CARS 2002 – H.U. Lemke, M.W. Vannier; K. Inamura, A.G. Farman, K. Doi & J.H.C. Reiber (Editors)

Resection Proposals for Oncologic Liver Surgery based on Vascular Territories

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Abstract. We describe the generation and visualization of resection proposals for oncologic liver surgery which are based on vascular territories of the portal and hepatic vein. Resection proposals are interactively controlled by one parameter: the desired security margin around a tumor. Resection proposals consider vascular structures inside this margin, dependend vascular structures in the periphery as well as the territories supplied by them. The methods have been applied to artificial data from corrosion casts as well as to 5 datasets obtained in the clinical routine from 3 hospitals.
Keywords : Liver surgery planning, vascular analysis, risk analysis

1. Introduction

In preoperative planning of liver surgery two major questions have to be answered. Most important is, whether the patient and the liver lesions are suitable for surgery. If this question could be affirmed, the extent of the resection must be determined precisely. If a resection with a sufficient security margin can be performed the probability that all tumor cells were removed increases, leading to a better long-term outcome. On the other hand, for sufficient function of the remnant liver as little as possible liver parenchyma should be resected. Calculation of resection proposals must take both of these contrary objectives into account. The basic idea of generating resection proposals is to consider the patient individual vascular branches in the security margin around a tumor, the dependend branches in the periphery, and the territories supplied by them.

Surgery planning is particularly difficult if several liver metastases are present or if a metastasis is located centrally, i.e. near one of the major vessels of the liver. Important factors for the assessment of the resectability are the blood supply of the surrounding tissue and the localization of large intra-hepatic vessels. The term “anatomical resection” comprises all resections that represent vascular territories. These are, for example, segment resections or sector resections, the latter affecting only the vascular territories of smaller branches [1]. In contrast to this, resections that are only based on the extent of the tumor are called “atypical resections”. The outcome of these atypical resections seems to be inferior to that of anatomical resections [1].
Intention of this study was to investigate the calculation of resection proposals taking into account both the portal venous and the hepatic venous system. The combination of two or more vascular systems in risk analysis is unique. Especially the importance of the venous drainage was underestimated in the past. A venous congestion can result in restricted out-

flow, stasis of the blood in the arterial or portal venous system, and thrombosis. Prospects and limits for calculation of anatomical liver resection proposals will be discussed.

2. Related Work

Only a few groups world-wide deal with computer support for preoperative planning in oncologic liver surgery. A french group focused their work on automatic segmentation of the relevant structures based on à priori knowledge of typical anatomical variants [2]. Previous work concerning resection proposals focused on the computational methodology for different security margins around the tumor . After graph analysis of the segmented portal vein the branches affected by a resection with a certain security margin were determined and the vascular territories of these branches were approximated. The result of this approximation was displayed as a resection proposal.

A shortcoming of the method is that it is based only on one vascular structure, namely the portal vein. This setting does not adequately represent reality where the hepatic artery and portal vein supply blood to the liver and the hepatic veins drain it. Resection proposals should reflect this situation by combining the results for the different vascular structures. Also, in previous work only one clinical example for the successful application was given and the appropriate visualization was not discussed.

3. Image Analysis for the Determination of Resection Proposals

The study is based on segmentation methods suitable for parenchymatous organs and tumors [5] and methods for the analysis of intrahepatic vessels [6]. Vascular analysis includes segmentation, skeletonization and separation of different vascular trees and the approximation of vascular territories. For efficient determination of the vascular branches within a certain security margin around the tumor the border voxels are detected by calculating the difference of the tumor and an eroded mask, using a $3\times3\times3$ structuring element for erosion. Distance transformation was applied to all border voxels, thus generating the security margin.

The calculation of resection proposals was first applied to two vascular models which result from an analysis of digitized corrosion casts of human livers. One model only contained the portal vein whereas the second model also contained hepatic veins. An artificial sphere (diameter 10 mm) as model for a tumor was placed into these models. The tumor position was translated in 5 mm steps in the *x*-, *y*-, and *z*-direction through the whole vascular model and for each position the affected vascular territories for five security margins were calculated and visualized with different colors. Thus giving about 1500 results for each cast which were summarized in movies for discussion with surgeons.

