Electronic Colon Cleansing by Colonic Material Tagging and Image Segmentation for Polyp Detection: Detection Model and Method Evaluation[1]

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Abstract

Virtual colonoscopy provides a safe, non-invasive approach to screening colonic polyps using medical imaging and computer graphics technologies, where computer aided or automated detection plays an important role. For model-based detection using geometrical features, the entire colonic lumen must be delineated first. A critical step to obtain a cleansed colonic lumen relies on bowel preparation. We have been developing an electronic colon-cleansing technology which minimizes the difficulties associated with the bowel preparation using low-residue diet and contrast solutions, and removes the tagged colonic materials electronically from the abdominal image by image-segmentation methods. In this work, we focused on the model description and method evaluation using volunteer studies. Both subjective and objective criteria were employed in the evaluation. The objective criteria measure whether the electronic cleansing results could meet the requirements of the detection model of geometrical features, while the subjective criteria evaluate whether the entire colonic lumen could be obtained. The results showed that the electronic cleansing technology could extract a clean colonic lumen if the volunteer follows the bowel preparation instructions. The objective validation demonstrated that the error due to partial volume effect can be minimized to a low level and the segmentation method showed a high reproducibility and repeatability. This work provides the evidence that the routine physical colon-washing procedure could be eliminated for automated polyp detection by virtual colonoscopy.

I. INTRODUCTION

Virtual colonoscopy searches for polyps inside the colon lumen of an abdominal image acquired from a patient. Automated or computer aided detection (CAD) of the polyps is highly desirable. For computer tomography (CT)-based virtual colonoscopy, where contrast feature of different tissues within the colonic wall is minimal, geometry model of the wall inner surface is usually utilized for polyp detection. The geometry model requires a well-cleansed colonic lumen. The accuracy and smoothness of the extracted lumen can greatly affect the performance of polyp detection. There are two critical steps to obtain a cleansed lumen: (1) bowel preparation and (2) image segmentation. The bowel preparation should be patient comfortable; and the image segmentation should be reliable and efficient.

We have been developing an electronic cleansing technology (ECT) using low-residue diet with contrast solutions and automated image segmentation [4,5], as an alternative to the conventional physical bowel cleansing procedure which requires hours for bowel movement and is not pleasant. The ECT was developed to remove the contrasted residual materials in the colon. The patient was asked to have three low-residue meals in the day prior to CT scan. Contrast solution of 250 cc barium sulfate suspension (2.1% w/v, E-Z-EM, Inc.) was mixed in each meal. Most colonic materials were moved out by ingesting magnesium citrate laxative tablets. The residual fluid/stool was tagged by the contrast solution and shown as enhanced voxels in the abdominal CT image. Markov random field (MRF)-based image segmentation was applied to label the tagged voxels. This previous work has two drawbacks: (1) the laxative bowel movement is not convenient and (2) the image segmentation is iterative and computationally intensive.

Recently we advanced our ECT by eliminating the laxative procedure and developing a new image segmentation method which is computationally efficient [1,6]. Without the laxative procedure, we aim to remove all the tagged fluid/stool inside the colon electronically. Since the tagged materials can cover the entire colon inner surface, we have to consider the surface geometry, as well as polyp geometry in order to avoiding errors during the electronic cleansing. In this study, we focus on evaluating the advanced ECT for automated polyp detection.

The ideal approach to evaluating the ECT would be to find some cases where some polyps are covered by the tagged materials, and further to examine whether those polyps are retained and can be detected after applying the ECT. However, it is difficult to find such datasets because the colonic materials and polyps are "randomly" distributed inside the colon. Furthermore, evaluation on polyp detection is model dependent. In this study, we introduce a polyp detection model based on geometry features. To successfully detect polyps with this model, several assumptions have to be made. Instead of evaluating how many polyps being found and how many polyps being missed using this model, we examine whether the colonic lumen obtained from the ECT meet the basic requirements for that detection model. From this point of view, only healthy volunteer datasets were utilized in the evaluation. Though there is no ground truth for the evaluation (except for the assumption that the healthy young volunteers do not have polyps), objective criteria parameters that

indirectly reflect the performance of the ECT were formulated and calculated, aiming to show the satisfaction of the geometry features on the wall inner surface and the retaining of small polyps. The extracted lumens of colon (LOCs) were further examined subjectively by an experienced radiologist using a virtual colonoscopy navigation system to inspect whether the entire colon is successfully delineated. This indirect evaluation approach integrates the objective and subjective judgments. It can be regarded as a pre-evaluation step to the validation of virtual colonoscopy system with ground truth.

