Automatic Estimation of Optimal Resected Liver Regions Considering Practical Surgical Conditions

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Abstract— *This article presents an automatic approach to estimate optimal resected-liver regions for oncologic surgery planning considering practical surgical conditions. Since the liver has complex vessel structure, it is difficult for human to find optimal resected liver regions. We provide efficient approaches for two types of practical problems: (1) Finding an optimal resected region under cut volume limitation, and (2) Finding an optimal cut surface based on a 3-dimensional(3-D) parabola model. For both problems, a tumor domination ratio is efficiently used to find all portal vessels related to tumors. The experimental results demonstrate that the resected liver regions of the proposed approach are much smaller than those of the conventional manual approach in most cases.*

Keywords: Medical imaging, 3D simulation analysis, anatomic hepatectomy, local thickness

1. Introduction

3D simulation plays an important role in surgical planning for hepatectomy since the liver has a complex structure, that is, some different vessels are arranged complexly as shown in Fig. 1. The estimation of regions perfused by the portal vein is especially one important task in anatomical hepatectomy, since the hepatocellular carcinoma(HCC) tends to metastasize via the portal vein [1], [2]. Figure 2 explains how the perfused region is estimated. The tumor affects the nearest parts of the portal vein; from the nearest parts, the HCC metastasize in the downstream direction via the portal vein. The overestimate of the perfused region tends to prevent the metastases, but it increases the possibility of the post-operative liver failure. Therefore, the volume of perfused region should be minimized while including all the perfused regions of the portal vein feeding the tumor.[2]

In preoperative planning, surgeons search for the combination of the cut points on the portal vein in a trial-and-error way until the tumor is covered by the perfused regions of the portal cut points. However, it is difficult and time-consuming for surgeons to find optimal or near-optimal combination since the portals vein has complex structure, that is, it has many branches. Surgeons select simple combinations, and this results in overestimation of the perfused region.

In order to solve this problem, an approach using a tumor domination ratio have been proposed[3],[3]. The tumor domination ratio reflects how much volume of the tumor a part of the portal vein feeds, and allows to pick up all the tumor-related parts of the portal vein.

However, the resected region resulting from the tumor donation ratio (called "100%" resected region) can not be used to practical surgeries in most cases. The patients suffering from HCC tends to have much lower liver functionality than normal persons; their upper limits of the resected-region volumes are much smaller than those of normal persons. As a result, 100% resected region must be shrunk so as to meet the upper limit of the resected-region volume.

Another problem of the 100% resected region that the cut-points may not be recognized by surgeons in real surgeries since surgeons cannot recognize veins thiner than 6mm. This problem occurs when tumors exists near the liver surface since the veins get thiner around liver surface.

In the following, we provide efficient approaches to solve these two practical problems:

(1) Finding an optimal resected region under cut volume limitation for the former problem
(2) Finding an optimal cut surface based on a 3-dimensional(3-D) parabola model for the latter problem

2. Estimating an 100% resected region using the tumor donation ratio[3],[4]

This section briefly explains 100% resected region and how to get it since the method given in Sections 3 and 4 is based on the 100% resected region. The region perfumed by a point on the portal vein is estimated by using a Voronoi diagram[2]. Figure 3 (a) shows a Voronoi diagram. A Voronoi diagram is a way of dividing space into a number of regions. A set of points (called seeds) is specified beforehand and for each seed there will be a corresponding region consisting of all points closer to that seed than to any other. The regions are called Voronoi cells. A seed and Voronoi cell in a Voronoi diagram correspond to a point on a portal vein and a region perfumed by the portal point as shown in Fig.3 .

The tumor domination ratio TDR of a portal point P is defined as follows.

$$TDR = \frac{\text{[Volume of the region perfused by } P \text{ in the tumor]}}{\text{[Volume of the tumor]}} \times 100 \quad [\%], \quad (1)$$

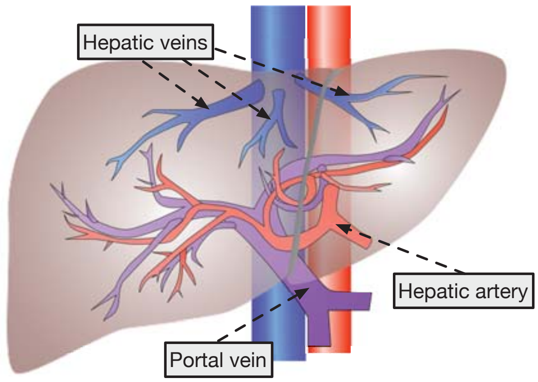


Fig. 1: Vascular system of the liver.

