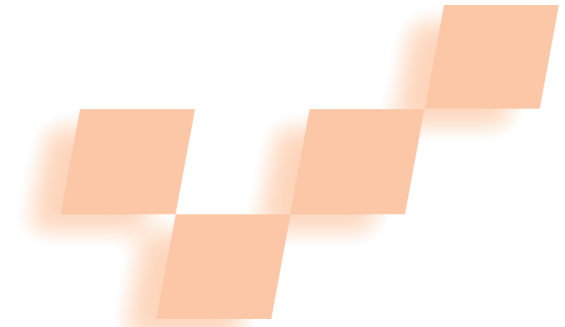# Liver Surgery Planning Using Virtual Reality

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In liver surgery planning, 2D
and desktop-based 3D systems
offer surgeons limited
assistance. By using VR
technology to liberate 3D from
2D input devices such as the
mouse and keyboard, this
surgery planning system better
supports surgeons. User studies
show that the system is both
effective and easy to use.

Cancer is one of the leading causes of death worldwide. Primary liver cancer (cancer that starts in the liver) affects approximately 1,000,000 people each year; in 2002, it caused 618,000 deaths (see http://www.who.int/whr/2004/en). Often, the only cure for primary liver cancer is liver resection, a surgical procedure in which doctors completely remove the diseased tissue. However, patients must meet several preconditions to qualify for liver resection. Among the key indices influencing such decisions are tumor location and size and postoperative liver function. To elaborate a surgical plan for each individual patient, doctors must retrieve the required indices during preoperative planning.

The literature reports many improvements in liver resection surgical techniques. However, only a few efforts have aimed at improving the procedure's planning process, which is critical to surgery success. Successful operations depend on quick and easy preoperative planning that gives surgeons a detailed understanding of the complex interior liver structure. Based on the knowledge they gain in the planning process, surgeons can decide whether or not to perform a surgery.

Currently, however, surgeons must rely on a stack of 2D gray-valued images and a knowledgeable radiologist to interpret them. From this, surgeons mentally build the 3D structures. This approach might not work for highly complex cases in which anatomical variations can lead to wrong interpretations. Moreover, the data set doesn't show important information, such as liver segments. To address such issues, we've developed LiverPlanner, a virtual liver surgery planning system that uses high-level image analysis algorithms and virtual reality technology to help physicians find the best resection plan for each individual patient. Preliminary user studies of LiverPlanner show that the proposed tools are well accepted by doctors and lead to much shorter planning times.

Surgery planning and visualization

Traditional surgical planning uses volumetric information stored in a stack of intensity-based images—usually from computerized tomography (CT) scanners. Surgeons can view these images using specific 2D image viewers. Based on a number of these image slices, surgeons build their own mental 3D model of liver, tumor, and vasculature. This task is difficult, even for experienced surgeons. Moreover, tumors can create anatomical variability, which further complicates the situation. Finally, unlike radiologists, surgeons aren't used to viewing 2D representations of volumetric data sets. As a consequence, they can miss important information or draw incorrect conclusions due to anatomical variability, either of which can lead to suboptimal treatment strategy decisions. The "Surgical Intervention Strategies" sidebar offers an overview of the surgical intervention strategies.

3D solutions

Using 3D visualizations based on segmentation of important objects can improve surgeons' understanding of the liver's complex interior structures. In the medical context, however, presenting 3D visualization on a conventional workstation is insufficient. Surgical planning is inherently a 3D-oriented task, and 2D input devices such as a keyboard and mouse are unsuitable. Using such interfaces for simple tasks, such as object selection or distance measurement, can be tedious. For more complex interactions—such as specifying a deformable plane for simulating a resection—the limits of 2D input devices are obvious.

While traditional desktop-based 3D systems sometimes claim to provide more natural, direct manipulation of 3D structures compared to 2D systems, the mouse interaction style is actually indirect when compared to a VR setup. (The "Related Work" sidebar offers an overview of some existing techniques.) Strong depth cues are obviously important for correct and fast spatial perception.[1] As Mine and colleagues point out, working within arms reach with a stereoscopic head-mounted display (HMD) provides such strong depth cues, allows fine motor control, and takes advantage of proprioception.[2] Further, Mason and colleagues show that a VR setup that provides

Surgical Intervention Strategies

A surgical intervention—that is, liver resection—might be the only curative solution if a patient suffers from a primary (hepatocellular carcinoma) or secondary (metastasis) liver tumor. Surgical removal of diseased liver tissue can prevent further dispersal of liver cancer. The intervention's aim is to completely remove infected liver tissue while considering a safety margin of about 1 cm around the tumor.

At this point, there are two different established resection strategies: anatomical resections, in which whole liver segments are removed, and atypical resections with nonanatomical resection margins. Atypical resection is the method of choice if the tumor is located in a peripheral section of the liver, or if the surgeon must preserve healthy liver tissue for correct postoperative liver function. In all other cases, an anatomical resection is preferred, in which one or more liver segments are removed. Surgeons prefer this because no main vessels are located near segment boundaries, and thus anatomical resection prevents bleeding during intervention. When tumors are very large, the strategy of choice is to completely remove one lobe of the liver (hemihepatectomy).

An anatomical resection plan requires surgeons to estimate liver segment boundaries before they operate. Because liver segments are not visible in computerized tomography images, surgeons often refer to a standard scheme and estimate boundaries according to the portal vein tree.

Although 80 percent of all surgical liver interventions result in an anatomical resection, the remaining 20 percent of cases are atypical operations (according to surgeons at the Medical University in Graz). If a patient doesn't suffer from cirrhosis, surgeons can remove up to 80 percent of the liver tissue. The percentage of liver tissue that they can remove is also strongly dependent on the patient's overall condition. Usually, one year after surgery, the remaining part of the liver can regenerate and can grow up to 75% of the original size.

Without a detailed planning process, the decision about which intervention strategy to choose is often unclear. Anatomical variations can lead surgeons to make wrong decisions, for example, or tumors located at segment boundaries can result in too much tissue being removed. By performing detailed preoperative planning, surgeons can create a more elaborate intervention plan.

Related Work

Research work in computer-aided liver surgical planning is primarily found in Europe, including work at the Center for Medical Diagnostic Systems and Visualization (MeVis) in Bremen, Germany; the German Cancer Research Center (DKFZ) in Heidelberg; and the French National Institute for Research in Computer Science and Control (INRIA) in Sophia Antipolis.

In the late 1990s, MeVis presented two desktop-based systems, HepaVision and SurgeryPlanner, for planning liver transplantations and resection.[1] These systems can generate a resection proposal using the portal vein tree and the hepatic vein structure. The system also includes visualizations of resection-related information, such as highlighting different security margin sizes and affected venous branches. User interaction is limited to the adjustment of the desired safety margin, which influences the resulting proposal.

