3D liver surface to initialize the resection

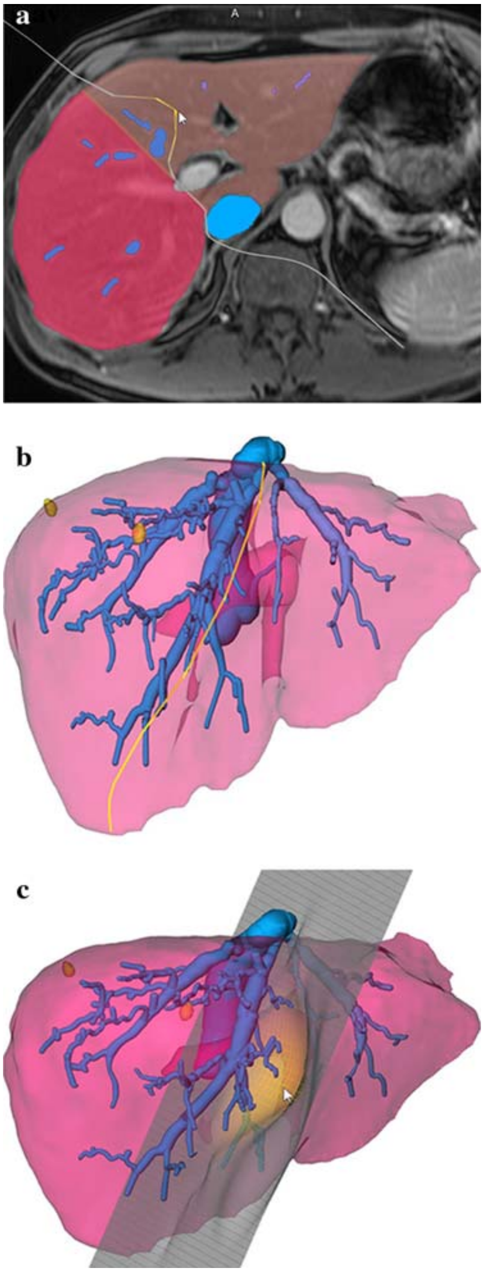

Fig. 1 **a** Resection planning by drawing into slices and **b** by drawing lines onto the individual 3D liver surface. **c** In both cases, a deformable cutting plane is generated out of the lines that can be modified interactively. The *yellow* part of the mesh indicates the influence range of the deformation

plane (Fig. 1b). Both methods can be used simultaneously. For further deformation in 3D, a deformable cutting plane (Fig. 1c) is generated by applying a principal component analysis (PCA) on the point-set forming the lines. The user can define a sphere of influence as well as the amplitude of the deformation to modify the cutting plane interactively. Both functions are controlled with mouse movements at the point which is modified. Besides the local modification of the grid, there is also a facility to translate the whole mesh. Finally, both techniques apply a volume calculation of the resected and remaining part of the liver to provide quantitative information for surgical decisions. The previous version of the algorithm [12] was optimized regarding the interaction time by using the graphics processing unit to compute the volumes.

Intraoperative modification of resection plans using an ultrasound-based navigation system

For the intraoperative modification of resection strategies, surgeons ask for an intuitive interaction device that can easily be integrated into the surgical workflow. As result, we propose an ultrasound-based navigation system for this purpose. Since IOUS has become a standard procedure during oncologic liver interventions, this device is very familiar to surgeons and implicates an intuitive handling. We propose the intraoperative modification of resection plans divided in three steps as follows:

(1) Pre-processing
(2) Redefinition of virtual resections
(3) Update of planning data

While step (1) and step (3) are provided by the IPA, the redefinition of virtual resections (2) is directly performed on the screen of the ultrasound-based navigation system which is located nearby the surgeon. We take a look at these steps in detail:

(1) Pre-processing: The preoperative planning results are based on contrast enhanced CT or MRI data acquired with standard examination protocols. Relevant intrahepatic structures are segmented semi-automatically by a physician in the pre-processing step. Affected vascular branches, as well as affected vascular territories, are computed and their geometric representation is saved. This service is provided by the IPA which runs on a workstation outside of the sterile area of an OR. The preoperative planning results can be accessed from a navigation system by sending a request to the IPA. The IPA responds by sending a message including the location of relevant data files, providing quantitative information (XML) and geometric objects (VRML), which can be downloaded via FTP. Figure 2 illustrates the XML-based exchange protocol, defined between IPA and navigation system. That data exchange allows a simultaneous visualization of planning results and navigated 2D-ultrasound at the screen of the ultrasound-based navigation system. The IPA loads all relevant volume data in a cache for fast memory access during the update of planning data. Furthermore, an Euclidean distance transform of the tumor segmentation mask is precomputed and also cached for subsequent tasks.

