MESENTERIC VASCULATURE-GUIDED SMALL BOWEL SEGMENTATION ON HIGH-RESOLUTION 3D CT ANGIOGRAPHY SCANS

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ABSTRACT

Due to the low image contrast and high tortuosity of the small bowel on CT scans, it is difficult for even experienced radiologists to localize small bowel. To facilitate this, we propose a novel mesenteric vasculature-guided method for small bowel region segmentation on high-resolution contrast-enhanced CT angiography (CTA) scans. It is essential and useful for further localizing small bowel tumors. The mesenteric vasculature is first segmented using multi-view multi-scale vesselness enhancement filters on maximum intensity projection images. Second, the small bowel region is automatically segmented based on the map of mesenteric vasculature and its relationship to the small bowel. The method is applied to high-resolution contrast-enhanced abdominal CTA scans of patients suspected of having carcinoid tumors. The result, 79.3% volume overlap accuracy compared with the reference standard, shows it is feasible to segment the small bowel using the mesenteric vasculature as a roadmap on CTA scans.

Index Terms— vessel segmentation, small bowel segmentation, maximum intensity projection

1. INTRODUCTION

Early diagnosis of small bowel tumors is a diagnostic challenge because of the absence of symptoms until late in their growth and because of the deep location of the small bowel [1]. Although widely used for small bowel tumor detection, the reliability of capsule endoscopy (CE) remains unclear because of limitations in its field of view and frame rate. Conventional computed tomography (CT) with contrast agents is well established for the overall evaluation of the abdomen and pelvis but still has limitations for detecting small bowel pathology. Nevertheless, CT now provides a complementary role to CE for the diagnosis of small bowel pathology [2].

Traditionally, CT scans are examined by radiologists slice-by-slice to localize small bowel tumors. It is time consuming and unreliable. Automatic segmentation of the small bowel would be very useful for visualization, localizing exact relative position of tumors in the small bowel and pre-operative planning. It is also useful for localizing tumors next to the small bowel and distinguishing tumors of the small bowel from those next to the small bowel. However, segmenting the small bowel directly on CT scans is very difficult because of the low image contrast and high tortuosity of the small bowel and its close proximity to other abdominal organs on CT scans.

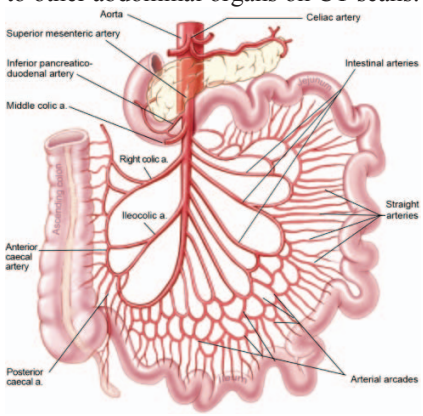


Figure 1. Mesenteric arterial vasculature of the small bowel.

We propose a novel mesenteric vasculature-guided method for small bowel region segmentation on high-resolution contrast-enhanced CT angiography (CTA) scans. To our knowledge, this is the first attempt to segment the entire small bowel on CT scans. The idea is motivated by two facts. The first is that vessels are much brighter than the small bowel on contrast-enhanced CTA scans, so its segmentation is easier than that of the small bowel. The second is that there are strong relationships between the mesenteric vasculature and the small bowel as shown in Fig.1. The mesenteric vasculature map can be used as a reference to locate and segment the small bowel. The mesenteric vasculature is automatically segmented using multi-view multi-scale vesselness enhancement filters. Noise, non-vessel lines and vessel branches not supplying the small bowel are removed using vessel shape and spatial

distribution characteristics. Using the map of the mesenteric vasculature and the vessels' spatial relationship to the small bowel, the small bowel region is segmented using fuzzy connectedness. The method is applied to high-resolution contrast-enhanced abdominal CT angiography scans of patients suspected of having carcinoid tumors. The results support our idea using the mesenteric vasculature as a roadmap to segment the small bowel on CTA scans.