The SurgeryPlanner carries out atypical resections only by defining resection regions analytically and performing voxel-based operations. It provides semitransparent manipulators—such as wedges, clipping planes, cylinders, and spheres—which the users must position in space using common desktop-oriented 2D input devices. Surgeons—especially untrained ones—seem to have a difficult time interacting with these manipulators. The system often requires two-handed interaction devices (such as a mouse and a spaceball) to rotate and place the manipulators in the correct position.

DKFZ also has a long history in developing methods for computer-aided liver surgery planning. In 1997, the Lena project introduced segmentation methods and 3D visualization tools.[2] L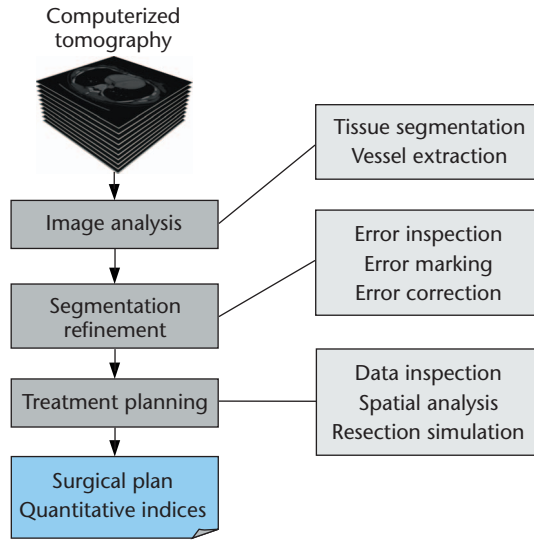ena offers surgery planning methods including segmentation of liver, tumor, and vessel structures and calculates an anatomical resection proposal. The resection proposal considers tumor size and position, the tumor's relation to the vessel structure, and user-defined security margins. The result displays the region targeted for resection on a desktop-based system. Similar to MeVis, user interaction is in 2D.

INRIA developed the Epidaure system, which includes segmentation, shape modeling, image registration, and simulation.[3] Epidaure features a data structure for modeling liver tissue with deformable properties. Moreover, INRIA has proposed a physical liver tissue model to simulate cutting within the liver structure using a force-feedback device combined with monoscopic visualization on the desktop. Although Epidaure's focus is not on resection planning, simulation with cutting can contribute to the training and practicing process of surgical operation planning.

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1 Overview of the virtual liver surgery planning system. Liver-Planner includes three main stages: image analysis, segmentation refinement, and treatment planning.

Computerized tomography

Image analysis → Tissue segmentation / Vessel extraction

Segmentation refinement → Error inspection / Error marking / Error correction

Treatment planning → Data inspection / Spatial analysis / Resection simulation

Surgical plan / Quantitative indices

visual feedback about a moving limb is extremely important for humans to effectively work in 3D.[3] Wang and MacKenzie demonstrate that contextual haptic feedback—such as that provided by a physical table surface or handheld plate—also improves 3D interaction.[4]

Surgery and virtual reality

The idea of using VR techniques for surgical planning is not new; in neurosurgery, doctors use VR environments to enhance their interaction and perception during the planning process. The Dextroscope, for example, is an interactive simulator that uses 3D stereoscopic visualization and 3D direct interaction.[5] Success in this area led us to believe that 3D interaction with stereoscopic visualization would also benefit surgeons in planning liver surgeries. We thus began our development of the LiverPlanner system.

LiverPlanner overview

LiverPlanner simplifies the planning of liver tumor resections through three main stages: image analysis, segmentation refinement, and treatment planning (see Figure 1). LiverPlanner's image analysis algorithms offer largely automatic segmentation of liver, tumor, and ves-

sels. Using segmentation refinement, surgeons can then correct any defects in the automatic segmentation. Thereafter, they can use the treatment-planning tool to elaborate a detailed strategy for surgical intervention, including an analysis of important quantitative indices, such as the volume of healthy liver tissue that will remain after surgery.

As the "Related Work" sidebar describes, most related systems use desktop planning systems. In our view, however, surgery planning's 3D nature requires a VR solution. We therefore developed LiverPlanner to offer users stereoscopic 3D visualization and 3D interaction for manipulating the liver model. Our evaluations with physicians have confirmed that the enhanced spatial perception in VR contributes to increased understanding of complex 3D structures, such as vasculature, and to improved interaction with 3D objects.

LiverPlanner's physical user interface consists of a large active-stereo back-projection wall used in combination with tracked shutterglasses for perspectively correct real-time viewing. The system's optical tracking system (an Advanced Realtime Tracking's ARTtrack) delivers position and orientation information for the user's head and all input devices.

In addition, we give users a secondary tabletop display (a Toshiba Tecra Tablet PC) for high-resolution monoscopic viewing and convenient high-precision 2D input. Both are particularly useful for manipulating segmentations in individual data set slices. As Figure 2 shows, our custom-designed hybrid 2D–3D input device, the Eye of Ra, allows seamless switching between manipulating the 2D and 3D views.[6] When users run the same 3D visualization and interaction code on both the 2D and 3D systems, all editing functions are equally accessible on both displays. The system also keeps the visualization synchronized through a distributed shared scene graph. The system control dialogs are only presented on the Tablet PC, which offers quick and convenient operation.

Stage 1: image analysis

Automatic preprocessing is an essential step in generating the anatomical models that the interactive planning procedures require. We've therefore developed
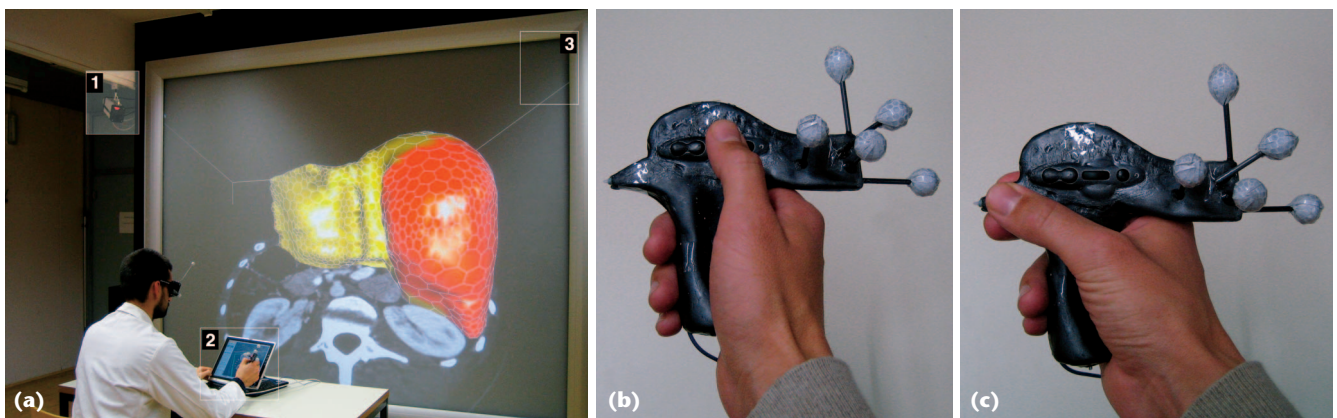
2 The LiverPlanner system setup. (a) The setup includes the optical tracking system's camera (1), a Tablet PC and the Eye of Ra input device (2), and the stereoscopic large-screen projection system (3). (b) The Eye of Ra power grip for 3D interaction has two buttons, a scroll wheel, and tracking targets. (c) The precision grip has a conventional Tablet PC stylus tip for 2D interaction.