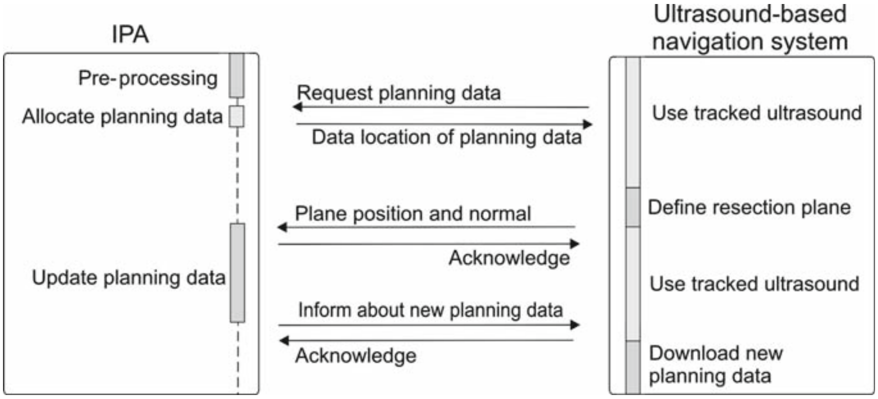

Fig. 2 Exchange protocol, defined between IPA and the ultrasound-based navigation system

(2) Redefinition of virtual resections: Recall that a simultaneous visualization of ultrasound probe and the resection plan is provided on the screen of the navigation system. Since this visualization is necessary for interaction, the redefinition of virtual resections is performed with the navigation system. To define a new resection plane, we provide a method to save the geometric representation of a current ultrasound plane in the planning dataset. The plane is confirmed using the navigation system's touch screen. In order to sculpt an arbitrary shape around newly detected tumors (e.g., a wedge-shaped resection) the surgeon can define a set of planes P_i. The plane normal determines the part of the liver to be resected. It is displayed as an arrow widget in the center of the current plane and can be swapped using the touch screen. When the definition of P_i is completed, the navigation system sends an update request to the IPA containing positions and normals of P_i (Fig. 2).

(3) Update of planning data: When the IPA receives a request from the navigation system the halfspaces of all planes P_i are voxelized into an intraoperative resection mask r_{new}. This is done by a fast raster function algorithm that takes the plane position and normal as input. The remaining liver volume r_{rem} and the resection volume r_{res} are computed by means of an AND-operation on r_{new} and the preoperative resection mask r. Thus, the result considers both, the preoperative resection plan and the new intraoperative resection volume. Finally, we compute the virtual resection plane r_{plane} that borders r_{rem} and r_{res}. Therefore, we calculate the hull of r_{rem} by applying a dilation ($3 \times 3 \times 3$ kernel) on r_{rem}, followed by a difference with the segmentation mask of the liver.

In some cases, preoperative segmented tumors are adjacent to the virtual resection plane. To avoid that the tumor (or parts thereof) are counted as remaining tissue r_{rem}, we access the pre-computed security margins and use this information to change the shape of a virtual resection. Therefore we merge the security margin with the resection volume r_{res} before applying the dilation. This ensures that tumors and their security margins are automatically labeled as resection tissue r_{res}.

Finally, the volumes of r_{res}, r_{rem} and r_{plane} are calculated and geometric surface representations of the updated volumes are generated (Fig. 3). After computation, the IPA sends a response to the navigation system including the location of relevant data files. These files provide updated volumetric information and geometric objects (VRML) which can be downloaded via FTP (Fig. 2). This data exchange allows a simultaneous visualization of the updated resection plan and tracked surgical instruments on the navigation system's screen.

If an ultrasound-based navigation system is used during surgery, no additional interaction device has to be installed in order to modify resection plans intraoperatively. This is a great advantage of the proposed method, since conventional interaction devices demand additional space, setup time or cannot be sterilized without reducing functionality. However, the proposed method is not feasible if navigation data is not available during surgery. Furthermore, since a planar sculpting tool (ultrasound plane) is used, the level of detail for the modification is limited. Defining a complex shape like a wedge or a curved surface means to approximate the shape by a set of planes, which could lead to a lengthy interaction task. In the following subsection we introduce a second approach for an intraoperative modification of resection plans using the *Wiimote* for intraoperative human-computer interaction.