2. OUR METHOD

The flowchart in Fig. 2 provides an overview of the method. It mainly consists of three steps. First, the internal abdomen region is automatically identified. Second, the mesenteric vasculature is extracted to create a map. Third, the small bowel region is segmented using the map.

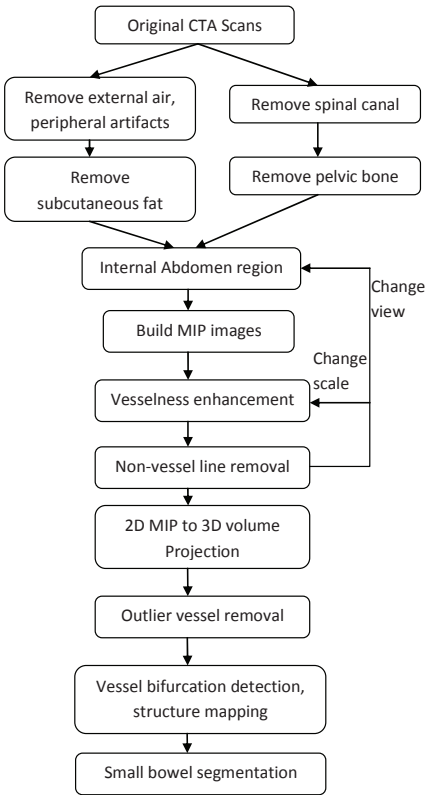


Figure 2. System architecture

2.1. Internal abdomen region segmentation

In order to build the map of the mesenteric vasculature, we must segment all of the vessels including small vessels which are sensitive to noise. To reduce computation time and avoid the effect line-like structures in fat and occlusions of bones, it is desirable to segment the internal abdomenal region. This part includes the following steps:

- Region growing and morphological techniques were used to get the body contour, then air region external to the patient and the CT table and tubing were removed.
- Fuzzy c-means was used to identify and cluster the fat regions. Active contour was used to separate visceral fat and subcutaneous fat [3].
- The spine was segmented and removed using a hybrid technique of thresholding, mathematical morphology, directed graph search, and a four-part vertebral model [4].
- Pelvic bones were roughly segmented and excluded by global thresholding.

Figure 3 shows an example of internal abdomen segmentation after excluding regions of undesired structures.

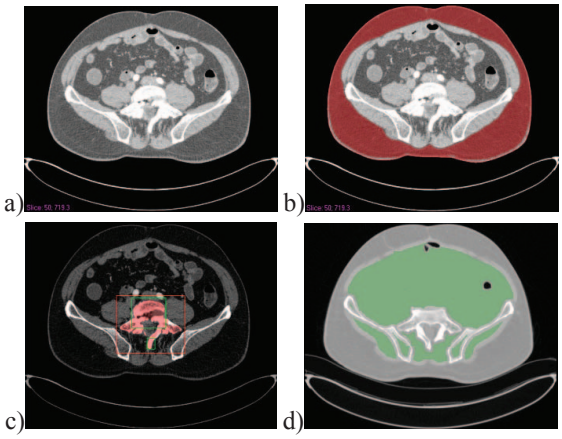


Figure 3. Example of internal abdomen segmentation. a) original CTA slice, b) fat segmentation (red), c) spinal bone segmentation (pink), d) internal abdomen region (green).

2.2. Mesenteric vasculature segmentation

Ideally, we would like to segment all of the mesenteric vessels including the tiny vessels closest to the small bowel. However, this is very challenging because of the low image contrast, high tortuosity and small size of these vessels. Most existing vessel segmentation methods only segmented large vessels [5,6]. In this section, an automated method is introduced to extract the mesenteric vasculature including small vessels on high-resolution abdominal CTA scans.