specific image-analysis algorithms for preparing raw CT input data for use in LiverPlanner's 3D visualization.[7] There are two main image-analysis challenges here:

■ Developing robust, automated algorithms for liver and tumor segmentation. This is nontrivial because the liver's local borders with neighboring structures, such as the heart, are sometimes barely detectable in the image source.
■ Developing filter and segmentation algorithms for extracting the high-resolution vessel tree that liver segment approximation requires.

Liver and tumor segmentation

Researchers have proposed several methods for liver and tumor segmentation.[7] For example, the Center for Medical Diagnostic Systems and Visualization in Bremen, Germany, developed an adapted version of the livewire method, while the German Cancer Research Center's Lena system offers a collection of segmentation tools. As the "Related Work" sidebar describes, both approaches are interactive.

LiverPlanner semiautomates liver and tumor segmentation using an extended, multiobject fuzzy connectedness approach that lets users contribute knowledge effectively. To reduce interaction time for the segmentation task, we introduce highly automated, model-based methods to separate the heart and liver in CT data. This aids liver segmentation. We used the active appearance model as a basis for our two model-based methods: a 3D AAM for segmenting the diaphragm dome surface, and a robust AAM matching algorithm to separate the heart from the liver. Users can also improve final segmentation by exploiting the temporary data—the segmentation chunks—produced in the automatic stage. LiverPlanner uses the multiobject fuzzy connectedness approach to derive these chunks directly from regions that are likely to be part of the final segmentation.[7]

Vessel extraction

To plan tumor resection, surgeons must have information about the spatial relation between tumor locations, liver vessels, and liver segments. The portal vein is of major interest, because it provides the main information for approximating liver segments. Researchers have thus proposed an optimal region growing approach to portal vein segmentation, along with several liver segment approximation methods.[8] These experiments show that smaller vessel branches are important to accurate liver segment approximation. Smaller vessels are hard to segment, however, due to noise and partial volume effects.

To overcome these problems, we developed a more robust, model-based vessel mining approach based on a tube-detection filter.[9] We use the nearest-neighbor segment approximation (NNSA) method[8] to compare our approach with the portal vein segmentation algorithm on a portal vein corrosion cast phantom.[9] The results show that our approach offers both increased robustness and better segment approximation. In addition, we've improved the tube-detection filter,[10] leading to highly robust vessel segmentation that doesn't show any leakage into contrast-enhanced tumors, for example.

Stage 2: segmentation refinement

A correct segmentation is a prerequisite for surgical planning. Slightly differing segmentation results might imply totally different surgical decisions. Although researchers have expended great effort on automating liver segmentation, a fully automated algorithm that produces 100 percent error-free liver segmentations is not yet available. This is primarily because of high shape variation, low contrast, and pathological data set findings. However, our image analysis algorithms recover major parts of the liver surface correctly, with only occasional local errors. So, repairing our mostly correct automatic segmentation should be much more time efficient than creating a new segmentation from scratch.

Based on this hypothesis, we developed a toolset for incremental segmentation refinement that lets a radiologist identify and correct erroneous segmentation regions. Segmentation refinement differs from two other interactive segmentation approaches—user steered or user intervened—in that the interaction is only necessary after the automatic stage.[11] As the "Related Work" sidebar describes, there are no existing 3D interactive segmentation refinement tools. The literature reports few other approaches, and all of them are based on a desktop setup and 2D interaction.[12]

In contrast, our system combines 2D and 3D user interaction. Segmentation repair evidence comes directly from the volumetric data set, which is displayed as an inspection plane showing CT data in direct spatial relation to the segmentation surface. Users can freely manipulate the inspection plane using the Eye of Ra for rapid and intuitive probing of the erroneous area.

Our interactive segmentation refinement consists of four steps:

1. *Chunk inspection/selection*. The user tries to locate errors in the automatic segmentation result, which is displayed as chunks. The user finds the set of chunks most accurately approximating the target structure by adding or removing individual chunks.
2. *Segmentation surface inspection*. The user tries to locate errors in the surface model by comparing raw CT data to the segmentation surface boundary.
3. *Error marking*. Users mark the erroneous surface-model regions found in step 2 for further processing. This lets users restrict correction (step 4) to erroneous regions, and avoids accidental modification of correct regions.

> **LiverPlanner semiautomates liver and tumor segmentation using an extended, multiobject fuzzy connectedness approach.**