Intraoperative modification and interaction using the Wiimote

Recall that the *Wiimote* is a wireless pointing device for Nintendo's gaming console *Wii*. Its motion sensing capability, based on optical sensor technology and an accelerometer, allows the user to interact with items on a screen. Recent APIs [16] offer a data exchange between *Wiimote* and an arbitrary operating system using the open Bluetooth standard for data transfer. Thus, the *Wiimote* runs independently of Ninten-

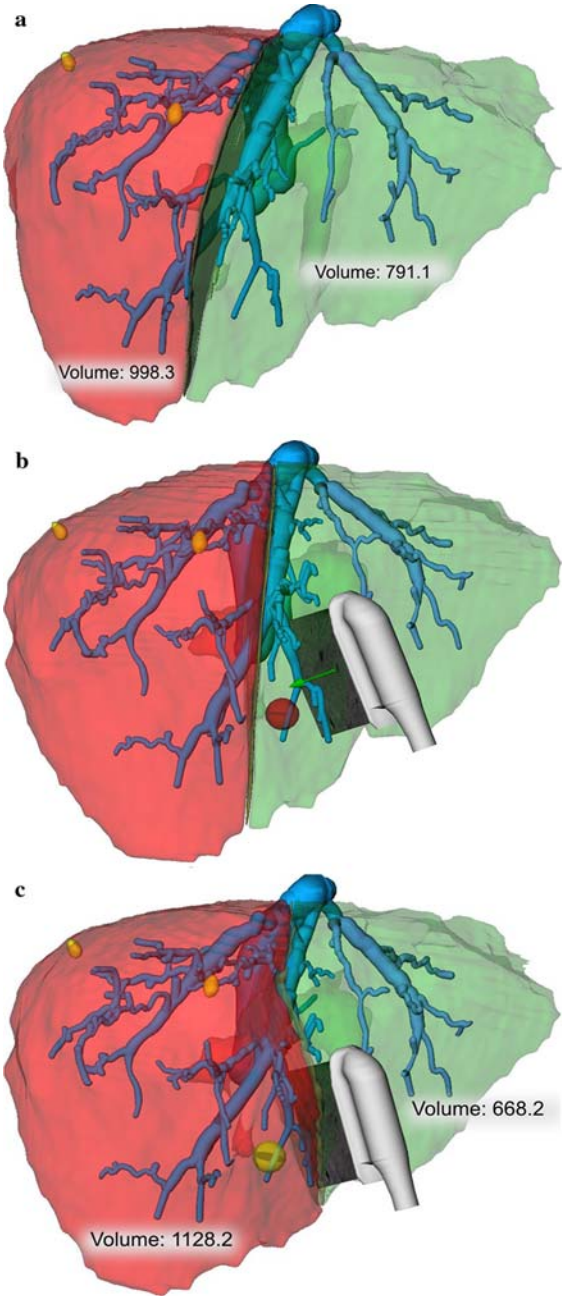

Fig. 3 **a** Preoperatively planned right hepatectomy. The *red* part of the liver model shows the parenchyma to be resected, while the *green* part is intended to remain. The *yellow nodules* represent segmented metastases. **b** A new resection plane is defined with the ultrasound-based navigation system. The *red sphere* represents an intraoperatively detected tumor **c** The preoperative resection plane is merged with the resection volume defined intraoperatively and the volume calculation is updated

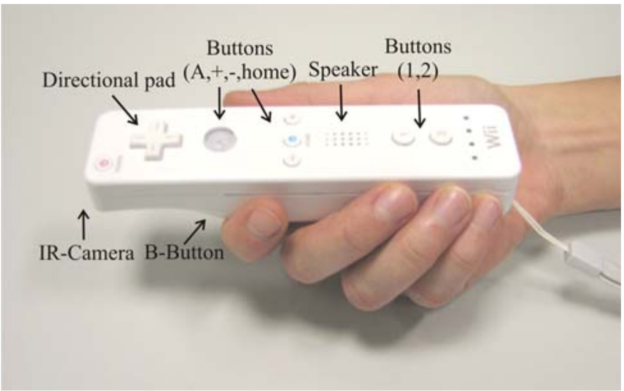

Fig. 4 Nintendo's controller *Wiimote*

do's gaming console and can be used in conventional applications. To utilize the optical sensor technology of the *Wiimote*, a *Sensor Bar* has to be installed nearby the interaction screen. The *Sensor Bar* features ten infrared LEDs, with five LEDs being arranged at each end of the bar. Thus, the *Wiimote* can locate the LEDs (i.e., the relative position of the interaction screen) by means of an integrated infrared camera. This allows for controlling the mouse pointer by moving the *Wiimote*. As shown in Fig. 4, the *Wiimote* offers several interaction buttons and a directional pad which can be mapped to mouse clicks, keyboard inputs or even complex instructions. To allow haptic and acoustic feedback, basic audio and rumble functionality is provided.

