

Resectograms: Real-Time 2D Visualization of Liver Virtual Resections

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Abstract

Visualization of virtual resections plays a central role in computer-assisted liver surgery planning. The complexity of the liver's internal structures often leads to difficulties in its proper visualization during the positioning of virtual resections. Occlusions by vessels and tumors are common problems leading to non-preservation of resection margin, incorrect intersection with vessels, and resections. To overcome these challenges, we introduce Resectograms: a visualization approach based on 2D representations of virtual resections, which enable the visualization of information associated with surgical planning. These representations are presented as an additional 2D view displaying anatomical, functional, and risk-associated information extracted from the virtual resection in real-time. This view offers surgeons a simple and occlusion-free visualization of the virtual resection during surgical planning. Our pilot experiment with clinicians shows that the use of this visualization tool provides more information while planning virtual resections and has the potential to enhance confidence in accurate resection. The code repository and supplementary materials for this work is available at: <https://github.com/ALive-research/Slicer-Liver>

CCS Concepts

• **Computing methodologies** → Virtual reality; • **Human-centered computing** → Visualization techniques; • **Applied computing** → Life and medical sciences;

1. Introduction

Liver cancer is one of the most common fatal malignancies worldwide [SMWJ23]. Surgical resection is a preferred treatment option for liver tumors, offering a promising chance of long-term survival [OA18]. In order to reduce the risks of intra- and postoperative complications, a well-prepared preoperative surgical plan can provide good support and better understanding for each specific case and thus it may improve efficiency and success rate [KPB*20]. Surgical planning systems have emerged as valuable tools in this context, aiding clinicians in decision-making for liver therapy planning, ultimately improving the understanding of complex internal structures within the organ [LRH*05].

The visualization of virtual surgery plans in 3D is a highly complex task: anatomical information (typically portal and hepatic venous systems, tumors and liver parenchyma) is represented as 3D triangle-based meshes with different transparency levels, intersected by virtual resections. This complexity can further increase in scenarios presenting multiple tumors and resections, functional

information (such as liver division into segments) as well as risk-associated information (i.e., resection margins). Occlusion emerges as one of the main problems for visualization of virtual resections and often leads to invalid resections: (1) a resection not completely exceed the parenchyma, (2) formation of multiple unconnected resections (islands), (3) resections invading neighbouring vascular territories, (4) resections not preserving safety margins and (5) resections involving longitudinal cuts to vessels.

The goal of this work is to address the problems derived from occlusion in virtual resection planning. To this end, we developed a new visualization prototype that integrates our novel approach into the existing resection planning method introduced by Palomar et al. [PCE*17]. Our prototype has been implemented as a module within the widely used medical visualization platform 3D Slicer [KPV13], offering an effective tool for evaluation purposes. The novel contributions of this work are as follows:

- We propose resectograms: a novel 2D visualization method, focused on the resection, that can address the problems derived from occlusions during virtual resection planning.
- We present preliminary results from the evaluation of the system by Hepato-pancreato-biliary (HPB) surgeons.
- We show that resectograms can be used to identify and charac-

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terize invalid resection types which are typically generated due to poor visualization in virtual resection planning.

2. Related Works

Visualizing 3D spatial data in a lower dimension is extensively utilized in medical visualization to address the challenges posed by complex structures [KMM*18]. The aim is to convert (embed) 3D information into 2D spaces, that can be easier to interpret, potentially reducing the need for user interaction [ERM*21].

While there is limited research on visualization techniques specifically for liver resection surgery plans in lower dimensions, there are notable studies in the field of radiofrequency ablation (RFA) with valuable insights. In the context of RFA therapy, Rieder et al. [RWS*10] present a Tumor Map that maps the tumor surface as well as all ablation zones onto a color-coded 2D cylindrical image, which helps fast recognize the critical area. Additionally, to provide a navigation tool as well as a better assessment of the RFA, combined with a 2D CT slices view, the corresponding position and orientation information was added to the risk map. Another study by Hettig et al. [HMR*17] proposed an approach to enhance the navigation of an ablation application in liver surgery through the effective 2D map visualization of 3D anatomical structures. The animated map display is a series of static 2D images with a multi-layer critical structure cut contour, desaturated color is then employed to represent the depth information of each layer. This visualization technique aims to reduce the visual complexity of anatomical structures by presenting unobstructed information, and shows that their method is notably better for decision-making speed and structure assessments as compared to conventional 3D volume navigation.

