Software-Supported Planning of Liver Interventions – Experience of more than 10 Years

Andrea Schenk, Holger Bourquain, Stephan Zidowitz,
Milo Hindennach, Olaf Konrad, and Heinz-Otto Peitgen

MeVis Research, Universitaetsallee 29, 28359 Bremen, Germany

andrea.schenk@mevis.de

Abstract: Computer assistance for the planning of liver interventions was the main focus of the initial project at our institution. Starting with the idea to compute patient-individual liver territories for tumor resections, dedicated algorithms were developed and integrated into a first prototypical software-assistant. Over one decade, experiences together with several clinical partners led to a software-tool that has proven clinical relevance. Until now, more than 1600 liver interventions like tumor resections, ablations, and living donor liver transplantations were planned with the help of the software, which was FDA-approved in 2005. While the planning itself is offered world-wide as a commercial service, the software is being extended continuously and builds the basis for subsequent new applications and studies in different research projects.

1 Introduction

Comparing vascular systems in the liver with fractals, one obviously observes the similarities in the hierarchical nature and volume filling property of both structures [Ha03]. Based on this analogy, the idea to compute patient-individual liver territories from the portal veins with numerical methods from the theory of fractals was developed. But before the subdivision of the liver into individual territories could be determined, the relevant structures have to be extracted from the radiological data, demanding different image processing approaches. Furthermore, if the software should be able to support the medical expert in the planning of liver surgery or interventions, a specific risk analysis, the calculation of resection proposals and a flexible three-dimensional visualization is mandatory.

The first algorithm published by our group in the context of preoperative planning for the liver was a wave-front propagation approach for the segmentation and analysis of vascular structures from CT data [Za95]. Since then several dedicated image processing methods have been developed and have been integrated into an FDA-approved software-assistant that is used by physicians directly in the hospital or acts as the basic tool for a distant service offered world-wide. In this paper, we summarize the experiences of more than ten years in the area of software-supported planning of liver interventions.

2 Liver Interventions

Due to the complex anatomy of the intrahepatic vascular structures, namely the portal vein, the hepatic vein, the hepatic artery and the bile ducts, the preoperative knowledge of these structures is of major importance. When medical experts plan a liver intervention they talk about virtual “segments” used to localize pathologic structures and anatomical variants. The determination of an anatomically correct and individual subdivision of the liver is a task for a software-assistant supporting the preoperative planning. Furthermore, the different types of liver therapy demand for specifically designed functionality of the software that is discussed in this chapter.

2.1 Liver anatomy, segments and territories

The liver anatomy is characterized by the perfusion via the portal venous system and the hepatic artery as well as by the drainage via the hepatic veins (Fig. 1). Portal vein, arteries and the bile ducts run almost parallel, suggesting with a first subdivision at the liver hilum a horizontal plane, while the main hepatic veins form three vertical planes. The well-known scheme of Couinaud uses these planes to divide the liver into eight segments [Cou57]. However, the Couinaud scheme is a rather crude representation and the Couinaud segments do not correspond well to the individual territories [Fas98]. For preoperative planning of liver interventions, it is an ultimate goal to obtain a precise individual model of the hepatic vessels that enables the calculation of the exact portal and hepatic venous territories from the patient’s clinical data.

2.2 Preoperative Planning

Detailed knowledge of the liver anatomy and of the perfusion and drainage territories is crucial for providing resection proposals as well as for preoperatively estimating resection volumes. While the portal venous territories are basis for segment-oriented and parenchyma-preserving resections, the computation of parenchymal regions with possi-

