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Interventional Planning of Liver Resections: An Overview

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Abstract— **Liver cancer is the third most common type of cancer. Among available treatment options, a surgical resection offers the best prognosis for long-term survival. It is important that such a surgical procedure is carefully prepared. Modern computer technology offers convenient ways to simulate different resection scenarios and help to determine the best treatment for a given case. This paper provides a non-exhaustive overview of existing computer-based systems for interventional planning of liver resections. They are reviewed according to their medical use case, e.g. if they support typical or atypical resections.**

I. INTRODUCTION

Cancer is the second leading cause of mortality worldwide. It led to 7.6 million deaths (approximately 13%) in 2008, of which 70% occurred in low- and middle-income countries. According to the World Health Organization (WHO), liver cancer is the third most common type of cancer, causing 700,000 deaths annually. Hepatocellular carcinoma (HCC) is the most common type of primary liver cancer. It usually develops after either a viral Hepatitis B/C infection (20%) or a liver cirrhosis (80%). Cirrhosis is a consequence of a chronic liver disease caused, for example, by alcohol abuse. It is characterized by replacement of healthy liver tissue with fibrosis, scar tissue, and nodules. About 50% of the deaths caused by HCC occurred in China. In Western countries, the most frequent liver tumors are metastasis. In Germany, 219,000 deaths (25.5%) were caused by cancer in 2010. Only 6000 people develop HCC per annum, but this is increasing.

The liver is essential for survival. It plays a major role in metabolism and is involved in detoxification, protein synthesis, glycogen storage, hormone production, and production of biochemicals necessary for digestion. In the widely used Couinaud system, the liver can be divided into eight functional lobes, which are independently supplied by its artery, veins, and bile duct. There is currently no long-term method of compensating for the absence of these functions. For this reason, it is important to diagnose the disease correctly at an early stage and choose the best treatment option available.

A multiphase computed tomogrphy (CT) scan of the abdomen is currently the best method to diagnose HCC. Therefore, a contrast agent (COA) is injected intravenously, reaching the liver twice. The first time is through the liver artery (arterial phase) and the second time is through the portal vein (venous phase). During these phases, the tumor changes its appearance and shows some key characteristics that reveal its true nature.

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Treatment options depend on tumor size, spread, involvement of vessels, metastasis, etc. A (partial) surgical resection (hepatectomy) offers the best prognosis for long-term survival, but this kind of treatment is suitable for only 10-15% of patients. Some other options are radiofrequency ablation (RFA), cryosurgery, high intensity focused ultrasound (HIFU), and transcatheter arterial chemoembolization (TACE).

If a hepatectomy is feasible for a particular case, it may be anatomic (segment oriented, typical), i.e., one or more functional segments are completely resected, or non-anatomic (atypical), i.e., arbitrary pieces are resected. The former is usually preferred due to the lower risk of bleeding. This is because main vessels are not located at anatomical boundaries. However, in selected cases, the latter can also be safely performed. This is the case, when the tumor is located in a peripheral location or when the surgeon must preserve as much liver tissue as possible. Skandalakis et al. [25] provided an overview of the surgical anatomy of the liver. Liau et al. [14] reviewed the rationale and techniques of anatomic liver resection.

Computer-based planning systems were proposed to support surgeons to prepare optimally for an intervention. They provide different features depending on the supported resection strategy. In this paper, an overview of state of the art computer systems for interventional planning of liver tumor resections is given. It is not intended to be exhaustive, but to give the reader an idea of recent research and developments. In section II, current planning system are reviewed according to their medical use case, e.g. if they support typical (section II-A) or atypical (section II-B) resections. In section III a short discussion is given before the paper is finally concluded.

II. INTERVENTIONAL PLANNING

Computer-based planning systems provide tools to support the surgeon during his decision making process and to plan treatment of a patient. One feature that every planning system provides is 3D visualization. This helps the surgeon to orient oneself to get an idea where the tumor is located and how the main hepatic vessels are spread within the organ. Beermann et al. [1] showed that 3D visualization significantly improves understanding of surgical liver anatomy. An example of 3D visualization of relevant structures (portal and hepatic veins and tumor) is shown in Figure 1(left).