3. Method

The method proposed in this work is based on two key ideas: (1) the unraveling of virtual resections (represented as 2D surfaces embedded in 3D space) into 2D canvases (Fig. 1); and (2) the mapping of information derived from segmented images along the trajectory of the resection, onto the 2D canvas space. Such information is established in terms of proximity and intersection of virtual resections with anatomical structures.

One important aspect of this method is the ability to update the information in real-time—this is particularly relevant since the user performs continuous interactions for deformation of the virtual resection. As opposed to traditional virtual resection definition based on deformable cutting surfaces, which operate on 3D surface models, resectograms establish intersection and proximity operators in terms of image processing over texture sampling. This, allows resectograms to use more precise information (e.g., derivatives from image segmentation, as opposed to 3D surface models which often introduce smoothing and decimation). It also leverages the massive parallel computing capabilities of GPUs.

An overview of the method and its components, is illustrated in Fig. 2. In the remaining of this section, the design of visual information presented in resectograms and the different components involved in the computation of resectograms are detailed.

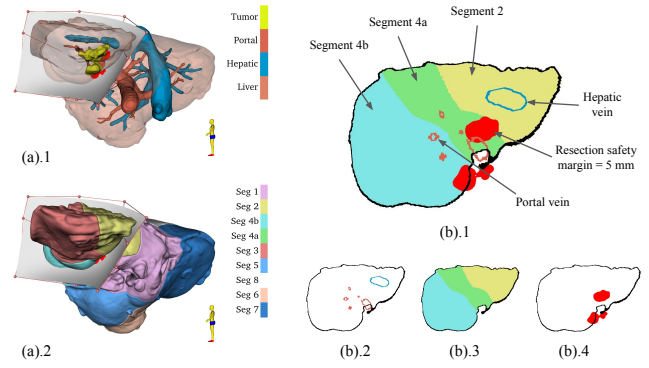


Figure 1: (a) 3D virtual resection as in [PCE*17] and (b).1, resectogram displaying intersection with liver, segments, vessels, resection margin and separate views of the resectogram: (b).2, Resection cross-section, (b).3, Resection anatomy segments, and (b).4, Resection safety margins.

Visual Information Design — The key idea behind the introduction of Resectograms is to address the occlusion problem of complex 3D structures during virtual surgery planning. In the 3D scene, it is often difficult to visualize how the resection surface intersects with liver parenchyma, vessels, and liver segments, leading to potential invalid resection. To overcome these issues, Resectogram introduces three separate views: **Resection cross-section, Resection anatomy segments, and Resection safety margins** (as depicted in Fig 1.b(2-4)).

- **The Resection Cross-section** view provides a clear representation of the intersection edges between vessels and the resection surface.
- **The Resection Anatomical Segments** view highlights the liver segments intersection with the resection surface. This and the Resection cross-section view utilize the same color scheme as the corresponding 3D models, aiding in their better understanding and interpretation.
- **The Resection Safety Margins** view offers an unobstructed visualization of the resection margin. Surgeons can easily assess its position in relation to other views and determine if it falls within an acceptable range such as when it extends beyond the boundaries of the liver parenchyma.

Computation of Distance Maps — Virtual surgery planning is performed entirely with the use of static models (e.g., information does not change over time). We take advantage of this fact to use the set of segmentations $\mathbb{S} = \{S_P, S_H, S_V, S_T\}$ and derive a set of distance maps $\mathbb{D} = \{D_P, D_H, D_V, D_T\}$, where each $D_i, i \in \{P, H, V, T\}$, is a function mapping segmentations (parenchyma, hepatic, portal and tumors, respectively) to distance maps:

$$D_i : \mathbb{N}_0^3 \rightarrow \mathbb{R}^3, \quad D_i(v) = d(v, S_i), \quad (1)$$

where d is the shortest 3D Euclidean distance from the center of a voxel v on the image space to the given segmented structure S_i . The computation of distance maps is known to be a costly operation in terms of processing. To reduce the computational cost our