3 Using direct deformation tools to correct small defects. (a) A liver model with leakage into the heart region. (b) The user marks the erroneous region in red. (c) The user corrects the model through direct deformation using the plane tool. (d) The segmentation refinement results.
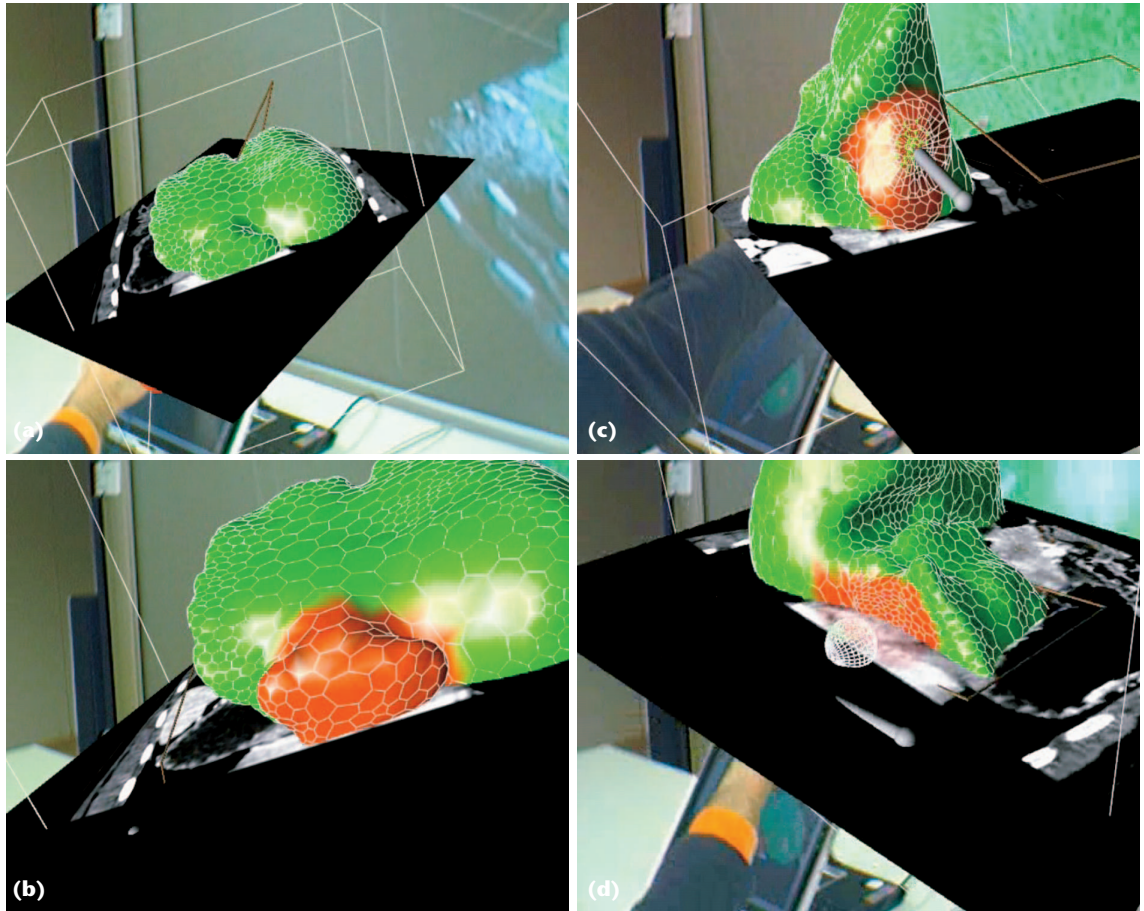
4. *Error correction*. Using special correction tools, users fix marked regions based on direct surface-model deformation or template-shape-based modeling.

Deformable model

Automatic segmentation converts the volumetric CT data into a compact surface model that delineates the boundary between anatomical or pathological structures. This compact surface model is also suitable for interactive rendering. For our data structure, we use simplex meshes,[13] which consist of polygons made up from vertices with exactly three neighbors. This convention makes it easy to calculate surface properties, such as the mean curvature, which is useful when setting up a force framework for mesh deformation. The system iteratively solves a force framework on a per vertex basis based on a Newtonian law of motion involving internal, regularizing forces and deforming external forces. We use internal forces to ensure smooth mesh deformation and external forces to set deformation targets. Initially, the system defines the target shape by the automatic segmentation preprocessing. During segmentation refinement, the user provides locally defined deformation targets for correcting errors.

Rendering deformable simplex meshes is a nontrivial task, because larger parts of the mesh are subject to frequent changes. Segmentation refinement operations cause vertex displacement and—less frequently—local mesh restructuring after excessive deformation. To avoid continuous retransmission of the large mesh structure to the graphics processing unit after each mesh edit, we organize the OpenGL vertex buffer as a vertex cache. As a result, only incremental retransmission occurs after the mesh changes.

Segmentation refinement tools

Our system offers two types of segmentation refinement tools: direct deformation and template-shape tools.

Direct deformation tools. To quickly correct small defects, users can apply direct deformation tools, which push or pull the mesh into the desired shape. Our system currently offers several such tools, including a sphere tool, a disk tool with a fat top, and a tweezers tool that lets users reposition individual mesh points.

When the sphere tool penetrates the mesh surface, the system pushes the mesh vertices toward the sphere's surface on the shortest path while obeying the force framework. The disk tool works similarly, except that the resulting mesh deformation is similar to modeling with a scraper (see Figure 3). The tools can be used in both 3D and 2D. In 3D, users can move the sphere freely in space; in 2D, users place the sphere on the inspection plane point corresponding to the screen position of the input device (a 2D pointing device in Figure 3). Finally, the point dragging tool lets users fine-tune individual vertices placement, while internal forces ensure smooth mesh deformation.
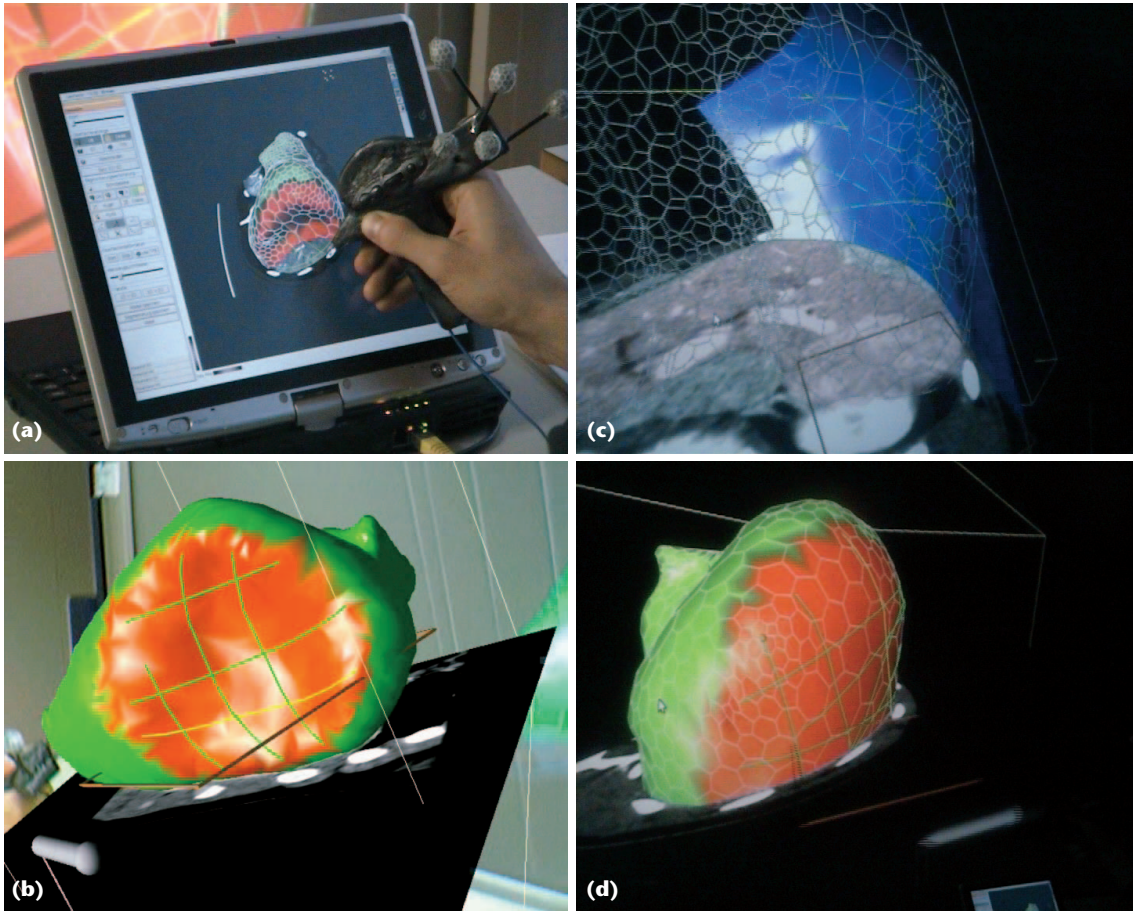
4 Template shaping tools. (a) The user draws contours in the erroneous region on the Tablet PC. (b) The final contour grid. (c) The resulting template shape displays instantly so users can verify the shape. (d) The segmentation refinement's results.