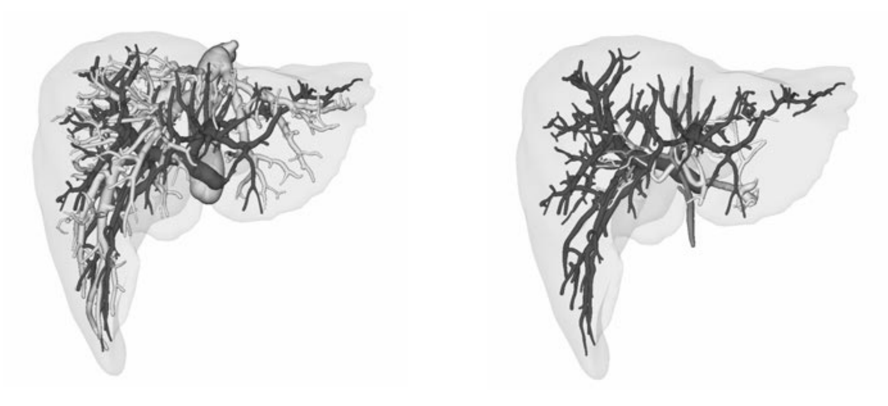

Figure 1: Vascular structures in the liver. Left: portal vein (dark) and hepatic vein. Right: hepatic artery (bright), bile ducts (middle grey) and portal vein. Data set has been provided by the Lahey Clinic Boston.

bly impaired outflow or perfusion shows the individual risk of a specific surgical strategy.

For oncologic resections, the spatial location of tumors and their relation to the main hepatic vessels and the parenchyma is essential. A resection proposal has to fully enclose the tumors to be removed, whereas main branches of the vascular systems should be preserved whenever possible. This guarantees that the remaining functional part of the liver is sufficient for the patient's survival. For the risk analysis with a given tumor safety margin of e.g. 1cm, all included vessels, depending subbranches and the supplied or drained liver parenchyma are determined (Fig. 2). If a specific vessel at risk should be preserved or reconstructed during the operation, the risk analysis has to be corrected. Furthermore, it is advisable to integrate the possibility to define user-specific resections and calculate the respective volumes and structures at risk.

The risk analysis for adult living donor liver transplantation takes into account the special problem of the middle hepatic vein. The resection line divides the liver into the graft for the recipient and the remnant liver that is kept in the donor. For adult recipients normally the right lobe is transplanted. The middle hepatic vein runs between the right and the left lobe, therefore it must be decided whether to resect to the right of this vein or to the left. With this resection, often larger subbranches or branches draining a relevant volume of the graft or remnant are "at risk", which means that they will be cut and not reconstructed during surgery and thus induce a territory of venous congestion and potentially restricted function (Fig. 2). It is important to know the potential reduction of functional liver volume in advance e.g. to avoid a small-for-size graft and to know and plan the reconstruction of those veins in advance [Bo03].

For non-resectable liver tumors which are the majority of more than 80% of all liver colorectal liver metastases, other therapies have been developed. While volumetry is most important to estimate the success of e.g. chemotherapy, the planning of a thermo-

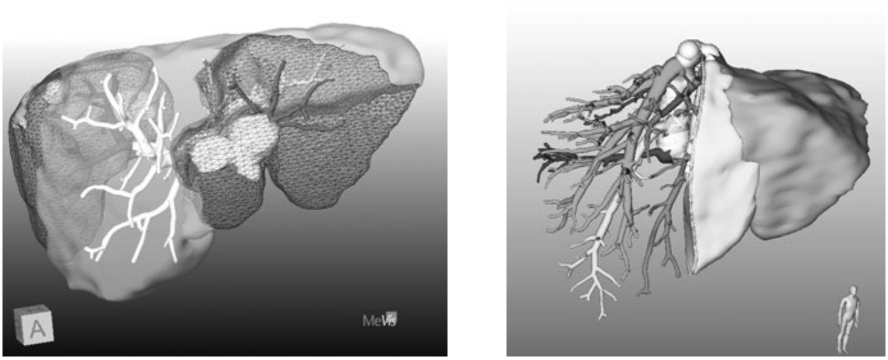

Figure 2 Left: Planning of a tumor resection; the area perfused by veins that have to be resected within a tumor safety margin of 1cm is shown in dark. Right: Planning of a living donor liver tranplantation; the brighter zone of the remnant liver is at risk due to venous congestion. Data sets have been provided by the University Hospital Groningen and the Lahey Clinic Boston.

