An automatic colon segmentation for 3D virtual colonoscopy

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SUMMARY The first important step in pre-processing data for 3D virtual colonoscopy requires careful segmentation of a complicated shaped colon. We describe an automatic colon segmentation method with a new patient-friendly bowel preparation scheme. This new bowel preparation makes the segmentation more appropriate for digitally removing undesirable remains in the colon. With the aim of segmenting the colon accurately, we propose two techniques which can solve the partial-volume-effect (PVE) problem on the boundaries between low and high intensity regions. Based on the features of the adverse PVE voxels on the gas and fluid boundary inside the colon, our vertical filter eliminates these PVE voxels. By seriously considering the PVE on the colon boundary, our gradient-magnitude-based region growing algorithm improves the accuracy of the boundary. The result of the automatic colon segmentation method is illustrated with both extracted 2D images from the experimental volumetric abdominal CT datasets and a reconstructed 3D colon model.

key words: volumetric segmentation, 3D virtual colonoscopy, partial-volume-effect

1. Introduction

Colon cancer is the second leading cause of cancer deaths in the United States. An optical colonoscopy has been commonly used for accurate diagnosis; however, it is often regarded as an invasive, highly uncomfortable and expensive technique. Recently, considerable interest has arisen in developing a computer-based screening modality as an alternative to the optical colonoscopy, by employing advanced computer graphics and visualization techniques [1]. SUNY at Stony Brook is a pioneer and leader in developing such a system, called “3D virtual colonoscopy” [2][3][4]. The virtual colonoscopy system takes a spiral CT (Computed Tomography) scan of the patient’s abdomen covering the entire colon. A reconstructed 3D model of the real colon is then segmented from the abdominal CT dataset. For the clinical utilization of the virtual colonoscopy, this segmentation needs automating in order to reduce the amount of user interactions. Last, the modeled colon lumen is carefully viewed to look for polyps either by automatic planned navigation or interactive navigation [2][3][4][5]. This can be processed non-invasively, patient-friendly, and cost-effectively, so it would lead a large population of colon screening and could detect small colon polyps at their early stages.

To make the virtual colonoscopy more patient-friendly, SUNY at Stony Brook developed a new bowel preparation scheme prior to imaging [6][7]. It enables a patient to avoid unpleasant physical colon cleansing, which is conducted before taking the CT images in our previous or other current virtual colonoscopies or just before applying the optical colonoscopy. Instead of physically cleansing the colon, the new bowel preparation scheme enhances the density of the residual fluid inside the colon so as to assist in electrically cleansing the colon at the following segmentation step. Because of this residue, the segmentation of the clean colon lumen becomes much more complicated than that with complete physical colon cleansing.

Figure 1a shows a normalized original axial image of the whole volumetric abdominal CT dataset after the new bowel preparation. We observe that there are many kinds of tissues besides the colon, for example, bones, portions of the lungs and stomach, etc. These complex anatomical structures make colon segmentation a difficult task. In addition, since our bowel preparation scheme does not involve complete colon cleansing prior to imaging for patient comfort, the colon is not absolutely clean and there is a significant amount of fluid residing in the colon.

Contemporary approaches to colon segmentation have typically concentrated on manual or semi-automatic algorithms [8]. Little effort has been made towards full automatic colon segmentation. Though Wyatt et al. [9] described an automatic segmentation of the colon, their result was not intended to be a highly accurate representation of the colon lumen, and also their algorithm was slow, taking 60-65 minutes. Current algorithms applied to the colon segmentation, such as thresholding [2][3] and dilate-eroding [8], cannot eliminate the undesirable partial-volume-effect (PVE). The PVE emerges on the boundary between low and high intensity regions during imaging, and voxels under the PVE are assigned incorrect intensities because they are strongly influenced by their neighbors. In addition, a typical abdominal CT dataset of 512 x 512 array and 400 slices takes a computer space of approximately 210 MB. Because of this size, the segmentation

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is usually time consuming [9][10].