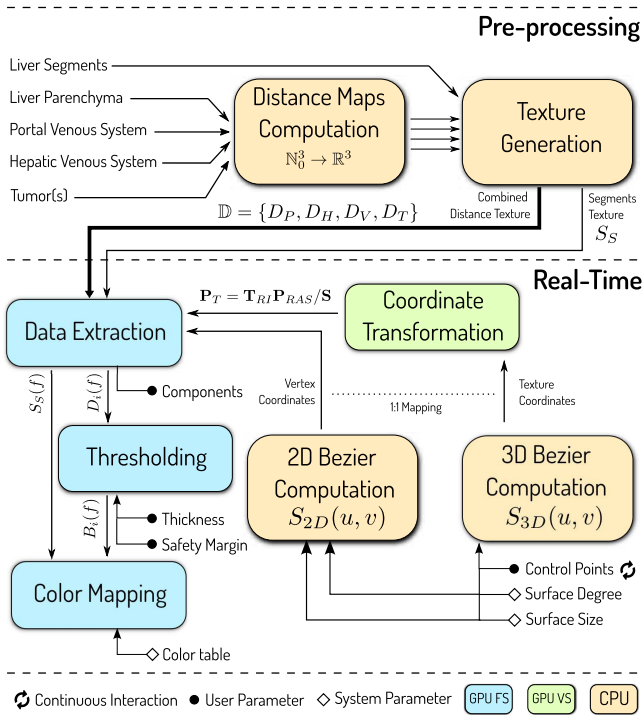


Figure 2: Workflow with processing stages and parameters for the generation of resectograms. Processing stages are classified according to the processing unit involved and parameters are classified in terms of their nature (user, system or user continuous interaction).

implementation uses the Maurer distance [MQR03], which provides good efficiency and accuracy. The reader should note that the anatomical segments of the liver are not converted into distance maps; instead, they are used in their original form.

Texture Generation — In order to enable the real-time exploitation of the distance maps, the anatomical segments of the liver are transferred to the GPU by means of 3D textures. We utilize floating-point 4-channels (RGBA) 3D textures for the distance maps (as they happen to be 4 scalar distance maps) and one integer 1-channel 3D texture for the liver anatomical segments. This scheme facilitates the extraction of information from any distance map as all distance maps lay on the same texture space: $T \in [0, 1]^3$. Specifically, for each texture coordinate $(s, t, r) \in T$, we have $T(s, t, r) = (D_P, D_H, D_V, D_T)$.

Bézier Surfaces in Virtual Resections and Resectograms Definition — In this study, we use parametric Bézier tensor-product to represent virtual resections:

$$S(u, v) = \sum_{i=0}^3 \sum_{j=0}^3 B_i^3(u) B_j^3(v) P_{ij}, \quad (2)$$

where $B_i^3(u)$ and $B_j^3(v)$ denote third-order Bernstein polynomials. The control points, $P_{ij} \in \mathbb{R}^3$, allow users to modify and determine the shape of the virtual resection.

To create a resectogram, a planar version of the virtual resection, S_{2D} , is derived using co-planar sets of control points (P_{ij}). This produces a 2D Bézier surface occupying the identical parametric domain (u, v) as its 3D counterpart, S_{3D} (1:1 mapping). Then, the 3D virtual resection's physical coordinates are assigned as texture coordinates to S_{2D} :

$$(r, s, t)_{S_{2D}(u, v)} = S_{3D}(u, v) \quad (3)$$

Using co-planar control points and transferring the physical coordinates of the virtual resection to the resectogram's texture coordinates enables the projection of 3D data from volumetric textures (distance maps) onto the 2D resectogram.

Coordinates Transformation — The 1:1 mapping between 3D and 2D Bézier surfaces is not enough to extract the information contained in the distance maps as this information is in the texture space T , which is different from the anatomical space in which the 3D Bézier surface lies (RAS—Right, Anterior, Superior). In order to bring everything into the same coordinates, we first transform these coordinates into image space (IJK), which has the property of having the same origin and orientation as the texture space T . Finally, the space is scaled to the range $[0, 1]$ using the image extent. The full chain of transformation is as follows:

$$P_T = T_{RI} P_{RAS} / S \quad (4)$$

where P_T is a transformed point in T space, P_{RAS} is the original point belonging to the 3D Bézier surface, T_{RI} is the transformation from RAS to IJK space, and $S = (S_I, S_J, S_K)$ is the size of the image along the three dimensions.

Data Extraction Techniques — Through equations (3) and (4), our planar representations of virtual resections have associated 3D texture coordinates within the same space as the distance maps (volumetric textures). This alignment enables the extraction of the information contained in volumetric textures through texture sampling mechanisms. For the sampling process, we employ linear interpolation for the distance maps and nearest-neighbor interpolation for the anatomical segments. Additionally, a clamp-to-border texture wrapping strategy is used, setting out-of-bound values to a contextually large number (i.e., 1000 mm). Resectograms have the ability to present partial information according to the preference of the users, therefore, the extraction process can extract information from different information textures in a process that can be configured by a *layers* parameter that the user controls.