Based on these initial results, selected patient data have been considered. Only cases where it was difficult to define a resection strategy were included. These were patients with tumors close to major vessels or where the decision was difficult due to a central location of the tumor or multiple metastases. Five datasets were chosen, three from a clinical site in Essen (E_1 … E_3), and one from Krefeld (K) and Marburg (M). Each dataset was a contrast enhanced CT scan. The data from E were multislice CT (slice thickness 2.5 and 3 mm), whereas K and M were spiral CT data with 4 mm slice thickness. In E_1 with a central metastasis the goal was to maximize the security margin while keeping the risk of surgery low. Datasets E_2, M and K had multiple metastases (3 or 4, respectively). Resection proposals were generated to support the decision if the metastases should be resected separately or en-bloc. For each security margin the resection proposal is visualized and quantitatively analyzed with respect to the liver volume which has to be resected and the remaining volume. The resection proposals were calculated both for the portal vein and for the hepatic veins. The methods used for the calculation of the security margins were identical. The risk analysis results for different vascular systems are combined. Thus, giving the maximum risk, that either the blood supply or drainage would not be sufficient if the tumor would be resected with this security margin. Fig. 1 illustrates the risk analysis for patient K. The generation of resection proposals is part of our software assistant HEPAVISION which integrates all steps to analyze CT data for pre-operative planning in liver surgery [7].

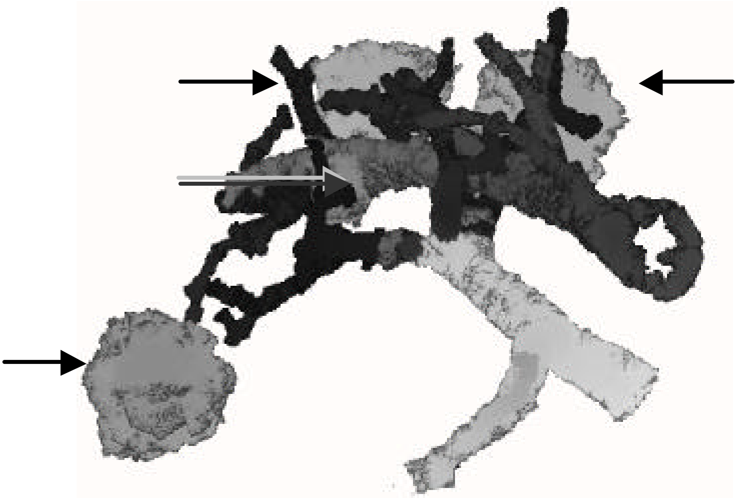

Fig 1: Portal vein and hepatic vein of a patient with four liver metastases (see the arrows). Resection proposals have been calculated for the 5 mm, 10 mm as well as the 15 mm margin. The brightest structure is the portal vein outside the security margin. The darkest structures are branches of either the portal vein or the hepatic vein inside the 5 mm security margin. The portal venous tree is pruned to reveal the major branches affected by a resection with different margins.

4. Visualization and Exploration of Resection Proposals

The visualization of resection proposals can be modified by multiple parameters. Different numbers and sizes of security margins lead to different resection proposals. We provide several ways to modify the visualization of the affected or not affected vascular branches as well as the vascular territories supplied by these branches. Our experience is that it is helpful to use three standard security margins with a distance of 5, 10 and 15 mm around the tumor. As default, we employ the red color for the 5 mm margin which must be definitely resected and orange and yellow for larger margins. Although security margins of more than 10 mm do not improve the outcome it is reasonable to consider these margins. Reasons are that resections can often not be performed exactly as proposed and that the tumor size determined by CT is not perfectly reliable. Often tumors intraoperatively turn out to be larger than expected estimated from the image data.

For all security margins the affected vascular branches were color coded and the respective territories were superimposed semi-transparently with the same color. For the liver casts vascular territories were not displayed, as they were identifiable by the corresponding vascular trees.

We provide several presentation modes to avoid that too much visual information confuses the viewer. Center lines (the skeleton) of the vascular tree can be displayed instead of a surface rendering of the complete lumen of vasculature. Furthermore, we offer facilities to smooth the segmentation result and to prune the visualization of vascular trees to make the interpretation easier. Another useful option is to use transparency to dilute branches of vasculature which are not in the focus of risk analysis.