Our goal in this paper is to automatically and accurately segment the newly prepared colon lumen by seriously considering the PVE. We here handle two types of the unpleasant PVE; that is, the PVE on the gas and fluid boundary inside the colon and the PVE along with the colon boundary. Because of our new bowel preparation scheme, we need to digitally remove the fluid inside the colon and get rid of the PVE voxels on the boundary between the low intensity gas and the enhanced high intensity fluid, which are disconnecting the colon lumen shown in Figure 1b. A vertical filter proposed in Subsection 3.2 solves this PVE problem. For colon boundary improvement, we consider the PVE along the colon boundary by applying our gradient-magnitude-based region growing algorithm explained in Subsection 3.4. Reliable performance of our automatic colon segmentation method is illustrated with both extracted 2D images from the experimental volumetric abdominal CT datasets and a reconstructed 3D colon model.

2. Bowel Preparation and Image Acquisition

Preparation of the bowel is essential to produce optimal virtual colonoscopy results. The new bowel preparation scheme provides patients with a much less uncomfortable experience than in the previous preparation scheme.

For an entire day before imaging, the patient is asked to eat only soft foods (such as yogurt, hot cereals, mashed potatoes, applesauce). Three bottles of 250 cc of CT Colonography Tracer (barium sulfate suspension solution, 2.1% w/v, E-Z-EM Inc) with each meal and 120 ml of MD-Gastroview (diatrizoate meglumine and diatrizoate sodium solution) are taken during this time period, so as to enhance the density of residues inside the colon. Additional oral sodium phosphate can be added for the purpose of liquidizing stools, making fluid more uniform and thus, facilitating the subsequent colon segmentation. On the next morning prior to the CT scan, 1 mg of intravenous glucagon is given for further prevention of colon collapse, and then the colon is distended with approximately 1000 cc of CO2 gas through a rectal tube.

A high speed spiral CT scanner (GE CTI model) is used to acquire the whole abdominal data. The protocol includes 120 kVp, 200-280 mA, 512 x 512 array for the field-of-view and 5 mm/1.0:1.5-2.0 pitch. The scanning time ranges from 30 to 40 seconds, so the acquisition is performed in a single breath hold. The acquired data is then reconstructed into 1 mm thick slice images. The number of slices varies from 350 to 450, depending on the height of the patient. Each image pixel has a 2-byte integer reflecting its intensity, and a typical total size of the volumetric abdominal CT image dataset is approximately 210 MB.

3. Automatic Colon Segmentation

Automatic and accurate segmentation of the colon lumen is critical for clinical application of virtual colonoscopy. Our algorithm automatically determines the colon boundary uncovering polyps from the fluid inside the colon.

Our segmentation method consists of the following five steps:

1. proper threshold selection for the gas and fluid inside the colon
2. a vertical filter for the PVE boundary between the gas and the fluid
3. a region growing algorithm for the colonic interior segmentation
4. a gradient-magnitude-based region growing algorithm for the colon boundary improvement
5. the vertical filter for the PVE boundary between the gas and the fluid in the improved colonic interior

The first step distinguishes most of the gas and the fluid and classifies them as the colonic interior. Next, our proposed vertical filter is applied to detect the PVE voxels on the boundary between the gas and the fluid, which cannot be just thresholded at the first step. As a result, the gas, the PVE boundary and the fluid are classified as the colonic interior. At the third step, the region growing algorithm with the automatically located seed segments this colonic interior from the other tissues and creates a connected colon region. Then, the boundary of the segmented colon region is improved by the last two steps. The fourth step is to calculate the gradient magnitudes based on the Sobel operator along the neighborhood of the colon boundary, and to redefine this boundary to have the most significant change of intensities between the colon and the other tissues. Last, the vertical filter is again applied in order to consider the PVE voxels between the gas and the fluid inside the new redefined colon region.