Template-shape tools. Our user observations have shown that direct deformation in 3D is efficient, but eventually causes user fatigue. Moreover, larger segmentation defects are tedious to repair using iterative deformation. To address this, LiverPlanner lets users correct larger areas using an indirect technique based on template shapes. Template shapes are thin-plate spline surfaces—that is, 2.5D free-form surfaces interpolating a few control points. While thin-plate splines are computationally inefficient for larger modeling tasks, they're ideal for local corrections in LiverPlanner.

As Figure 4 shows, in our technique, users simply draw a few supporting polylines (usually 2×2 or 3×3) in the erroneous region. They can best do this by positioning the inspection plane in the 3D view, then switching to the Tablet PC for drawing the polyline in the 2D touchscreen's inspection plane—thus combining high-precision input with a convenient arm rest. The resulting template shape displays instantly, so the user can immediately verify the shape. If the user is satisfied, the segmentation surface is locally attracted by the template shape and deforms accordingly, without introducing discontinuities.

Stage 3: treatment planning

Once the radiologist verifies the required models, the surgeon can start the actual planning procedure. Together with our partner surgeons, we identified the necessary tools for treatment planning. These include interactive branch labeling, liver segment approximation, safety margin calculation, and spatial analysis tools.

In addition, a simulation environment for surgical resections lets surgeons test different intervention strategies.

Tetrahedral model for mesh partitioning

Segmentation refinement tools operate only on surface models. In contrast, surgical planning requires a volumetric data structure that can store all relevant information consistently in one model. Such a data structure must encode multiple volumetric regions, such as healthy liver tissue, tumor, healthy tissue inside safety margins, removed tissue, any remaining tissue after resection, and so on. Separately storing or editing these regions can create inconsistent representations (such as boundary surfaces). Also, to let users undo resection operations, the system must label the target data as removed rather than simply deleting it.

To address these issues, our information-preserving data structure combines a tetrahedral mesh and a binary tree.[14] Every mesh partitioning encountered during the resection simulation splits the mesh into two disjoint parts—the removed and the remaining part—thus adding one binary tree level. Each leaf node in this tree represents a region and stores the indices of associated tetrahedra.

Given the nature of tetrahedral meshes, users can optionally apply a biomechanical behavior that allows deformation in combination with haptic user interfaces. However, this ability is useful only for intervention training and simulation and intraoperative navigation; it's not required for preoperative planning.
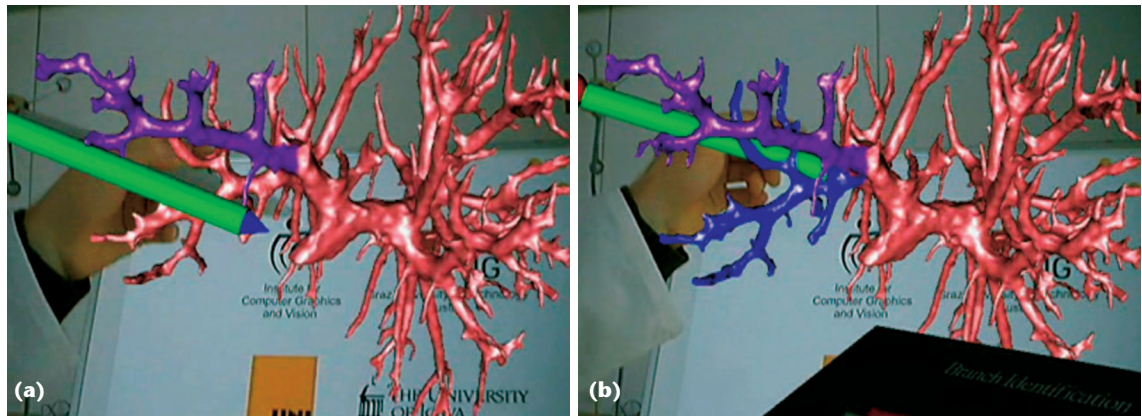
5 The labeling procedure. (a) The user targets a major vessel using a tracked pen. (b) The user presses a button and the system recursively marks the tree.

To visualize a set of tetrahedral mesh regions, the system directly extracts the boundary faces from the tetrahedral data structure. The extraction algorithm traverses the binary tree to identify the list of regions targeted for rendering. The algorithm searches all visited leaf nodes and their lists of associated tetrahedra for boundary faces. It extracts a tetrahedron face if the neighboring tetrahedron doesn't belong to a region targeted for rendering. Because the extracted faces are triangles, the system can use standard hardware-accelerated surface rendering techniques.

Global modification, such as tetrahedral mesh partitioning, is computationally expensive; acceptable computation times require efficient algorithms. The user interactively defines the tissue boundary to be resected by specifying a partitioning shape. The system then computes the partitioning as follows:

■ Collision detection: detect tetrahedra that are intersected by the partitioning tool.
■ Intersection point calculations: test to see if intersection points are calculated; if so store them in a hash table.
■ Subdivision: split intersected tetrahedra according to the intersection points for a unique region assignment.
■ Assignment to regions and binary tree update: assign all tetrahedra to one of the newly created regions and add a new level to the binary tree.

The system uses these partitioning operations to simulate atypical resections such as the ones we describe later.

Surgical planning workflow

Following radiological validation, the surgeon begins the planning process by inspecting the data, paying particular attention to the tumor's location and the portal vessel tree's arrangement. For malignant tumors, segmentation approximation is necessary to retrieve information about affected liver segments. Therefore, the surgeon labels the vessel tree according to anatomical knowledge about segment-feeding branches. This must be done manually, as it requires detailed insight into human anatomy—especially in the presence of unforeseeable pathological structures. The system then calculates the liver segments based on the labels and presents the resulting liver segments to the surgeon, who then determines whether an anatomical or atypical resection strategy is adequate.