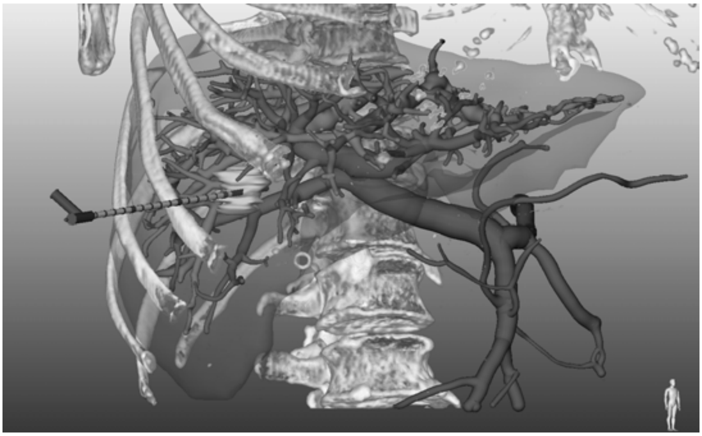

Figure 3: Positioning of the needle for a radiofrequency ablation. Based on the localization of all relevant structures (tumor, vessels, and electrodes) an individual numerical simulation of the ablation procedure can be performed to estimate the coagulation area and optimal parameters. Data set has been provided by the Technical University of Munich.

therapy like a radiofrequency ablation[1] benefits from a dedicated 3D-visualization for the planning of the needle positioning and a numerical model that is able to simulate the intervention and determines the optimal parameters for every individual patient (Fig. 3).

3 Software and Service

Computer-aided planning for liver intervention is a demanding task that consists of several image processing steps and a dedicated visualization for the interactive exploration of the results. We give an overview of the image processing that is used in our software-assistants and of the development from the first clinical approach to the certified software.

3.1 Image Processing and Visualization

After the first step of importing the data in DICOM format into the system, all relevant anatomical and pathological structures are segmented. For living donor liver transplantations these structures are the liver parenchyma, the vascular systems, and the bile ducts if enhanced in the data. In case of oncologic resections the tumors must also be segmented.

The liver segmentation is performed with a modified live-wire algorithm, a semi-automatic edge-oriented algorithm as described in [SPP00]. Other approaches are currently under evaluation, showing that the results of several automatic segmentation

[1] For radiofrequency ablations one or more thin needles are placed (through the skin) into the liver tumor. Electrical energy delivered through electrodes at the tip of the needles causes a zone of thermal destruction.

algorithms require often a correction step that is even more time-consuming than the semi-automatic user-steered approach.

The analysis of the vascular systems is described in detail in [Se02] and consists of four steps: (1) an image preprocessing step to eliminate inhomogeneities within the liver, (2) segmentation of the vascular structures with a modified region growing algorithm, (3) determination of the centerlines (skeletonization) of this segmentation results, and (4) the structural analysis of the vascular trees. From the skeletonized vessels the different vascular systems are separated semi-automatically and analysis of each of these systems can be performed. Based on the segmentation of the hepatic veins and the liver itself, it is possible to apply a mathematical model for the approximation of perfusion territories. Selle et al. showed in a study with human corrosion casts that the computed territories agree with those determined by the anatomical expert up to 98% depending on the resolution of the segmented vessels [Se02].

Several methods for tumor segmentation are supported: threshold based methods restricted to the previously determined liver mask, contour based algorithms, and a method utilizing thresholds and morphological operations (e.g. an extension of the algorithm in [Ku04]). For the risk analysis of tumors, a distance transformation is used to identify vascular structures that are directly or indirectly affected by a given or interactively adjusted safety margin. The territories that are perfused or drained by these vessels are computed and adjusted during user-interaction [Pr02].

Furthermore, there are several other image processing steps included in the software, e.g. for registration of the different timepoints of multi-phasic CT or MR data, correction of inhomogeneities in MR data, combination of segmentation and other results, and for interactive resection planning [KPL04].

All results of the data analysis are visualized in two and tree dimensions using overlays onto the original data, surface shaded displays and volume renderings. Using this, the attending physician is allowed to approve and explore all results calculated by the software. For the vascular structures a dedicated visualization method based on the skeletonization data was developed [Pr00]. It is possible to assess the data, e.g., by adjusting the view orientation, selecting objects, and altering their colors and opacities.

3.2 From the first prototypical application to FDA-approved software assistants

The first software used in the hospitals for research studies was given to radiologists in form of ILAB[2]-networks and the different modules were directly steered with the help of several control windows. Although it was possible to plan the interventions, it was a demanding task for the user. With the extension of the software platform to build application interfaces, the first software assistant HepaVision was introduced in 1998 [Sch99]. It included ten image processing steps and also the visualization of the results. In the following time, the clinical routine showed that a separation of analysis and

[2] ILAB was the predecessor of the software platform MeVisLab (www.mevislab.de).