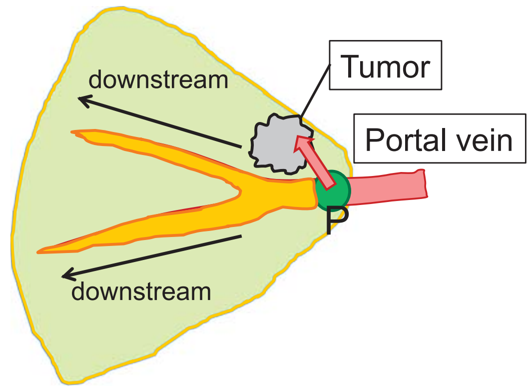


Fig. 2: Region perfused by the portal point P and its downstream.

where the denominator and the enumerator are illustrated in Fig.3 (c). The tumor donation ratio reflects how much the portal-vein point feed the tumor and is affected by the tumor.

Given a tumor location, let us compute an 100% resected region by using the tumor donation ratio, where the 100% resected region means a minimum region including all sub-regions perfused by tumor-related portal points. All tumor-related portal points are found by using the tumor donation ratio; all the portal point with TDR larger than 0 are picked up as tumor-related portal points. Finally, the 100% resected region is given as the union of all the regions perfused by the tumor-related portal points.

This procedure to find an 100% resected region is extended so as to consider more practical conditions such as condition limiting cut points to branch points with pre-set thickness of veins[3].

3. Finding an optimal resected region under a cut-volume limitation

Although the 100% resected region is ideal from the view of preventing the cancer from metastasizing, it may not be acceptable for most patients because of their low liver functionality. In pre-operative planning, surgeons usually determine the upper limit of the cut volume depending the liver functionality of each patient. Hence, from the practical view, it is important to finding an optimal resected region under a cut-volume limitation.

In the following, we describe the formulation. Let V_{max} be the upper limit of the total cut volume for a patient. This parameter is given by surgeons based on the result of the pre-operative tests for a patient. Let TDR_{low} be the lower limit of the tumor donation ratio; we do not consider the cut points whose tumor donation ratio is less than TDR_{low}. Parameter TDR_{low} is empirically set to around 5% so as to the optimization result is acceptable for most surgeons. The reason why we use TDR_{low} is that, without this parameter, the search procedure sometimes select the cut points with large cut volumes and small tumor donation ratios, and this optimization result is unacceptable for most surgeons. As cut points, we select portal-vein branch points that satisfies the following conditions:

- branch points,
- the thickness is larger than the pre-set thickness,
- the tumor donation ratio is larger than TDR_{low}.

Let $CP = \{c_i | 1 \leq i \leq N\}$ the set of the cut points, where N is the total number of the cut points.

The optimization problem can be formulated as follows:

$$minimize \quad \sum_{i}^{N} T_i \tag{2}$$

under the condition

$$\sum_{i}^{N} V_i \leq V_{max}. \tag{3}$$

Figures 4 and 5 shows the optimization results for two samples. The left figure (a) shows the 100% resected region; the right figure (b) shows the proposed resected region in this paper. These results demonstrate that our proposed method can reduce the total cut volume, and provides almost same results as those by surgeons automatically.

4. Finding an optimal cut surface based on a 3-D parabola model

This section describes another optimization problem where the tumor exists around the liver surface. When the tumor exists around the liver surface, surgeons usually plan to scoop the tumor out from the liver. The shape of the scooped region can be well approximated by a 3-dimensional(3-D) parabola as shown in Figure **??**. In order to prevent the cancer from metastasizing, the scooped region should include the 100% resected region while the its volume is minimized. A arbitrary 3-D parabola has 8 parameters as