3.1 Proper Threshold Selection for Gas and Fluid

As the first step, we choose proper thresholds in order to classify the gas and the fluid as the colonic interior. Based on the intensity differences among the whole abdominal CT dataset, we can find almost all the gas and the fluid. Figure 2 shows the histogram obtained from the whole volumetric abdominal CT dataset. The first two peaks of the histogram correspond to the gas and the background. The third and fourth peaks include the region of soft tissues, fat and muscle. The fluid and bones fall into a flat range after the fourth peak. It is very important to take into account the fact that there
are PVE voxels on the boundary between the gas and the fluid, the gas and the surrounding tissues, and the fluid and the surrounding tissues. For instance, due to the PVE, the intensities of the voxels along with the gas boundary are raised by the neighboring higher intensity voxels, so we can not count on these intensities. By our experimentation, we determine thresholds $T_{\text{gas}}$ and $T_{\text{fluid}}$, and classify the gas and fluid voxels as the colonic interior if their intensities are lower than the $T_{\text{gas}}$ or greater than the $T_{\text{fluid}}$. To consider the PVE between the gas and the surrounding tissues, and between the fluid and the surrounding tissues, the $T_{\text{gas}}$ and the $T_{\text{fluid}}$ should threshold only the voxels which are not under the PVE; that is, their intensities are relied on. The range between the right of the second peak and the left of the third peak in the histogram has the PVE voxels on the colon boundary between the gas and the surrounding tissues. Similarly, the range between the right of the fourth peak and the beginning of the flat range has the PVE voxels between the fluid and the surrounding tissues. Hence, we select the $T_{\text{gas}}$ at the right bottom of the second peak and the $T_{\text{fluid}}$ at the left beginning of the flat range to avoid including the PVE voxels along the colon boundary. These PVE voxels are examined in Subsection 3.4.

The result of thresholding is shown in white in Figure 1b, which is corresponded to Figure 1a. We classify most of the gas and the fluid inside the colon as the colonic interior. It is a problem that the background and the bones are also classified as the colonic interior, but this can be solved in Subsection 3.3. Figure 1b shows the unwanted PVE boundary between the gas and the fluid, which are not thresholded by the $T_{\text{gas}}$ or the $T_{\text{fluid}}$ and have not yet been classified as the colonic interior. This PVE boundary disconnects the colonic interior and make it impossible to segment a connected colon region. The next subsection deals with this PVE boundary.

3.2 Vertical Filter for Gas and Fluid PVE Voxels

Here, we focus on the PVE on the gas and fluid boundary, with the aim of classifying the PVE voxels as the colonic interior and forming the colonic interior as a connected colon region. A contemporary technique of morphological dilation and erosion combination across this boundary is not found to be reliable, because the shape of the colon is so complex that it may remove some details. Our proposed vertical filter makes it possible to detect and classify only the PVE voxels on the gas and fluid boundary as the colonic interior, even though the PVE boundary may have the same intensity range as soft tissues, fat and muscle and its width is not constant.

3.2.1 Features of Gas and Fluid PVE Voxels

After thresholding the gas and the fluid, we observe that the voxels on the boundary between the gas and the fluid still exist. Because of the PVE, the intensities of these voxels do not belong to either the gas or the fluid ranges. When CT images are acquired, due to gravity, the fluid inside the colon gathers into some concave parts of the colon, where the fluid's surfaces are horizontal. In Figure 1a, we can see these horizontal surfaces of the fluid. Based on this natural phenomenon, in addition to the intensity information, we consider that the voxels are PVE of the gas and the fluid, if the voxels satisfy the following conditions:

a. regions vertically above the voxels are the gas.

b. regions vertically below the voxels are the fluid.

c. intensities of the voxels are between the $T_{\text{gas}}$ and the $T_{\text{fluid}}$.

d. the voxels are vertically continuous.

e. vertical lengths of the voxels are less than or equal to a threshold $T_{\text{length}} - 2$.

The condition e especially yields the restriction that the filter chooses only the voxels inside the colon. By our experimentation, we determine the threshold value $T_{\text{length}}$.