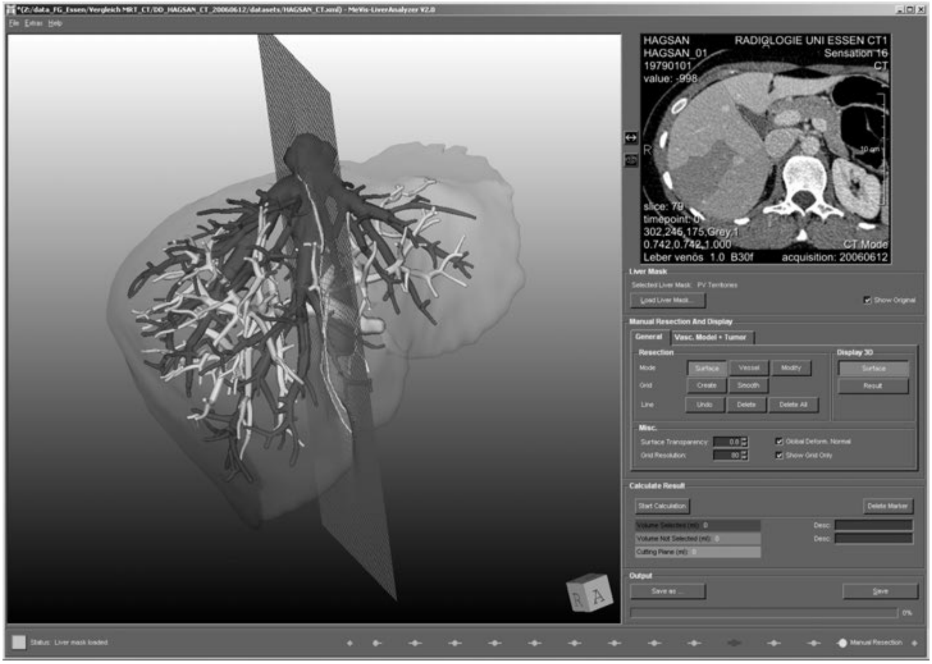

Figure 4: Snapshot of the software-assistant MeVis LiverAnalyzer showing the step „Manual Resection“. The workflow pipeline of all image processing steps is symbolized by the dots at the bottom; here, each step can be selected directly.

visualization was mandatory since the image processing was usually evaluated by one person in a laboratory while the exploration of the results, the discussion and detailed planning of the intervention was done within an interdisciplinary team, often localized elsewhere. Therefore, a second software-assistant was introduced, the InterventionPlanner [Pr02] with its successor MeVis LiverExplorer. With a change of the operational system in 2001, the software-assistant HepaVision was completely redesigned and optimized for routine clinical practice [Bo02].

Driven by clinical requests it was decided to aim at an FDA approval of the developed software to allow the use of the surgery planning outside of dedicated research projects. This aim was reached in summer 2005 and the software-assistants MeVis LiverAnalyzer (formerly HepaVision) and MeVis LiverViewer, which is a simplified version of the LiverExplorer, were FDA-approved.

The development of the software-assistant MeVis SAFIR [We06] for the planning and assessment of radiofrequency ablations was started in 2004. The software includes fast image processing methods enabling the user to segment the relevant structures and position the ablation device in less than ten minutes, a sophisticated numerical simulation of the ablation process, and tools for the comparison of pre- and postoperative data.

3.3 The distant service

The developed image-based risk analysis established an increasing importance for preoperative surgery planning. However, highly trained personnel are required. Therefore, in-house solutions would lead to considerable costs for clinics. With the research project SIMPL, funded by the BMBF from 2002 to 2004, a distant service for image analysis and risk analysis in liver surgery planning was established and evaluated. Using secure internet connections, CT data from hospitals worldwide are sent to the central image processing laboratory at our institute. Here, the software-assisted image analysis is established as a standardized service and results are sent back to the clinicians. The embedding into clinical routine calls for easy to use organizational concepts. Data transfer problems arising from restrictive firewall configurations and proxy servers can be avoided by the developed communication software, which sends small data packages via http and https ports [He06].