Thresholding — While texture sampling is enough to provide distance information and label information from the anatomical segments, the intersection of vessels and resection margin information requires thresholding. For this purpose, we define a new set of binary maps $B = \{B_i\}_{i=1}^n$, where each B_i is a function that labels a fragment f to either i or 0 based on the distance map D_i employed:

$$B_i(f) = \begin{cases} i & \text{if } -d \leq D_i(f) \leq d \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

This formulation effectively thresholds the distance maps at 0 with a distance of d set by the user, and labels the fragment based on the target texture.

Color Mapping — Finally, every output fragment f is assigned

an RGB color value according to a color table. This color table conciliates the colors of the resectogram with the colors of the virtual resection 3D scene so the user is able to identify the different elements in both views.

4. Results

4.1. Use of Resectograms to Identify Malformed Resections

Resectograms offer real-time visualization of the resection surface and intersected structures, providing clear and unobstructed views of resection shapes and resection margins. This provides a straightforward method for identifying inadequate resections during the virtual resection planning process. In Fig 3, various examples of inadequate resections are shown alongside their corresponding views in Resectogram. For instance, in Fig 3.e, the small violation of resection margins is difficult to observe in the 3D scene alone, but it becomes evident in the Resection Safety Margins view of the Resectogram. Similarly, in Fig 3.c, the cutting edges of vessels require close inspection and rotation of the 3D model in the 3D scene, whereas Resection cross-section in Resectogram provides an intuitive representation of this information. Furthermore, verifying if the intersection edge between the resection plane and the liver surface forms a closed curve can help to assess if the resection surface fully cut through the liver and accurately calculate the volume of the resected specimen. Additionally, the Resection Anatomy Segments view in Resectogram facilitates the identification of the involved liver segments during the resection, thereby helping to preserve liver parenchyma (Fig 3.b).

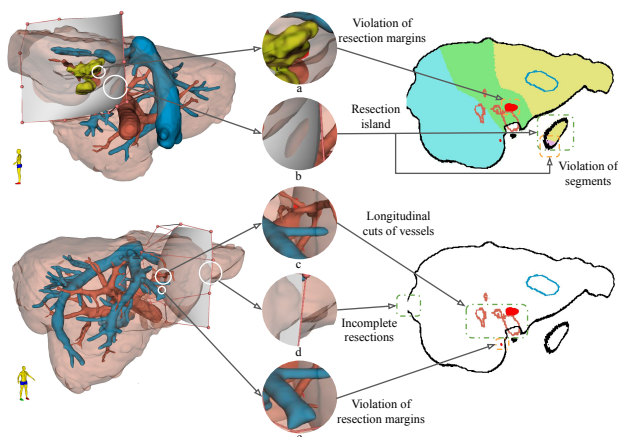


Figure 3: Resectograms help identify invalid resections.: (a) violation of resection safety margin (3mm), (b) resection islands and violation of liver segment 1, (c) longitudinal cuts of vessels, (d) incomplete resections, and (e) hidden resection safety margin (3mm).

4.2. Pilot Evaluation by Clinicians

To assess the clinical potential of resectograms, we conducted a pilot study on retrospective data involving three surgeons. The data used was a clinical case with a liver tumor located in the middle of segment 4b. Prior to the study, the surgeons underwent a brief

training session on how to perform a 3D resection plan and utilize the software tools.

The study was divided into two stages. In the first stage, surgeons were asked to plan a liver resection surgery using virtual resections as in Palomar et al [PCE*17]. Once satisfied with their resection plan, the resectograms were enabled, providing a combined view of resection cross-section, resection anatomy segments, and resection safety margins. Surgeons were encouraged to explore the additional information and make modifications to their plan based on the resectograms.

Following the completion of both stages, surgeons provided feedback through a questionnaire. The questionnaire utilized a Likert scale ranging from 1 to 5. Its purpose was to gather their opinions and observations regarding the usefulness and effectiveness of resectograms in the liver resection planning process.

The participating surgeons had varying levels of experience in general and HPB surgery: 15, 7 and 9 years of surgical experience respectively. It is worth noting that Surgeon 1 had previous experience using virtual resection planning tools.