A. *Typical anatomic resections*

For surgical practice, the liver is divided into several functional independent segments. Each segment has its own

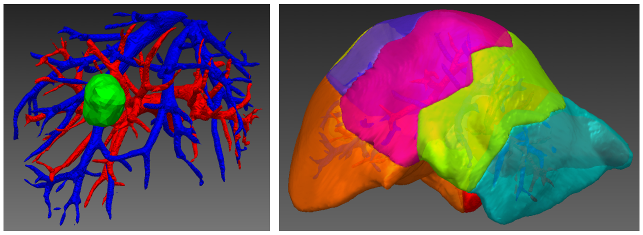

Fig. 1. Left: Visualization of hepatic veins and the tumor. 3D visualization helps to orient oneself and learn about the relationships between these major structures. Right: Patient-specific liver segments visualized as semi-transparent surface. The hepatic veins can be seen through the surface in red (portal vein) and blue (hepatic vein).

portal venous supply and hepatic venous and biliary drain. Claude Couinaud suggested to divide the liver into eight segments by the third order branch of the portal vein. Later, Bismuth proposed three planes aligned along the three main hepatic branches and the portal vein to classify the liver. Fasel [7], [8] noted that due to anatomical variations, Couinaud's classification scheme is questionable. He has observed that between 9 and 44 second-order branches exist and concluded that the liver does not consist of just eight segments, but of many more. Thus, he proposed a flexible 1-2-20 scheme to classify the liver. A review of different liver classification schemes was published by Rutkauskas et al. [19].

A big advantage of anatomical resections is that no main vessels are close to segmental boundaries. Bleeding is therefore reduced by completely resecting one or more segments by cutting along these boundaries. Computer-based planning systems for anatomic resections allow for the calculation of liver segments. They can be classified into vessel-based methods and plane-based methods.

Selle et al. [23] proposed to classify a segmented liver using annotated portal veins. Therefore, they segment the liver vessels using a region-growing-based method. The segmentation usually contains both the portal and hepatic veins. They are interconnected at some points due to partial volume effects and false positive segmentation results. To separate them, they transform the vessels into a formal graph which is analyzed for violations to some model assumptions. The graph is also used to label branches of the portal vein. This is then used to calculate liver segments as follows. Let L be the set of liver voxels, P_j a portal vein branch with label j, $j = 0, .., n-1$. The function $g(x, y)$ assigns label y to voxel x and $dist(x, y)$ calculates the Euclidean distance between voxel x and y. Then $\forall v \in L.g(v, f(v))$, with

$$f(v) = \underset{j=0,\dots,n-1}{\operatorname{argmin}} \; \underset{v_i \in B_j}{\operatorname{argmin}} \, dist(v, v_i) \qquad (1)$$

The result is an approximation of the portal venous territories with respect to the defined labels. The accuracy of this method was evaluated to be between 80-90%. Later work built on these results [10], [22], [9], [13], [12], [20]. Figure 1(right) shows patient-specific liver segments calculated using the approach proposed by Selle et al. [23].

Soler et al. [26] proposed to calculate the portal venous territories for all branches. These branches are then merged in a bottom-up manner using anatomical information from a labeled atlas that is registered to the current dataset.

In the web-based system developed by Meinzer et al. [15], different CT phases can be registered to combine vessels visible in each phase using an affine approach. After interactive separation of interconnected vessels, dependent tissue is calculated. Resection lines are visualized on the surface of the liver and volumetric analysis can be performed. The system allows access to the generated data over a secure virtual private network (VPN) connection.

Reitinger et al. [18] developed an augmented reality system with stereoscopic 3D visualization and 3D interaction for manipulating a liver model. They used the methodology proposed by Beichel et al. [2] to segment liver vessels and transform them into a formal graph representation. Liver segments are calculated using the approach by Selle et al. [23]. For anatomical resections, the user can select individual segments for removal and perform quantitative analysis. An evaluation of this system was presented by Sorantin et al. [28].