Our method uses vesselness enhancement on multi-view multi-scale maximum intensity projection (MIP) images. The MIP algorithm enables detection of the smaller vessels through signal enhancement. We first partitioned the CT volume into overlapping slabs of 16 mm thickness. One MIP image was generated from one slab, where the index for each voxel is stored. To complement spatial information lost by the MIP algorithm, multi-view method was used. That is, the slabs and MIP images are generated by rotating and resampling the 3D coronal volume.

Frangi's line filter [7], a multi-scale vesselness enhancement filter, was used to detect vessels on the MIP images. The Frangi filter requires calculation of a local Hessian matrix and its eigenvalues. The Hessian matrix for each pixel is computed by convolution with the second order derivatives of a Gaussian with scale σ

$$H_\sigma = \begin{vmatrix} I_{xx} & I_{xy} \\ I_{yx} & I_{yy} \end{vmatrix} \quad (1)$$

where $I(x,y)$ is the image intensity at pixel (x,y). Its corresponding eigenvalues are λ_1 and λ_2 ($|\lambda_1| \le |\lambda_2|$). Four scales of filters were used in our experiment, from 1 mm to 12 mm. Vesselness enhancement results are shown in Fig.5b.

Frangi filter detects many non-vessel lines, most of which are located at the edges of various abdominal organs and tissues. The intensity distribution of vessel regions as shown in Fig.4 follows two-dimension Gaussian, which is peaking at the center of the region. We define the intensity distributions of the test region and reference as $p(x) \sim N(\boldsymbol{\mu}, \Sigma)$ and $q(x) \sim N(\boldsymbol{\mu}_0, \Sigma_0)$, respectively, where $N(\cdot)$ is the Gaussian distribution, $\boldsymbol{\mu}$ is the mean and Σ is the variance. The distance between the test and reference was measured by the Kullback-Leibler distance [8], $D(\cdot \| \cdot)$,

$$\begin{aligned} D(p \| q) &= \int_x \{\log p(x) \cdot \{\log p(x) - \log q(x)\}\} \\ &= EP[\log p(x) - \log q(x)] \\ &= \frac{1}{2}\Big(tr(\Sigma_0^{-1}\Sigma_1) + (\boldsymbol{\mu}_0 - \boldsymbol{\mu}_1)^T \Sigma_0^{-1}(\boldsymbol{\mu}_0 - \boldsymbol{\mu}_1) \\ &\quad - \big(\ln(\det \Sigma_1) - \ln(\det \Sigma_0)\big) - k\Big) \end{aligned} \quad (2)$$

where $EP[\cdot]$ is the expectation under the density p, k is a constant. Given current vessel scale σ, reference parameters were learned from positive vessel line regions. $\boldsymbol{\mu}$ and Σ were calculated for every test region. Test candidates with large distance from the reference will be considered as non-vessels. Non-vessel line removal results are shown in Fig. 5c. After the removal of non-vessels, center-line detection and morphological operations were executed).



Figure 4. Examples of vessel regions.

Vesselness enhancement and non-vessel removal were executed on multi-scale and multi-view MIP images to detect different size vessels. The 2D vessel masks were backprojected onto the original 3D volume based on the stored indexes when building the MIPs.

Vessels which supply the large bowel and organs other than the small bowel were excluded based on a local distance map [9]. One point belonging to the superior mesenteric artery supplying the small bowel was first manually initialized, and then local distance map around this point was calculated and propagated along vessel branches in 3D space to evaluate the membership of vessel candidates. Outliers were removed using the scale-based thresholds of membership values. Results are shown in Fig. 5.d.