Interactive branch labeling. Liver segment boundaries are critical to surgical planning. Because each liver segment is implicitly defined by its supplying vessel branches' location, surgeons must use their knowledge to label each segment-feeding vessel tree.

To automatically generate liver segments, the system needs an abstract graph model of the vessel tree. It generates this model using a tube detection filter for 3D centerline extraction, followed by a reconnection procedure.[10] The system links each vessel graph segment to the corresponding vertices on the vessel surface model. The surgeon labels the vessel system parts with a simple click-to-color interaction (see Figure 5). All smaller, connected vessels in the graph are selected recursively, making this interaction efficient. During tests with physicians, we observed an average labeling time of about 17 minutes, depending on the data set. This makes labeling the most time-consuming step in the planning procedure. The reason is that labeling usually involves some trial and error on the user's part because of tumors that infiltrate the vessels or other anatomical variations. However, accurate segment computation is essential for treatment planning. Surgeons can then use the final labeled model for initiating the automated liver segment approximation algorithm, which classifies each of the model's tetrahedron according to the closest vessel branch (that is, the NNSA method proposed by Selle and colleagues[8]).

Anatomical resection simulation. For anatomical resection, surgeons mark individual liver segments for removal. They can also use measurement tools for further quantitative analysis. This process might be iterative if different safety margins affect additional segments. Once the liver segments are generated, surgeons can immediately use a liver resection simulation and incrementally remove liver segments affected by the tumor.

Figure 6 shows an example for an anatomical resection simulation. To aid the surgeon's decision, the system can transparently display a safety margin around the tumor. This ensures that the surgeon will remove all diseased liver tissue. Surgeons can select from an automated margin calculation of 5, 10, 15, or 20 mm.

Atypical resection simulation. In some cases, an anatomical resection is not possible because the remaining functional liver capacity is insufficient. In such cases, a surgeon might choose an atypical resection. Here, rather than orienting the resection paths at segment boundaries, the surgeon specifies the paths according to the lesion's position and orientation.

During discussions with surgeons, we identified three partitioning shapes covering all atypical resection approaches: a plane for straight resection paths, a sphere for resecting at peripheral regions, and a deformable plane for more complex resection cases. In most cases, it's sufficient to specify the resection region with a straight path using one or two planes. The surgeon positions the plane interactively in 3D and triggers the partitioning. As Figure 7a shows, the resected tissue is transparent, showing the enclosed tumor.

Small tumors that are located at the liver's boundary are primarily removed through a wedge resection. Surgeons do this by shearing the affected part with a sphere-like cutting tool. To simulate such interventions, LiverPlanner offers a scalable sphere tool. After placing the sphere in 3D, the surgeon can interactively adjust its radius to simulate the desired safety margin (see Figure 7b). The sphere is also useful in specifying disc-like resection paths.

The most complex partitioning shape is the deformable plane, which lets surgeons specify an arbitrary polygonal shape. After positioning the grid, the surgeon can adjust deformation radius and height. To ensure smooth deformations—which are similar to the actual surgery—the tool uses a cosine function by interactively specifying the peak in 3D (see Figure 7c).

Spatial analysis tools

For preoperative planning, quantitative analysis of
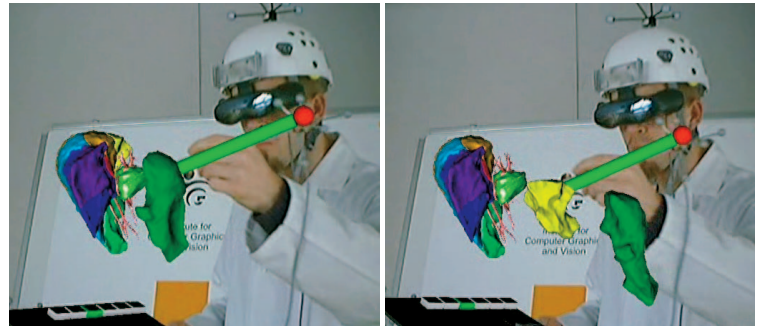
6 Anatomical resection simulation. The surgeon uses a tracking pencil to automatically select and remove different segments of the liver.

distances, volumes, and angles is essential for surgeons to assess a surgical intervention's risk for each patient. LiverPlanner supports the following 3D measurements, which are required in a surgical planning environment:

- *Distance measurements.* Freehanded measurements are important to manually verify whether a required safety distance around tumors is guaranteed in all places, or to measure the minimal distance between two tumors. In addition, surgeons often must measure the distance between a tumor and major vessel branches. Surgeons can specify two different points in LiverPlanner to create a measure line that includes their current freehand measurements.
- *Volume measurements.* Both absolute and relative volume measurements are extremely important to assess the tumor's size and the liver tissue that will remain after the resection. LiverPlanner's jug tool computes the aggregated volume of resection tissue that users drop into the jug.
- *Angular measurements.* Angular measurements help surgeons determine geometric configuration properties of extended objects, such as important branches of the vascular structures. Using LiverPlanner, surgeons can simply specify three different points to measure an angle.