Vascular territories of the portal vein and drainage territories of the hepatic veins can be visualized separately. For risk analysis the vascular tree affected by a smaller security margin is enhanced by determining the branch with the shortest distance to the tumor. Only branches with a certain diameter are considered. In order to check the validity of the resection proposals and to assess their feasibility it is essential that the results can also be displayed in a 2d slice view. For this purpose, the approximation of vascular territories is transparently overlaid the original radiological data. Corresponding structures in the 2d and 3d view are displayed with identical colors. This is illustrated in Fig. 2 for patient E_2 and in Fig. 3 for patient E_3.

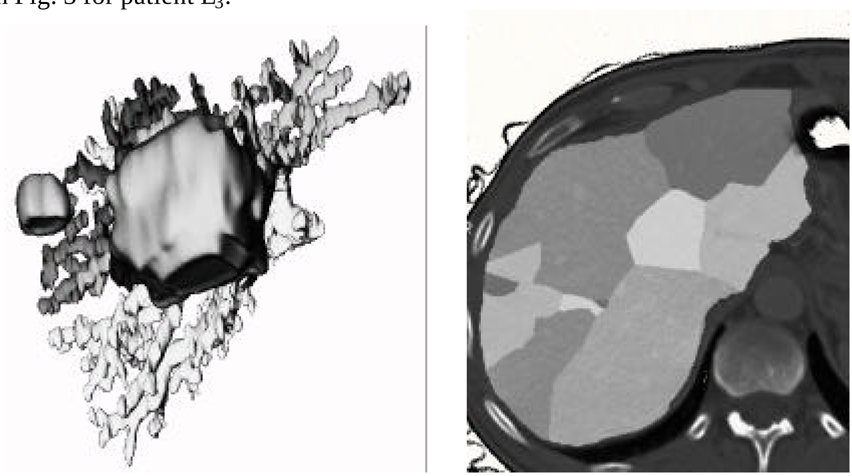

Fig. 2: Resection proposal for the larger metastasis based on the portal vein. Left image: the vascular structures involved for the three standard margins (5, 10, and 15 mm). On the right, the corresponding vascular territories are also displayed.

Exploration of Resection Proposals. A typical sequence of interactions is as follows. The user starts the analysis with the metastasis which is probably the most difficult to resect and performs the analysis of security margins for the portal vein. Following this step, the analysis is separately carried out for the hepatic vein and subsequently both results are integrated in one visualization with the vascular trees pruned appropriately. The visualization of the vascular territory should be restricted to one such territory. However, the volumetric analysis is carried out simultaneously for all security margins which have been considered. If other metastases have to be treated, the analysis is carried out for these lesions afterwards and finally an overall visualization and volumetric analysis is carried out.

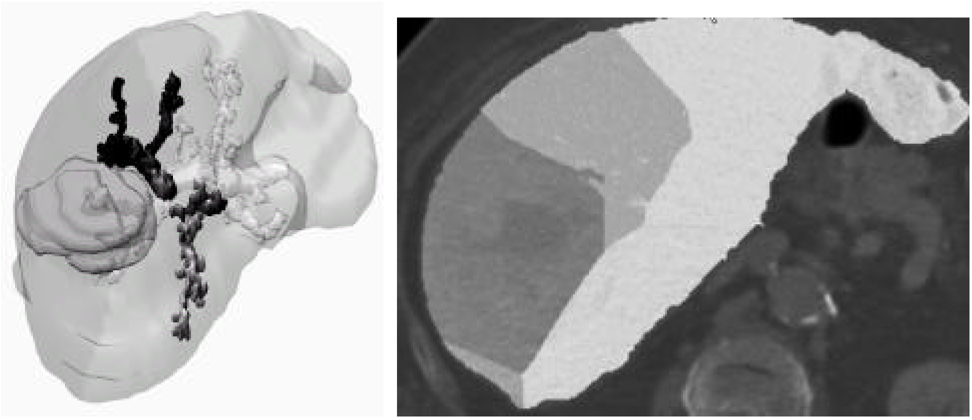

Fig. 3: Risk analysis for the large lesion (see the arrow). It is visualized which branches of the portal vein are inside the standard security margins (5, 10, 15 mm). Dark branches are located in the 5 mm zone, wheras lighter branches are more distant from the lesion. The right image shows the 2d slice view with risk areas transparently overlaid.