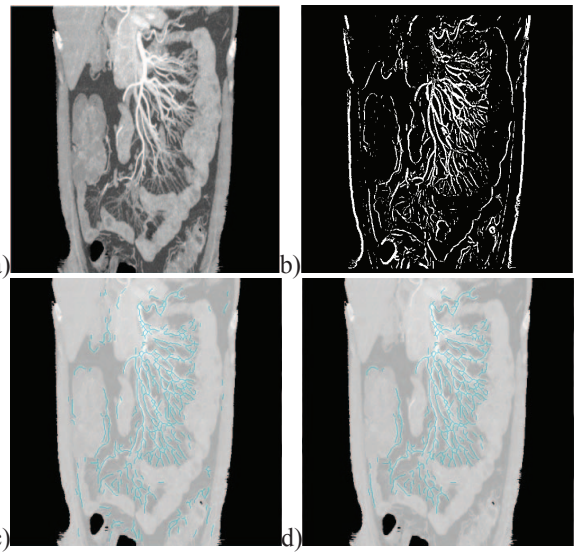


Figure 5. Mesenteric vessel segmentation. a) MIP image after excluding external abdominal structures and bones, b) vessel enhancement using Frangi's filter, c) initial vessel centerlines after non-vessel removal (blue), d) final vessel centerlines after outlier vessel removal.

2.3. Small bowel region segmentation

Identifying vessel bifurcations and constructing chains of bifurcation points make it easier to map the structure of the mesenteric vasculature. We adopted connected component method [10] to detect the vessel bifurcations in MIP images. A hollow circle centered at the voxel with inner radius r_{in} and outer radius r_{out} was placed. Then the number of connected components inside the hollow circle was counted. A bifurcation (such as points 3 and 4 in Fig. 6a) should have three or more components. Then, bifurcation points were linked into chains according to their connectivity.

The small bowel is located at the extrema of the mesenteric vasculature (leaf nodes of the mesenteric vessel tree as shown in Fig.6b). First, we identified the extrema points of the mesenteric vasculature. From the last point of each chain of bifurcation points, we find the other vessel endpoint which is not a bifurcation point. These points are located on one side of the wall of the small bowel (the "mesenteric" side). Using intensity thresholding, mesenteric

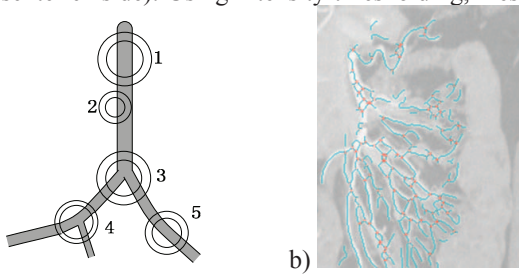


Figure 6. Bifurcation detection. a) schematic showing bifurcation (3, 4) and non-bifurcation (1, 2, 5) points, b) detection results (red points, part of Fig.5 for display).

side was identified around these extrema points. Second, we identified the other side of the wall of the small bowel (the "anti-mesenteric" side) using fuzzy-connectedness (FC) [11] based on intensity and shape starting from the mesenteric side of the small bowel. Regions between these boundaries and close to mesenteric vessels were connected as the expected small bowel. The final result is shown in Fig. 7.

3. EXPERIMENTAL RESULTS

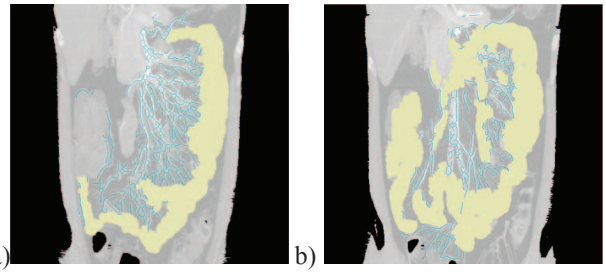
To evaluate the performance of our system, high-resolution contrast-enhanced abdominal CT angiograms of patients suspected of having small bowel carcinoid tumors were acquired at 1 mm thickness, 0.5 mm reconstruction interval and 0.86 mm pixel size, following oral administration of Volumen and intravenous administration of Isovue-300. Data acquisition and analysis were conducted under IRB approval. The mesenteric vasculature of one case and small bowel of 6 cases were manually labeled as a set of tubular segments in the 3D volume using Vascular Editor software [12] as the reference standard for evaluation.