3.2.2 Vertical Filter

Here we propose a vertical filter which can detect the PVE voxels satisfying the above conditions. To check the conditions a, b, d and e, the proposed vertical filter follows the direction of gravity; that is, the vertical filter and the fluid surfaces intersect perpendicularly. Figure 3 explains our vertical filter whose size is $1 \times 1 \times n(n \leq T_{\text{length}})$. In Figure 3, our vertical filter considers the voxels, $a_1, a_2, \ldots, a_i, \ldots, a_n(i < n)$, and determines that $a_i$ belongs to the PVE voxels if $a_1$ belongs to the gas, $a_n$ belongs to the fluid and the intensities of all the $a_2, \ldots, a_{n-1}$ are in the range between the $T_{\text{gas}}$ and the $T_{\text{fluid}}$. Note that $n$ is a flexible number between 3 and the $T_{\text{length}}$, so we employ all $T_{\text{length}} - 2$
filters whose lengths are from 3 to the $T_{length}$. By applying the vertical filter to all voxels in the raster order, we can find out all the gas and fluid PVE voxels and classify them as the colonic interior. Now, even though we need to consider the PVE voxels on the colon boundary, we have the continuous colonic interior voxels, so that we are ready to segment a connected colon region.

3.3 Region Growing Algorithm for Colonic Interior Segmentation

Next, an ordinary region growing algorithm [11][12] is employed to segment only a connected colon region from other tissues. From the previous subsection, any PVE voxel on the boundary between the gas and the fluid can be chosen as a seed point. The 26-connected neighbors of the seed point are first examined as to whether they are the voxels classified as the colonic interior. If they are parts of the colonic interior, then we check their neighbors in the same way. This examination process is repeated until no connected colonic interior voxel is found. As a result, we can segment a connected colon region from the surrounding tissues.

By thresholding in Subsection 3.1, the background and the bones are also classified as the colonic interior. The region growing algorithm, however, counts only the voxels connected to the seed point which is inside the colon. It is obvious that the background and the bones are not connected to the colon, so that we can easily ignore these misclassified voxels.

3.4 Gradient-Magnitude-Based Region Growing Algorithm for Colon Boundary Improvement

To further solve the PVE problem on the colon boundary, we employ a gradient-magnitude-based region growing algorithm, in which the gradient magnitude is computed by the Sobel operator and used as the definition of the homogeneity criterion.

We expect a voxel on the boundary to reflect a significant rate of change of intensities in its immediate neighborhood. The rate of change is precisely what is measured by the gradient of the voxel. According to Zhang [13], the Sobel operator using 26-connected neighbors has several good properties both in the magnitude response and in the direction responses. For the 26-connected neighborhood Sobel operator, we apply three $3 \times 3 \times 3$ filter masks in each of the three principal directions and compute the norm to obtain the gradient magnitude. By analyzing the gradient magnitude, we can see the sufficient and vital contrast on the boundary between the colon region and its surrounding region.

In Subsection 3.1, the $T_{gas}$ and the $T_{fluid}$ are selected so as not to include the PVE voxels on the colon boundary. Consequently, the segmented colon region, which is the result of the previous processes, is smaller than the actual colon region and needs to consider its exterior PVE voxels along the colon boundary. First, let us refer to the boundary between the segmented colon region and its surrounding region as the 1st boundary region. We calculate a gradient magnitude based on the Sobel operator for a voxel on the 1st boundary region. Then, voxels, which are the 26-connected neighbors of the voxel on the 1st boundary and outside the segmented colon region, are inspected by calculating their gradient magnitudes. If each of these voxels has a greater gradient magnitude than that the voxel on the 1st boundary does, it is assigned to the next boundary region, in this case, the 2nd boundary region. After all the voxels on the 1st boundary region finish this process, it is continued for voxels on the 2nd boundary region. This process is repeated recursively until no further boundary region is created. We then add the 1st, 2nd, 3rd, ..., nth boundary regions to the segmented colon region. As a result, we have a new segmented colon region with the improved boundary. Figure 4 explains our gradient-magnitude-based region growing algorithm for a voxel on the 1st boundary region toward the outside of the original segmented colon region. In Figure 4, S is a voxel on the 1st boundary region and voxels marked N are in its neighborhood and outside the colon. If the gradient magnitude of N is greater than that of S, N is then assigned to the 2nd boundary region.