In the system proposed by Debarba et al. [4], vessels are annotated by placing points on the vessels. Those points are then used to calculate the liver segments similar to the approach proposed by Selle et al. [23]. The actual planning step consist of selecting one or more segments to be removed and displaying volumetric information.

The method proposed by Oliveira et al. [17] fits three approximately vertical planes to the main branches of the hepatic vein and one approximately horizontal plane to the orientation of the portal vein. The planes are fitted using voxels of the corresponding vessel branches in a least squares manner.

Drechsler and Oyarzun [6] presented a planning system that uses Selle et al's [23] approach to simulate the effect of intraoperative portal vein clamping. This technique is used by surgeons to detect the real segmental boundaries during intervention. By clamping the vein, the dependent parenchyma changes its color and the surgeon can use a coagulator to mark the boundaries on the liver surface. Chouillard et al. [3] gave an overview of vascular clamping techniques.

B. Atypical non-anatomic resections

In cases when the tumor is in the periphery of the liver or when liver tissue must be preserved, the surgeon can perform a non-anatomic resection. Hereby, the tumor is resected with an arbitrary cut along a safety margin around the tumor. In comparison to anatomical resections, main vessels can cross the cutting line. Thus, a careful preparation is necessary to determine, if a non-anatomic resection is feasible. This mainly depends on possible safety margins without cutting major hepatic vessels. Each cut portal vein causes bleeding and an undersupply of parts of the liver, which can become necrotic. On the other side, each cut hepatic vein causes a loss of drain for some parts of the liver.

Computer-based planning systems support the surgeon in different ways. Resections of peripheral tumors can be simulated using tools that allow to 'draw' resections lines, either with a specific shape or arbitrarily shaped. Other tools allow to assess surgical risk and provide quantitative measurements.

Numminen et al. [16] presented a system that allows to use straight planes to divide the liver into two parts.

Konrad-Verse et al. [13] developed a deformable cutting plane for virtual resections. The basic idea of their method is to convert resection lines drawn on the surface of a liver model into an initial mesh, which can be further deformed with a sphere shaped tool.

The augmented reality planning system by Reitinger et al. [18] provides three tools for non-anatomical resection. A plane for straight cuts through the liver (multiple planes can be used for a resection), a scalable sphere for resections of tumors at peripheral locations and a deformable plane for complex cases. The authors noted that for most cases, it is sufficient to define straight paths using one or two planes.

Song et al. [27] developed a system where the surgeon can draw arbitrary resection lines to resect the tumor. Furthermore, they provide tools for quantitative analysis.

Hansen et al. [12] proposed a tool to determine robust safety margins around the tumor. Therefore, their method analyzes cut vessels and their sub-branches using different safety margins. It then calculates corresponding portal and hepatic venous territories using Selle et al's [23] approach. The remnant liver volume versus safety margin is plotted in a graph and shows the optimal safety margin with respect to the liver remnant. Affected vessels and territories are visualized in 3D.

Shevchenko et al. [24] and Schwaiger et al. [21] presented a system that fully automatically segments liver vessels and performs risk analysis by means of visualization of affected vessels within three predefined margins around the tumor.

Drechsler et al. [5] presented a planning system that performs a deformable registration of multiple CT acquisition phases in order to fuse complementary information. Concretely, tumors visible in the arterial phase can be fused with hepatic veins visible in the venous phase. Afterwards surgical risk can be assessed by detecting affected vessels within a safety margin around the tumor and visualization of the corresponding portal and hepatic venous territories. Figure 2(left) shows the affected portal venous territory if the tumor is resected with a safety margin of 10mm. Figure 2(right) shows the same situation, but with a safety margin of 15mm. It can be seen that a slightly larger safety margin affects a bigger area of the liver.