Figure 8 (on the next page) shows LiverPlanner's manual and automated measurement tools.[15]
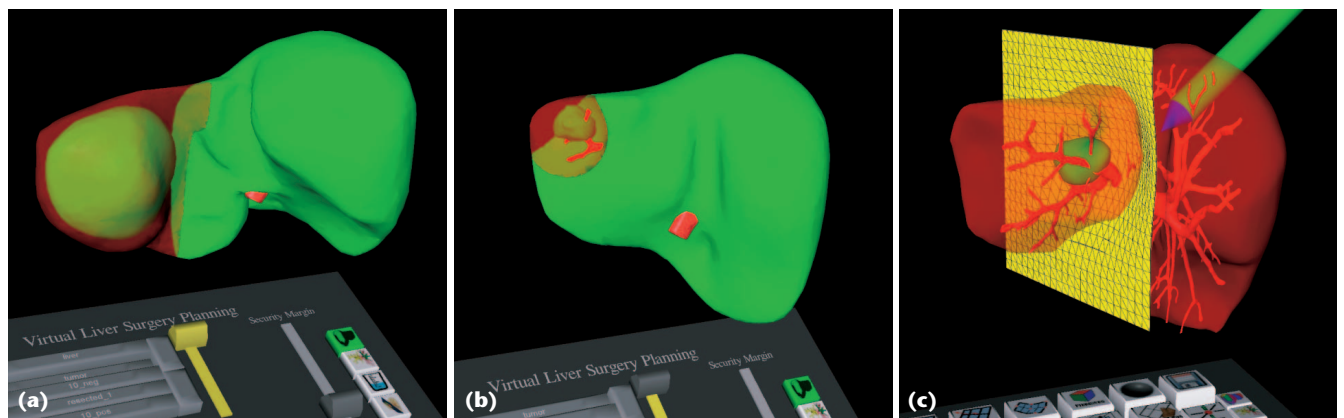
7 Different partitioning tools for simulating atypical resections. Surgeons can use (a) a plane for performing coarse partitioning and (b) a sphere-shaped object to simulate a wedge resection. (c) The deformable plane gives surgeons a more flexible resection possibility.
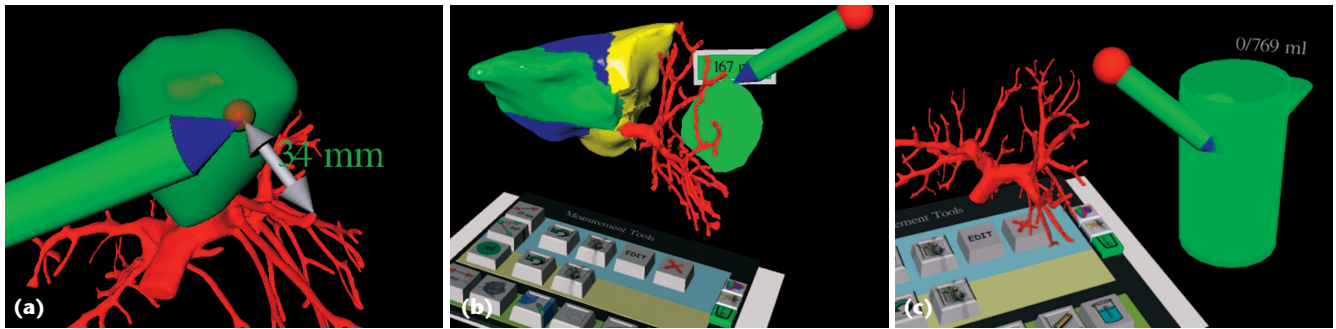
8 3D measurement tools for spatial analysis. The three key measures are (a) distance measurement, (b) volume measurement of individual objects, and (c) the sum of volumes calculated by the measurement jug (an additional tracked input device).

User study results

We tested our segmentation refinement tools with both artificial and real data sets in a study with medical students and physicians. We also evaluated treatment planning using clinical data by a surgeon from the Medical University in Graz.

Segmentation refinement

We conducted two major studies to test our segmentation refinement tools' performance. The first study focused on the usability of the hybrid 2D/3D setup with a group of 18 human-medicine students with no previous experience of VR applications. Following a 10-minute system introduction and 10 minutes in which we let the students use the system, we gave them 12 minutes to complete two segmentation refinement tasks.

According to questionnaires, most students liked the overall system, the hybrid workflow, and the Eye of Ra input device. Users found the refinement tools easy to use and efficient. Ten minutes of training were sufficient for 50 percent of the users to solve the tasks within the allotted time. The remaining users were still too unfamiliar with the system and could not complete the tasks in the 12-minute time period. After the tests, those users stated that they would have been able to solve the tasks if they'd been given a second chance. The refinement results' accuracy was high compared to reference models of the test data sets. Users who completed the tasks produced refined models with a mean-relative volume error of around 2 percent, compared to 7 to 64 percent in the initial models.

In a second study, we gave expert users (radiologists and surgeons) unlimited time to use the system before participating in our study. These users delivered similar values to our previous participants in terms of accuracy. Task completion times ranged between 7 and 12 minutes, with 10 minutes on average. For comparison, a fully manual segmentation of our test's volumetric data sets would typically take a trained operator between 45 and 60 minutes.

Treatment planning

To evaluate treatment planning, we asked an expert surgeon from the Medical University in Graz to plan several real-world cases using the LiverPlanner. The surgeon planned the patients' treatment under the assumption that each had a primary liver tumor.

We prepared four different patient data sets (c014, c006, d048, and x61) of potential liver resection patients using our segmentation tools. For each data set, LiverPlanner's image analysis algorithms generated an initial data model containing the liver and tumor. The system automatically reconstructed the portal vein tree and established a graph model.

We asked the surgeon—who had no prior knowledge of these data sets—to perform a surgical planning procedure for each patient. For a quantitative analysis of the evaluation, we recorded the time required for planning a patient's surgery, the volumes of the resected and remaining tissue, and the decision about which parts of the tissue to resect. During evaluation, the surgeon decided that two data sets indicated atypical resection and used the available resection tools to remove the tumors. The surgeon found a suitable surgical decision for all data sets.

The first data set, c014, indicated two tumors in the right liver lobe. As Table 1 shows, labeling the reconstructed portal vein tree was not trivial, because branches between liver segments IV and V were too coarse. However, the surgeon decided to apply an extended right-sided hemihepatectomy. Because only segments II and III would remain, the surgical intervention depended on the patient's overall condition. If not enough liver function after resection could be guaranteed, the surgeon wouldn't operate. Figure 9a shows the visualization of the result.

The second data set, c006, had one tumor located in the right liver lobe. Because the reconstructed portal vein tree was sufficiently complex, the labeling only took

Case	Visual Inspection (minutes)	Tree Labeling (minutes)	Actual Planning (minutes)	Time (minutes)
c014	3	25	2	30
c006	5	9	6*	20
d048	2	6	7*	15
x61	5	15	8	28
mean	3.75	13.75	5.75	23.25
%	~16	~59	~25	100

Table 1: Time required for planning four different cases.