We here examine all 26-connected neighbors when expanding the colon boundary, because the 6-connected or 18-connected expansions, or only the direction of the outward normal expansion, which is orthogonal with the boundary surface, are not tight enough to avoid making holes on the boundary region. The examination of 26-connected neighbors is a little expensive; however, this algorithm focuses only on the neighborhood
of the colon boundary, not on the whole large volumetric dataset itself, making it more computationally efficient.

3.5 Vertical Filter for Gas and Fluid PVE Voxels in Improved Colonic Interior

From the previous step, the new improved colon region is created, which means the regions considered as the gas and the fluid are expanded. There are some undiscovered PVE voxels on the boundary between the gas and the fluid in this new colon region. As the last step, we again make use of the vertical filter for the purpose of taking account of all the gas and fluid PVE voxels.

4. Results

Our automatic segmentation method was applied to several newly prepared volumetric abdominal CT datasets, and a variety of complicated shaped colon segments were segmented. We use one of the tested datasets, whose size is $512 \times 512 \times 411$, to demonstrate our results. Since the new bowel preparation did not involve complete colon cleansing prior to imaging, a considerable amount of fluid remained inside the colon. Figure 1a shows a normalized original axial image which needs to be digitally cleansed. By using the histogram obtained from the whole abdominal CT dataset, we employed the intensity-based threshold. In our experiment, we selected the thresholds $T_{gas} = 20$ and $T_{fluid} = 111$. The result of thresholding the gas and the fluid inside the colon in Figure 1a is shown in Figure 1b, in which the gas and the fluid is colored white. As we can clearly see in Figure 1b, the PVE problem on the gas and fluid boundary which disconnected the colon region could not be solved by thresholding. Also, it is easy to understand that the morphological dilate-erode operation does not work for this problem because of the intricate colon shape. Based on the property of our experimental abdominal CT datasets, we selected $T_{length} = 4$ as the length of our vertical filter. Figure 1c shows the result of applying our vertical filter to Figure 1a with thresholding. Our vertical filter detected nicely the PVE voxels on the gas and fluid boundary; therefore, we could merge these PVE voxels with the gas and the fluid to produce a connected colon region, which is shown in white in Figure 1c. Figure 5a shows another normalized original sagittal image including many kinds of tissue besides the colon. By applying the ordinary region growing algorithm with an automatically selected seed point, we could extract only the colon region shown in Figure 5b. In Figure 5b, we can see a reconstructed 3D model of the colon region with the fluid colored white. Figure 5b also shows a significant amount of fluid still remaining inside the colon after the new bowel preparation. The result of our gradient-magnitude-based region growing algorithm and the final vertical filter is given in Figure 1d. In Figure 1c, voxels along the colon boundary were under the PVE between the colon region and its surroundings; therefore, their intensity values could not be fully counted on. Even though the colon region in Figure 1c was better segmented after our vertical filter, we needed to solve the PVE problem on the colon boundary. Our gradient-magnitude-based region growing algorithm selected the voxels with the highest gradient magnitudes among the neighborhood of the colon boundary, so that these voxels presented a sufficient contrast between the colonic interior and its exterior. We used this contrast to increase the accuracy of the colon boundary. Figure 6 shows the close look of the other part of the colon region. Figure 6a, 6b, 6c, 6d are corresponding to the each step explained with Figure 1a, 1b, 1c, 1d, respectively. Through Figure 6, we can see how our segmentation method creates the colon boundary at each step considering the PVE.