5. Results

Resection proposals were first calculated for two vascular models of digitized human liver casts. The resection proposals of selected results for each cast were presented to a surgeon. The shape of the calculated pattern corresponded well to the shape of resection usually applied in clinical practice.

Although in clinical data images of less quality is available the approach turned out to be useful for surgeons also in the clinical cases. 4 of 5 cases were regarded suitable for surgery. Patient E_1 could not be resected (even with a small margin of 5 mm the whole portal tree would be affected). Patient E_2 (recall Fig. 2) was regarded not resectable, partly because the remnant parenchyma is rather low, and partly due to an accompanying liver cirrhosis. Patient E_3 (recall Fig. 3) was considered resectable, however, it was decided to treat the patient first with a chemotherapy in order to debulk the lesion. For patient M a hemihepatectomy was carried out. The resection proposal with 15 mm security margin revealed that the remnant parenchyma cannot be increased by resecting the 3 metastasis separately. Volumetric analysis of the resection proposal yielded a volume of 51% of the whole liver parenchyma. Patient K with its 4 metastases had one metastasis too close to the main branch of the portal vein. The other 3 metastases were removed. The remaining metastases was treated by a minimally-invasive therapy which does less damage to surrounding vessels. Results of the quantitative analysis are summarized in Table 1.

Table 1: Quantitative results of risk analysis. All numbers in paranthesis refer to percentage of whole liver volume.

Patient	Liver volume	Number and vol. of lesions	Resection proposal 5 mm margin	Resection proposal 10 mm margin	Resection proposal 15 mm margin
E1	1 196 ml	1; 13 ml (1.1%)	1 196 ml (100%)	1 196 ml (100%)	1 196 ml (100%)
E2	1 470 ml	2; 99 ml (6.8%)	201 ml (13.7%)	465 ml (31.6%)	670 ml (45.6%)
E3	2 035 ml	1; 69 ml (3.4%)	327 ml (15.7%)	526 ml (25.8 %)	635 ml (31.2%)
M	1 606 ml	3; 29 ml (1.8%)	101 ml (6.3%)	205 ml (12.8%)	795 ml (49.4%)

6. Conclusion

Generation and visualization of resection proposals can facilitate planning of anatomical resections in patients with liver tumors. The case of patient K revealed that it should be possible to generate resection proposals for individual metastases to support decisions for combined therapies (surgical removal and minimally-invasive destruction). The reliability of the generated resection proposal depends on the quality of the radiological data, in particular on the vascular structures which can be segmented in the vicinity of the lesion. In about 5% of clinical liver tumors the location of the tumor in the posterocentral portion of the liver prohibits a normal approach, therefore the automatically generated resection proposal would surgically be impossible. As the presented resection proposals are not perfectly reliable and sometimes difficult to realize surgically the option to interactively modify these proposals is mandatory. The methods have been applied successfully to clinical data with varying image quality. This clearly indicates that the method is in most cases feasible for preoperative planning. However, the decision whether a patient can tolerate a resection is not fully supported. In particular, primary liver cancer is often inoperable due to the extent of liver cirrhosis which caused the cancer disease.

There are several areas open for future work. A larger validation with clinical data could verify the benefit for the clinical routine for centrally located tumors and multiple metastases. The approach can be modified in such a way that also minimally-invasive therapies, such as radiofrequency ablation, are considered. Also for these interventions it is crucial to respect the vascular architecture.

Acknowledgement. We want to thank our colleague Milo Hindennach for generating the visualizations for Fig. 2 and 3. We also thank our clinical partners, Prof. Debatin, University Hospital Essen, PD Dr. Fiedler from Hospital Krefeld as well as Prof. Klose, Philipps University Marburg for providing us with high quality radiological data. We want to acknowledge the support by the Deutsche Forschungsgemeinschaft (Pe 199/9-1).

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