We found that the *Wiimote* is appropriate for intraoperative interaction tasks like the modification and refinement of a virtual resection plane, or basic user interactions. In order to use the capability of the *Wiimote*, we integrated an open-source Bluetooth API [16] for the *Wiimote* into the IPA. For the use in the OR, the *Wiimote* is wrapped in a sterile plastic hull. In order to allow precise user interaction, the location of the screen, its size and the distance between user and screen must be adequate. Assuming a 19" display, we found that a distance of 0.5–3.0 m between user and screen is adequate for the intended interaction tasks.

We implemented new interaction techniques for intraoperative modification of resection plans by extending existing methods for the modification of virtual resections (introduced in "Resection planning for liver surgery"). Both techniques, "drawing into slices" and "drawing onto a virtual 3D liver surface" were extended for the use with the *Wiimote*. For drawing in slices we reserved the A-button to enable slicing by moving the *Wiimote*, while the B-button is used to pick and translate resection lines (see Fig. 5b). The + and − buttons allow to step precisely through the slices. For drawing onto a virtual 3D liver surface, the 2-Button is used to draw an initial line set, while the 1-Button is used for the deformation of the deformable cutting plane. Camera rotations are possible by pressing an arbitrary button at the directional pad and moving the *Wiimote* in the intended direction. In both methods, the sphere of influence for the current deformation can be changed by keep pressing '+' and moving the *Wiimote* up or down. The button mapping is of course customizable to support individual preferences.

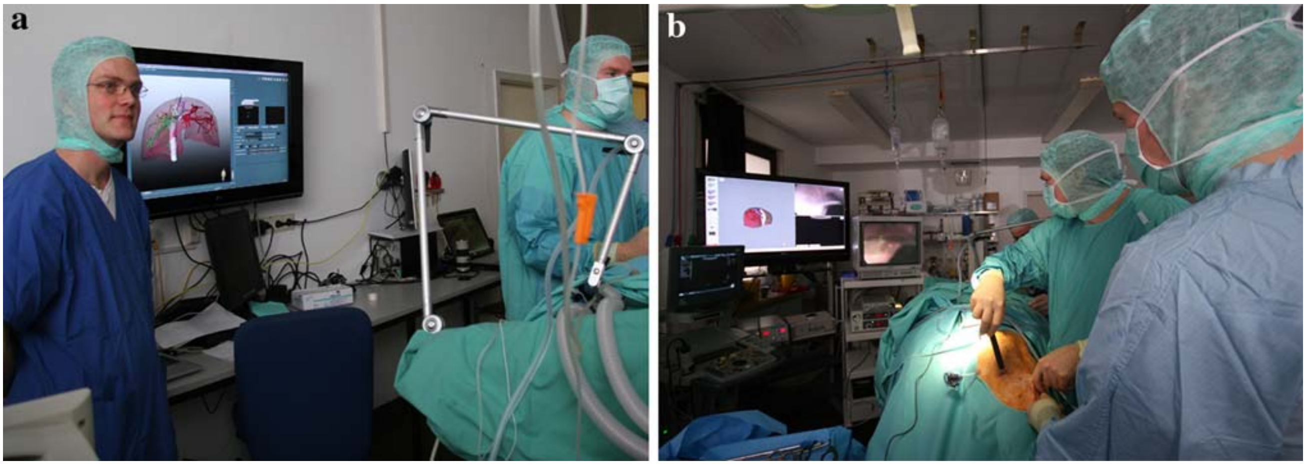

Fig. 5 Preliminary evaluations in the OR using the IPA **a** and the ultrasound-based navigation system **b** for laparoscopic liver surgery on pigs. While the navigation system is located in the sterile area of the OR, the IPA runs on a workstation outside of the sterile area. The communication between both systems is based on a SOA