III. DISCUSSION

This paper reviewed recent developments of computer-based systems for interventional planning of liver resections. They can be classified according to their medical use case into systems for anatomical or non-anatomical resection planning. The former allows for the calculation of functional liver segments, which can be calculated based on annotated hepatic vessels or based on planes fitted to the main hepatic branches. The latter provides tools to simulate arbitrary resections and perform risk analysis based on individual safety margins around the tumor. Proposed systems mainly differ in the used algorithms, the degree of automatism and provided planning tools integrated into the application. Some systems do not offer methods to separate interconnected vessels, others do not provide the fusion of information spread in multiple datasets. Table I provides a summary of the publications mentioned in this work. It contains information about used methods for data preparation and which tools are provided for resection planning. The former is divided into organ, vessel and tumor segmentation methods. Usually, these structures are segmented using variations of threshold-, region- or model-based approaches. But also manual methods (drawing in each slice) were used. Meinzer et al. [15], for example, provides a set of basic tools, like region growing and active contours. Furthermore, the table lists if vessels are separated using a graph representation or if it is soly based on voxel information. If data fusion is provided, it is listed if the registration process is performed in a rigid-, affine or deformable manner.

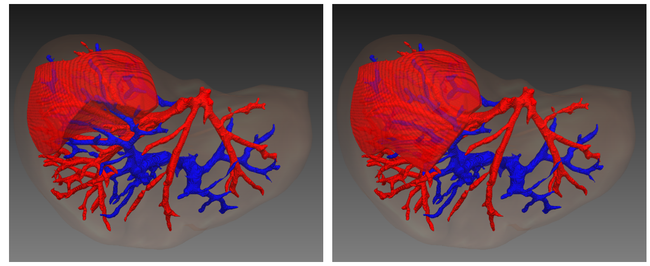

Fig. 2. Affected portal venous territory if the tumor is resected with a safety margin of 10mm (left) and 15mm (right). Images taken from [5].

This paper shows that liver resection planning systems reached a stable state and are already used in clinical practice. But the full potential of computer assisted liver resection planning is not unleashed yet. Several researchers are still actively investigating ways to improve and extend possibilities. Current trends include the fusion of information from multiple datasets and the automation of various steps in the workflow. Hansen et al. [11], for example, investigated ways to automatically generate resection proposals. This is quite challenging due to the lack of expert knowledge. For instance, surrounding structures and deformation must be taken into account to plan access to the tumor. Furthermore, a fully automatic segmentation of all relevant structures is highly desired to safe time and reduce inter- and intraobserver variability.

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	Data preparation					Planning tools			
						Typical		Atypical	
Publication	Organ	Vessels	Separation	Tumor	Fusion	Vessels	Planes	Arbitrary	Risk analysis
Selle et al. [23]	Livewire	Region	Graph	n/a	n/a	•			
Soler et al. [26]	Model	Threshold	Graph		n/a	•			
Meinzer et al. [15]	Basic tools	Region	Graph	Basic tools	Affine	•			
Reitinger et al. [18]	Model	Region	n/a	Model	n/a	•		•	
Debarba et al. [4]	Livewire	n/a	n/a	n/a	n/a	•			
Oliveira et al. [17]	Model	Region	Voxel	Region	n/a		•		
Drechsler & Oyarzun [6]	Model	Region	Graph	Sphere	n/a	•			•
Numminen et al. [16]	Threshold	Manually	n/a	Manually	n/a			•	
Konrad-Verse et al. [13]	n/s	n/s	n/s	n/s	n/a			•	
Song et al. [27]	Level set	Region	n/a	Region	n/a			•	
Hansen et al. [12]	Livewire	Region	Graph	Region	n/a				•
Shevchenko et al. [24]	Region	Region	n/a	Region	n/a				•
Drechsler et al. [5]	Model	Region	Graph	1. Graph-cut 2. Radial rays	Deformable				•

TABLE I

SUMMARY OF DISCUSSED PUBLICATIONS. ALGORITHMS FOR DATA PREPARATION AND PROVIDED PLANNING TOOLS ARE LISTED. N/A: NOT AVAILABLE BY THE DESCRIBED SYSTEM. N/S: SUPPORTED, BUT NOT SPECIFIED IN THE PAPER.

In J. M. Fitzpatrick and M. Sonka, editors, *SPIE Medical Imaging 2004: Image Processing*, volume 5370, pages 1435–1446. SPIE, 2004.

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