* This measurement also includes the time required for planning atypically.
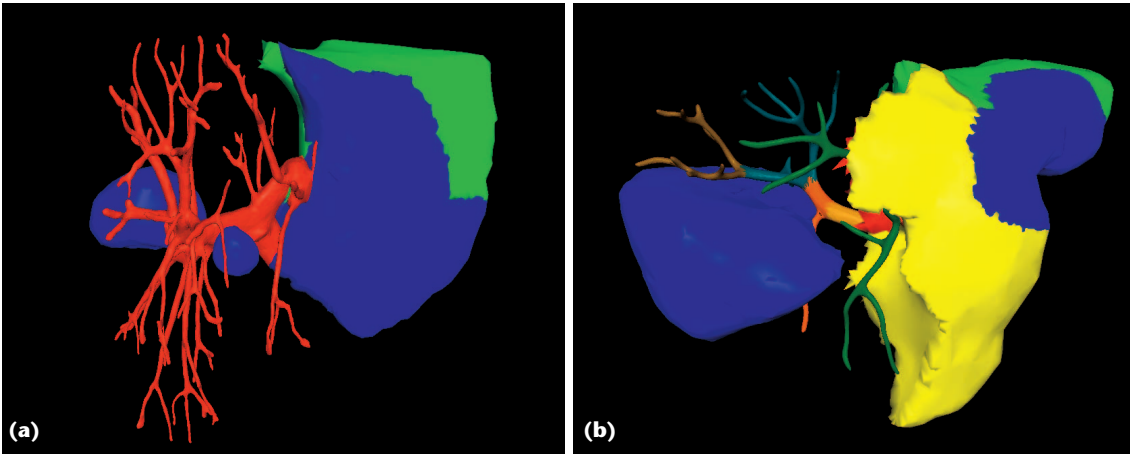
9 Anatomical liver resections. (a) For data set c014, two liver segments (II and III) would remain after resection. The tumor is shown in blue on the left side. (b) For data set x61, three segments would remain (II, III, and IV). The large blue blob on the left indicates the tumor targeted for resection.
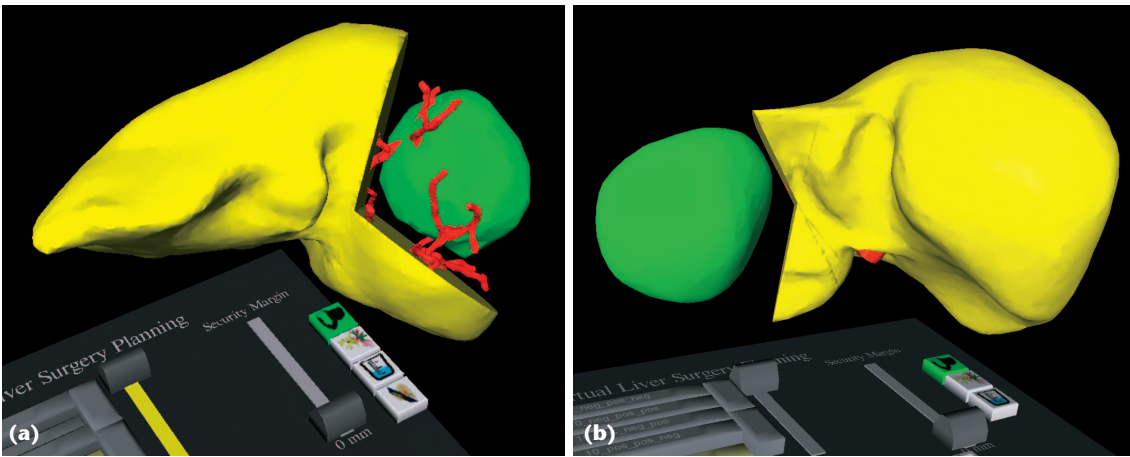
10 Atypical liver resections. (a) Data set c006's tumor was located in the right lobe, whereas (b) the tumor in data set d048 was in the leftmost part of the liver.

about 9 minutes. Following a detailed inspection of the tumor location, the surgeon proposed an atypical resection to save most parts of segments V and VIII. The surgeon planned the atypical resection using two planes: one for partitioning left and right, and another for top and bottom. Figure 10a shows a screenshot of the result.

The third data set, d048, had one tumor in the leftmost part of the liver. LiverPlanner estimated liver segments based on the labeling results. The labeling took about 6 minutes. The surgeon again carried out an atypical resection using the plane partitioning tool. Figure 10b shows the result.

The final data set, x61, had a tumor located in the right liver lobe. The labeling required 15 minutes. The surgeon proposed a right-sided hemihepatectomy, but the tumor was located quite close to segment IV. Using LiverPlanner's analysis tools, the surgeon was able to answer a key question: was an extended hemihepatectomy—including segment IV—required? The surgeon said he couldn't make such a decision using CT images to plan the resection because they don't show segment boundaries. Figure 9b shows the result of the anatomical resection, which included segment IV.

Table 1 shows the time required to plan each patient. The surgeon spent most of the time (59 percent) on tree labeling. Depending on the anatomical variation and the complexity of the reconstructed portal vein tree, the labeling task can be time-consuming. However, it's important for surgical planning and might not succeed unless it's done manually. So, with LiverPlanner, it seems that the actual planning is no longer a dominant time factor; getting the actual resection plan takes only a few minutes. However, surgeons can only achieve this if data preparation—such as liver/tumor segmentation and vessel extraction—is done carefully.

Discussion

Although we've not yet run a full-scale clinical evaluation, our preliminary studies offer promising results. More than a dozen physicians performed informal tests and gave us valuable feedback. All saw the potential for LiverPlanner to become part of the clinical routine. Participants didn't rate working with VR equipment (such as shutterglasses) or tracked 3D input devices as disturbing. The main benefits they reported were with:

- the stereoscopic display, which offers a wide field of view and thus a high degree of spatial perception; and
- the 3D interaction, which allows more intuitive planning tasks with faster interaction.

A 2D user interface is insufficient—especially for specifying resection areas—because it only allows for indirect interaction and manipulation.

Costs. Compared to a conventional 2D radiological workstation or 3D desktop-based planning systems, our system's crucial factor is the hardware cost. For 3D user interaction, reliable tracking is required, and thus using a commercial tracking system is inevitable. This increases the overall hardware costs. However, we believe that VR devices, such as trackers and projection systems, will soon become commodity components comparable to graphics cards.

A VR-based planning system's return on investment lies mainly in planning highly complicated cases in which it's difficult to decide whether the patient can undergo a resection. Preparing data sets for individual cases requires a significant amount of time. In clinical practice, however, part of this effort can be shifted from physicians to trained operators. Once the segmented models (liver, tumors, and vessels) are available, the actual planning by the physician takes between 10 and 15 minutes.

Data quality. Our approach shares the problem of source-data quality with conventional 2D/3D planning systems. If the CT doesn't adequately capture the portal vein tree, the liver segment approximation algorithm might not deliver correct segment boundaries, which influence the planning outcome. A well-defined acquisition protocol that delivers high-quality CT data is essential.

Conclusion

We're currently working on developing a documentation system to archive planning results and record surgical planning procedures. Our focus is on taking snapshots during planning, which surgeons can later inspect in an offline stage. We've added several documentation tools—including screenshots, movies, and 3D snapshots of the current volumetric model—to the interface. Users are able to perform audio annotations, which is common in the clinical routine for diagnosis. This work is a first step toward intraoperative navigation, in which we'll make planning results available during surgery in the operating theater.

Also, we're currently planning a full-scale clinical evaluation with our clinical partners. This evaluation will consist of performing planning both conventionally and using LiverPlanner; we'll then compare both approaches with the actual outcome based on a postoperative CT scan. ∎

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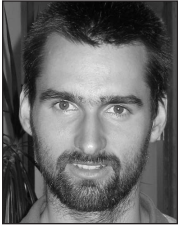
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