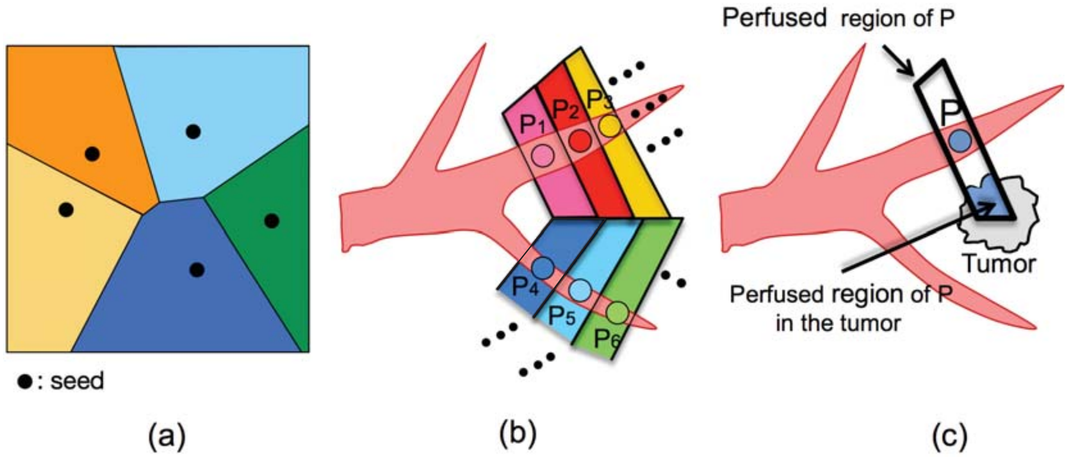


Fig. 3: Estimating perfused regions by portal-vein points based on Voronoi diagram.

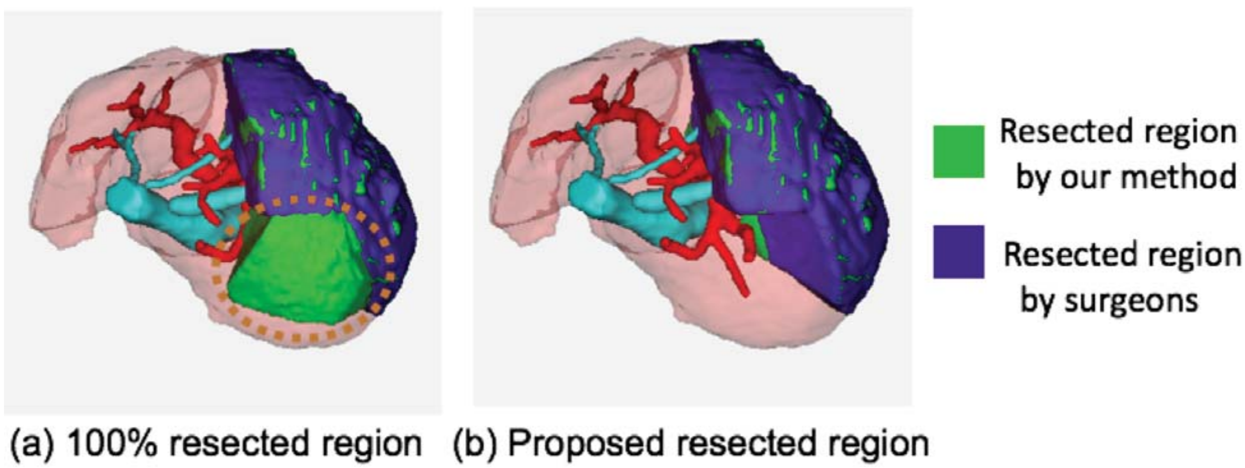


Fig. 4: Result for sample 1.

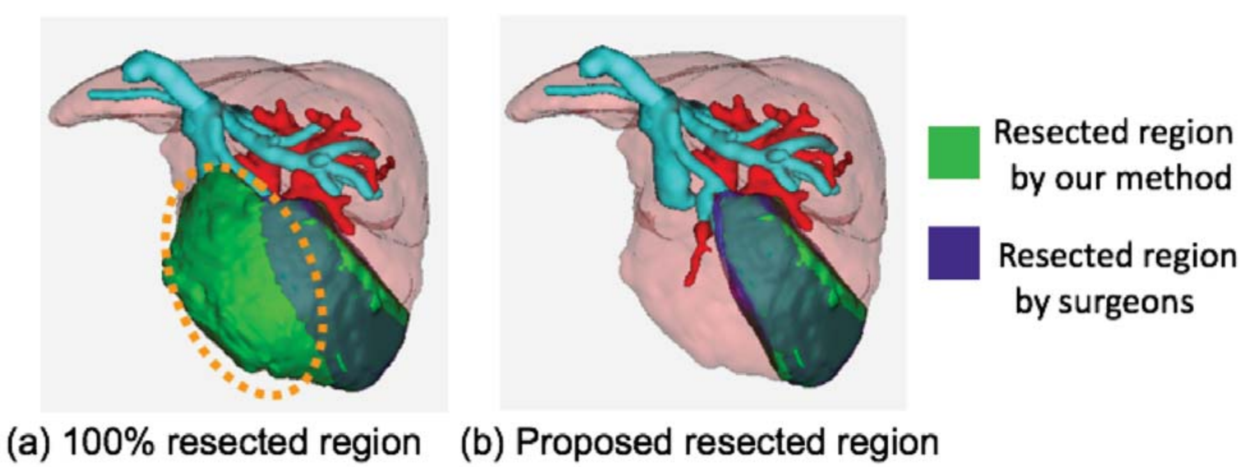


Fig. 5: Result for sample 2.