To assess the accuracy of our method, we report some standard error metrics. We define reference volume A and segmented volume B. Then, precision (PR), recall (RE) and false positive rate (FPR) were defined according to Eqn. 3-5. The experimental results are shown in Fig. 7 and Table 1. The system can automatically detect small mesenteric vessels with diameter approximately 1 mm and localize the small bowel region accurately. Some false positives were located on nearby organs and tissues with similar intensity and some were caused by errors in the reference because of the difficulty in precisely manually segmenting the small bowel. False negatives were mainly caused by missing small mesenteric vessels by image quality and segment algorithm.

$$\Pr ecision = volume(A \cap B) / volume(B) \quad (3)$$

$$\mathrm{Re}\, call = volume(A \cap B) / volume(A) \quad (4)$$

$$FPR = volume(\overline{A} \cap B) / volume(A) \quad (5)$$



a) b)

Figure 7. Small bowel final segmentation (yellow). The mesenteric vasculature (blue) is included. These pictures are different views of the same patient in Fig. 5.

Table 1. Segmentation results of mesenteric vasculature and small bowel.

Mesenteric vessel (%)			Small bowel (%)		
PR	RE	FPR	PR	RE	FPR
95.8	82.3	3.6	79.1 ± 2.7	79.3 ± 3.8	21.2 ± 4.5

4. CONCLUSIONS

To help localize tumors and assist pre-operative planning, we propose a vessel map-guided method for segmenting the small bowel. The method consists of mesenteric vasculature segmentation using multi-view multi-scale vesselness enhancement followed by small bowel segmentation using the mesenteric vasculature as a roadmap. The preliminary results show the potential of our method to enable precise small bowel localization. This segmentation may be used as the initial stage of a computer-aided detection system to detect small bowel tumors such as carcinoid.

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REFERENCES

[1] P. Soyer, M. Boudiaf, E.K. Fishman, et al, "Imaging of malignant neoplasms of the mesenteric small bowel: New trends and perspectives," *Critical Reviews in Oncology/Hematology*, pp. 10-30, 2011.

[2] M.P. Federle, "CT of the small intestine: enterography and angiography", *Supplement to Applied Radiology*, pp. 55-62, 2007.

[3] J. Yao, D. Sussman, R.M. Summers. "Fully automated adipose tissue measurement on abdominal CT," In Proceedings of SPIE, Proc. SPIE 7965, 79651Z (2011).

[4] J. Yao, S. O'Connor and R.M. Summers. "Computer aided detection of lytic bone metastases in the spine using routine CT images," in IEEE ISBI. 2007, 512-515, Arlington, VA.

[5] D. Lesage, E.D. Angelini, I. Bloch and G. Funka-Lea, "A review of 3D vessel lumen segmentation techniques: Models, features and extraction schemes," *Medical Image Analysis*, pp. 819-845, 2009

[6] C. Kirbas and F. Quek, "A Review of Vessel Extraction Techniques and Algorithms," *ACM Computing Surveys*, pp.81-121, 2004

[7] A. Frangi, W. Niessen, K.Vincken and M.Viergever, "Multiscale vessel enhancement filtering," In Lecture Notes in Computer Science vol. 1496: 130-137, Springer, New York, NY, 1998.

[8] S. Zhou, R. Chellappa, "Kullback-Leibler Distance between Two Gaussian Densities in Reproducing Kernel Hilbert Space," In Proceedings of the ISIT, 2004.

[9] O. Cuisenaire, "Distance transformations: fast algorithms and applications to medical image processing," Ph.D thesis of EPFL, 1999.

[10] G. Xiong and L. Xie, "Automated detection of junctions structures and tracking of their trajectories in 4D images," information processing in medical imaging proceedings of the conference, 2011

[11] J.K.Udupa and P.K. Saha, "Fuzzy Connectedness and Image Segmentation," *Proceedings of the IEEE*, pp. 1649-1669, 2003

[12] Y. Marchenko, I. Volkau and WL. Nowinski, "Vascular editor: from angiographic images to 3D vascular models," *Journal of Digital Imaging*, pp. 386-398, 2010.