After enabling the resectogram, surgeons 1 and 2 modified their initial resection plans based on the additional information provided by the resectogram. Surgeon 1 observed formation of unconnected resections (islands) not clearly visible in the 3D virtual resection (Similar to Fig 3.b) and made appropriate adjustments to avoid unnecessary cuts. Surgeon 2 identified significant risks associated with the cutting shape of the hepatic vein but struggled to adequately address the identified risk due to a lack of proficiency in virtual resection planning.

The overall feedback (Table 1) on the information provided by Resectogram was positive, indicating a favorable reception of Resectogram's capabilities (Q4-Q6). Regarding specific results from Q1-Q3, Surgeon 1 had a positive self-reflection on his final resection plan, stating that Resectogram helped improve his confidence and accuracy in the surgical planning process. Surgeon 2, on the other hand, expressed confusion regarding the orientation mapping between the 3D and 2D surfaces, which resulted in his final resection plan not being as satisfactory. Surgeon 3, was satisfied with the resection plan after reviewing the resectograms and didn't make any changes, still acknowledged the positive impact of Resectogram's potential to enhance confidence in surgical planning.

5. Discussion

Resectograms require a choice in the co-planar set of control points P_{ij} that constructs their 2D representation. In this study, we chose rectangular representations to maintain a sense of regularity, despite the potential introduction of area and angle distortions. These distortions have a limited impact on identifying features like resection islands or incomplete resections, as these aspects remain distinguishable. However, some concerns arise when considering vessel cross-section and anatomical segment violations. Angle distortions might have a greater impact on vessel cross-sections, where preserving distinctions between longitudinal and true cross-sections (circles) is crucial. Since resection plans generally do not have extreme curvature or large discrepancies in aspect

Table 1: Questionnaire performed by the participants after use of resectograms for surgery planning.

Questions	Surg. 1	Surg. 2	Surg. 3
Q1: I was satisfied with the result of the Resection Planning (the right shape & position of the plane)	5	3	3
Q2: I increased my accuracy in putting proper resection plan thanks to the help of the Resectogram.	5	2	N/A
Q3: Resectogram provides more information and confidence.	5	2	4
Q4: I was satisfied with the visualization of the safety margin around the tumors shown in 2D.	5	5	4
Q5: I found it useful to have a clear 3D and 2D view showing the cutting edge of intersections between the resection surface and critical structures (liver, vessels) while planning resection.	5	5	4
Q6: The 2D view combined with intersections between the resection surface and the liver segments provides information on segmental involvement	5	5	4

ratio along their axes, we note that longitudinal sections remain discernible. Regarding the area distortion of anatomical segment injuries, there's a potential risk of underestimation, for example, when the injury area shown in resectograms appears smaller than in reality. However, as resectograms serve as aids for visualizing 3D resection plans with highlighted risk information, users are still required to swiftly verify the corresponding 3D scenes to ensure optimal resection planning. Thus, we believe that these distortions are unlikely to significantly compromise the overall interpretation of resectograms.

The method's design has been significantly influenced by real-time considerations. This stems from the fact that resection adjustments occur in real-time, and any disruption to this process can hinder resection planning's effectiveness. In this context, the pre-calculation of distance maps, which can be utilized as 3D textures during rendering, has emerged as a robust solution. This approach can be effectively applied to devices with modest computing capabilities. The subsequent process involves simple texture sampling and thresholding on the generated 3D textures using GPU. Importantly, no noticeable performance impact was observed during both the development and experimentation phases. It should be noted, however, that the utilization of 3D textures increases GPU memory requirements, which could pose challenges for GPUs with limited memory. To mitigate this, potential strategies such as image cropping or sub-sampling could be employed, offering a way to achieve high accuracy even with reduced memory usage.

6. Conclusion

This paper introduces Resectograms, a novel method that offers intuitive and occlusion-free visualization of liver virtual resection plans as an accompanying 2D representation that can be computed in real-time. The method includes three distinct 2D components: resection cross-section, resection anatomy segments, and resection safety margins, which collectively provide comprehensive information for liver surgery planning. Resectogram can effectively identify and characterize invalid resection types, which often arise due to inadequate visualization in virtual resection planning. Our preliminary results (Table 1) indicate the added value of resectograms for surgery planning, given the surgeons rating on average was 4.67 out of 5.0 (Q4-Q6).

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