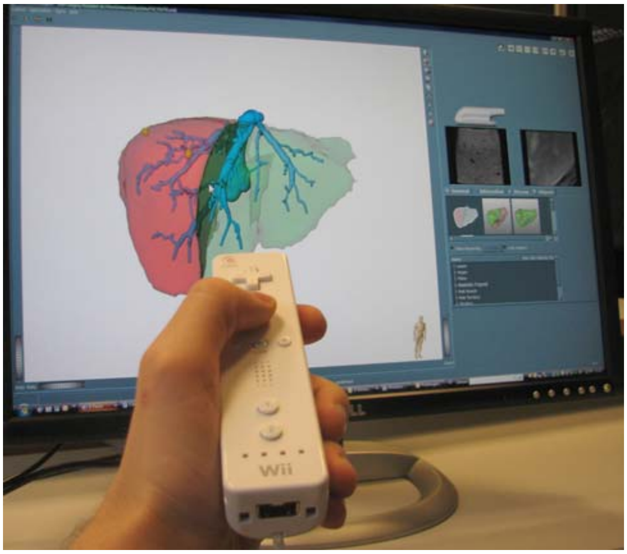

Fig. 6 Using the *Wiimote* to modify a virtual resection plane by drawing lines on the virtual 3D liver surface

Results

So far, resection plans for oncologic liver surgery were of limited value during interventions if resection strategies needed to be updated. We analyzed the surgical workflow for the intraoperative modification of resection plans and proved the feasibility of our concept in close collaboration with liver surgeons. The IPA has been evaluated in the operation room (OR) during laparoscopic liver interventions on pigs. Two gold fiducials (IZI Medical Products, Baltimore, MD, USA) were inserted in the liver under ultrasound guidance directly before the CT scan and a resection plan was prepared. These fiducials simulate small lesions inside the liver. During surgery, two new gold markers were inserted into the liver and interpreted as new detected tumors and the resection plan was modified during surgery using the IPA.

These preliminary evaluations confirm that intraoperative modifications of resection plans are both feasible and beneficial for precise liver surgery. Figure 5 shows the setup of the system in the OR. For the case that an ultrasound-based navigation system is not available during surgery, the IPA in combination with the *Wiimote* allows an intuitive modification of preoperatively defined resection plans during surgery (Fig. 6).

With a prototypical implementation of the IPA on the developer platform MeVisLab, an intraoperative update of planning data within 10 s is achieved (Intel Core 2 Quad, GeForce 8800 GTX). While volume calculations are processed on the GPU to speed up computation time, the generation of geometric presentations (VRML) is the current bottleneck. We expect real-time updates after transferring this part to the GPU and introduction of progressive update strategies.

Discussion

In order to understand how surgeons use the techniques described here, preliminary evaluations have been carried out. As described above, the level of detail for the modification using a planar sculpting tool (ultrasound plane) is limited. Defining a complex shape like a curved surface means to approximate the shape by a set of planes, which leads to a lengthy interaction task. In case of the *Wiimote* interaction, the tracked ultrasound information is not used and the surgeon has to transform the intraoperative findings mentally into the resection plan. Consequently, both modification techniques have clear limitations. A combination of both seems to be promising, e.g., to use the tracked ultrasound probe to define a first approximation of the desired resection plane, and subsequently use the *Wiimote* for further refinement.

According to discussions with surgeons, a color-coded visualization of spatial distances between current resection plane and risk structures (vessels, territory borders) would ease the sculpting process. In addition, a semi-automatic adaptation of the intraoperatively modified resection plane to territories at risk is desired in order to reduce interaction time. Therefore, we want to take adapted risk analyses [17] into account that compute territories at risk depending on intraoperatively detected tumors.

It is important to measure how inaccuracies in tracking and registration influence the modification of the resection plan. Therefore, we want to evaluate postoperative CT scans of pigs being operated using an intraoperatively modified resection plan. Furthermore, we will evaluate the IPA under realistic conditions during oncological interventions. For the near future, we plan to extend the navigation system by an intensity-based elastic registration described by Papenberg et al. [8]. This approach minimizes a special kind of energy functional to get the deformation. It combines the distance measure of the normalized gradient field with a penalizer that forces the deformation that is applied to fulfill the landmark condition. Regarding clinical applicability, a trade-off between registration accuracy and computation time needs to be found.

For the interaction using the *Wiimote,* we have to prove the concept in a user study. We plan to compare the task of modifying resection plans using the mouse with the *Wiimote* interaction according to interaction time and accuracy of results. Besides that, we want to investigate gesture recognition using the accelerometer data of the *Wiimote*. Additionally, a very promising idea [18] is to invert the whole *Wiimote*/IR LED setup and using multiple *Wiimotes* to detect infrared LEDs attached to sterile pen, which would allow for true 3D interactions. In case there is no tracking system available, this solution would offer a low-cost tracking device that provides adequate accuracy to interact with items on a screen.

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