To further prove the colon boundary improvement by our gradient-magnitude-based region growing algorithm, we also applied our algorithm to another volumetric abdominal CT dataset, which was prepared with physical colon cleansing and of size $512 \times 512 \times 361$. A normalized original axial image of this dataset is given in Figure 7a. Figure 7b shows the result of the commonly used method for the previous bowel preparation, which is thresholding with a careful study of each intensity range and is applying the ordinary region growing algorithm. In Figure 7c, the result of our gradient-magnitude-based region growing algorithm is shown in white after our proper thresholding of the gas inside the colon (in this case $T_{gas} = 27$) and the ordinary region growing algorithm. For instance, we can compare the segmentation results in the middle part of Figure 7a. In Figure 7b, the dark area around the colon region was the gas inside the colon, but the commonly used method could not segmented it properly because of the PVE. On the other hand, our gradient-magnitude-based region growing algorithm could count this area as the gas. The result of segmenting the colon lumen by our algorithm shown in Figure 7c is obviously better than that.
by the commonly used method shown in Figure 7b.

The implementation of our automatic segmentation method is a prototype, and has not been fully optimized yet. Our segmentation method took less than 5 minutes for a typical 512 x 512 x 411 volumetric abdominal CT dataset running on an SGI Onyx2.

Through our experimentation with newly prepared abdominal CT datasets, we found a few datasets in which the colon closely touched parts of itself or the lungs. In these cases, the intensity of the colon boundary was very low and thresholded as the gas. As a result, the ordinary region growing connected all the touched region into one region, so that the real shape of the colon could not be found. Especially, if the colon closely touched the lungs, the ribs were mistaken for the fluid, because the ribs often touched the lungs, and because the intensity range of the ribs was similar to the fluid. Hence, the colon, the lungs and the ribs were incorrectly segmented as one connected region. This touching problem needs to be considered, not only with the segmentation manner, but also with the bowel preparation as to how well the colon needs to be distended.

5. Conclusions

The automatic colon segmentation with the new bowel preparation scheme was presented with serious consideration of the PVE. In our segmentation method, two techniques: the vertical filter and the gradient-magnitude-based region growing algorithm, were proposed to solve the PVE problem on the boundaries between the low and high intensity regions. Our vertical filter adequately removed the PVE voxels on the gas and fluid boundary, and the gradient-magnitude-based region growing algorithm presented the highest contrast on the colon boundary. The result of our automatic colon segmentation method demonstrated its robust performance with the running time less than 5 minutes and proved to facilitate a more accurate 3D virtual colonoscopy.

This work is a part of the virtual colonoscopy pre-processing project whose aim is to develop a software that includes all the essential pre-processing techniques for 3D virtual colonoscopy, including automatic segmentation and flight path generation. We are currently optimizing our automatic colon segmentation method to make it more computationally efficient and to implement it as part of our virtual colonoscopy pre-processing software.

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References


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(a) The normalized original axial image slice from the newly prepared volumetric abdominal CT dataset.

(b) The result after the proper thresholding of the gas and the fluid inside the colon. There is the PVE boundary between the gas and the fluid.

(c) The result after applying our vertical filter. The PVE boundary is removed.

(d) The result after applying our gradient-magnitude-based region growing algorithm and the final vertical filter. The colon boundary is improved.

Fig. 1 The result of our automatic colon segmentation method with the newly prepared volumetric abdominal CT dataset.
Fig. 5  (a) The normalized original sagittal image slice of the newly prepared volumetric abdominal CT dataset. (b) The reconstructed 3D model of the colon region with the fluid colored white.

Fig. 6  (a) The close look of another part of a normalized original axial image slice. (b) The PVE boundary between the gas and the fluid after the proper thresholding. (c) The PVE boundary removed by our vertical filter. (d) The colon boundary improved by our gradient-magnitude-based region growing algorithm and the final vertical filter.

Fig. 7  (a) The normalized original axial image slice of the whole volumetric abdominal CT dataset with physically colon cleansing. (b) The result of the commonly used method. (c) The result of our gradient-magnitude-based region growing algorithm.