Starting with 13 clinical partners in 2002, the service has been tested with more than 50 partners in Europe, Asia, America, Australia, and Africa. More than 1600 cases were processed until now – mainly addressing the surgery planning in living donor liver transplantation and oncological liver surgery. Today surgeons worldwide use this service in their regular preoperative planning. Based on the project SIMPL, the MeVis Distant Service AG has been founded in 2004 to provide the image analysis service on a commercial base.

4 Conclusion

This article tries to summarize ten years of research, development, and experience, which we know is not possible on a few pages. Nevertheless, it shows how software support can have a significant impact to an ambitious medical field and to fascinating fields of research. Gaining this experience was only possible together with our clinical partners world-wide whom we would like to thank for their cooperation and support.

References

[Ha03] Hahn HK, Evertsz CJG, Fasel JHD, Peitgen HO. Fractal properties, segment anatomy, interdependence of the human portal vein and the hepatic vein in 3D. Fractals 11(1): 53–62, 2003.

[Za95] Zahlten C, Jurgens H, Evertsz CJ, Leppek R, Peitgen HO, Klose KJ. Portal vein reconstruction based on topology. Eur J Radiol 19(2): 96-100, 1995.

[Co57] Couinaud C. Le foie. etudes anatomiques et chirurgicales. 1957.

[Fa98] Fasel JHD, Selle D, Evertsz CJG, Terrier F, Peitgen HO, Gailloud P. Segmental anatomy of the liver: Poor correlation with CT. Radiology 206, 151–156, 1998.

[Bo03] Bourquain H, Schenk A, Peitgen HO. Computer-assisted planning and decision-making in living-donor liver transplantation. In Living-donor liver transplantation - Surgical techniques and innovations. (Eds.: K. Tanaka, Y. Inomata, and S. Kaihara), Prous Science, Barcelona, pp. 23-28, 2003.

[SPP00] Schenk A, Prause G, Peitgen HO. Efficient semiautomatic segmentation of 3D objects. Proceedings of MICCAI, Springer, LNCS 1935:186-195, 2000.

[Se02] Selle D, Preim B, Schenk A, Peitgen HO. Analysis of Vasculature for Liver Surgery Planning, IEEE Transactions on Medical Imaging, Vol. 21 (11), pp. 1344-1357, 2002.

[Ku04] Kuhnigk JM, Dicken V, Bornemann L, Wormanns D, Krass S, Peitgen HO. Fast Automated Segmentation and Reproducible Volumetry of Pulmonary Metastases in CT-Scans for Therapy Monitoring, MICCAI - Medical Image Computing and Computer-Assisted Intervention, Springer, LNCS 3217: 933-941, 2004.

[Pr02] Preim B, Bourquain H, Selle D, Peitgen HO, Oldhafer KJ. Resection Proposals for Oncologic Liver Surgery based on Vascular Territories. In Computer Assisted Radiology and Surgery (CARS), Springer, pp. 353-358, 2002.

[KPL04] Konrad-Verse O, Preim B, Littmann A Virtual Resection with a Deformable Cutting Plane, Proceedings of Simulation und Visualisierung: 203-214, SCS, Ghent, 2004.

[Pr00] Preim B, Selle D, Spindler W, Oldhafer KJ, Peitgen HO. Interaction Techniques and Vessel Analysis for Liver Surgery Planning. Proceedings of MICCAI, Springer, LNCS 1935:608-617, 2000.

[Bo02] Bourquain H, Schenk A, Link F, Preim B, Prause G, Peitgen HO. HepaVision2 – A software assistant for preoperative planning in living-related liver transplantation and oncologic liver surgery. In Computer Assisted Radiology and Surgery (CARS), 341-346, 2002.

[We06] Weihusen A, Ritter F, Pereira PL, Helmberger T, Hoffmann, RT, Peitgen HO. Towards a workflow oriented software assistance for the radiofrequency ablation. This volume, 2006.

[He06] Hennemuth A, Bourquain H, Berghorn W, Wetzel I, Lang M, Schenk A, Peitgen HO. Web-based Support of Time-critical Services for Image-based Intervention Planning. This volume, 2006.