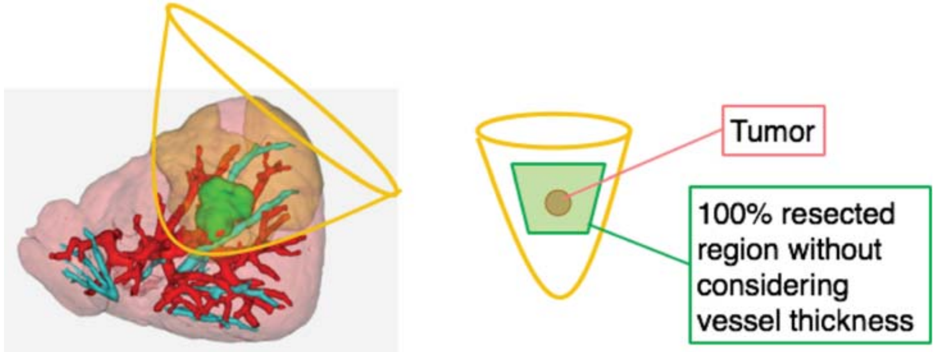
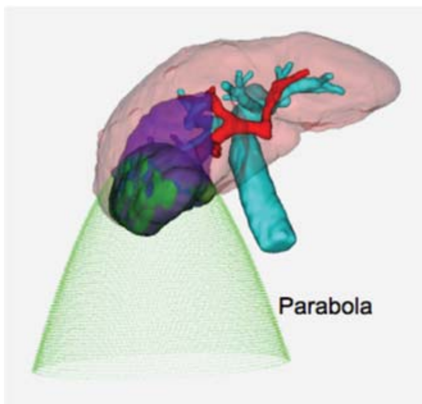


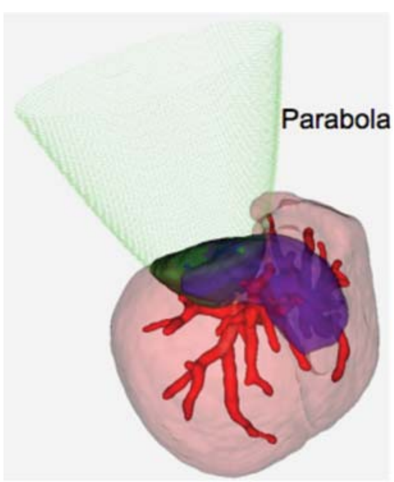
Fig. 6: Scooping a tumor out in the parabola shape.



100% resected region	75.5[cc]
Resected region by parabola-baesd optimization	123.8[cc]
Resected region by surgeon	189.9[cc]

Resected region planned by surgeons manually
Resected region by parabola-based optimization

Fig. 7: Result 1.



100% resected region	11.5[cc]
Resected region by parabola-baesd optimization	66.2[cc]
Resected region by surgeon	116.4[cc]

Resected region planned by surgeons manually
Resected region by parabola-based optimization

Fig. 8: Result 2.

follows:

Shape parameters(Curvatures): A_x, A_y

Rotation angles in 3-D space: roll, pitch, yaw

Translation distances in 3-D space: T_x, T_y, T_z

When the tumor shape, the tumor location, and the 100% resected region are given, the 8 parameters of a parabola are optimized in such a way that the scooped volume is minimized while the parabola still includes the 100% resected region. Note the 100% resected region without considering the thickness of vessels is used here, and is obtained through the processing described in Section 2. In search process, some efficient search techniques are used since the search has a lot of time consuming procedures such as 3-D inclusion check. Figures **??** and **??** show the optimization results. In each result, the cut volume using parabola approximation is reduced to around half of the manual planning by surgeons. Note that the 100% resected region used here cannot be used cut volume in real surgery although its volume is smaller than that of the volume using parabola approximation; this is because the 100% resected region does not consider vessel thickness to obtain as small a resected region as possible; the vessel thickness used to compute the 100% resected region is too thin for surgeons to recognize in real surgery. From this observation, we can say that our approach provides good results from a practical view point.

5. Conclusion

This paper have presented practical approaches to estimate an optimal resected region for practical surgical conditions. The key to success to minimize the cut volume while preventing a cancer from metastasizing is the use of the tumor donation ratio that reflects how much portal-vein point affects the cancer tumor. As future work, cut volume estimation considering hepatic veins is remaining since, the blood congestion occurs which reduces the liver functionality when the hepatic vein is cut.

References

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