In the followings, we present the bowel preparation procedure first. Then, the image segmentation method is briefly described. Thereafter, a polyp-detection model based on geometrical features is conceptually stated. Based on the basic requirements of the detection model, several objective evaluation parameters are designed. Finally, the evaluation results on volunteer datasets are presented and discussed.

II. METHODS AND MATERIALS

A. Method Description

Five healthy volunteers of 31-year old in average were recruited for this study. Each volunteer was scanned by a GE/CTI spiral CT imager in two consecutive days. Two datasets, in both supine and prone positions, were acquired in each day for validation purpose. During the day prior to the first CT scan, the volunteers were asked to take a high fluid, low residue diet for the three meals. In order to enhance the colonic materials, the contrast solution of 250 cc barium sulfate suspension (2.1% w/v, E-Z-EM, Inc.) was mixed with each meal. (In addition, 120 ml of MD-Gastroview (diatriuzoate meglumine and diatriozoate sodium solution) in equal 60 ml amounts was ingested during the evening and in the morning before the CT scan). The diet procedure was repeated after the first CT scan in the following three meals of that day for the next day CT scan.

Prior to acquiring CT images, 1.0 mg of Glucagon was given intravenously in order to reduce colonic motion and spasm, followed by introducing approximately 1000 cc of CO_2 through a small bore rectal tube to inflate the colon. All CT images were acquired in less than 40 seconds during a single breath hold. Using the GE/CTI spiral CT scanner, 5 mm collimation with pitches between 1.5-2.0:1, depending upon the span of the colon as determined from a digital scout radiograph, were performed. Scan parameters included 120 kVp, 100-280 mA (lower mA for smaller body size) and field of view (FOV) between 34-40 cm based on the abdominal size. The acquired data were reconstructed at 1 mm intervals with a 512 x 512 array, resulting in 300-450 slices for each dataset. This large volume of datasets demands very efficient image segmentation.

The segmentation algorithm [1] was then applied to the acquired images. The segmentation had two steps. The first step is to label voxels of the abdominal images based on their neighbor intensities. The second step is to connect the labeled voxels of the same type and then to extract a continuous lumen

of the colon. Finally, a three-dimensional (3D) surface model of the extracted LOC was constructed and displayed in different visualization modes for user's choices.

B. Pre-set of Class Number for Segmentation

The first step of the segmentation algorithm is similar to an unsupervised clustering method. The number of classes and their representative vectors of created classes are updated continuously when more vectors are included in the calculation. The algorithm depends only on two parameters: **K** - the upper bound of possible classes and **T** - the vector similarity threshold. The upper bound **K** must be pre-set depending on the application, while the threshold **T** is determined from the image data. In abdominal CT images, there are roughly 4 classes that can be perceived based on their intensity features: (1) air, (2) soft tissue, (3) muscle, and (4) bone and tagged materials. The intensity values of these 4 classes increase from the lowest to the highest. Due to partial volume effect, there exists an intensity slope between two spatially contiguous tissue areas (see Figure 1). The voxels in the slope area are called partial volume voxels. To mitigate either under- or over-estimation of tissue boundary, it is reasonable to find the tissue boundary within the slope area, rather than on the edges of the slope area. In other words, the partial volume area should be divided into two sub-regions. The left partial-volume class is called partial volume from A to B and is labeled as tissue A. The right one is called partial volume from B to A and is labeled as tissue B. In the CT images, there are two kinds of voxels within the colon lumen: (1) air and (2) tagged materials. Each kind has a partial volume overlap to area of soft tissue/muscle. Assigning two partial volume classes to each of the overlap areas results in 4 partial volume classes in the total. Therefore, the maximum class number **K** for the segmentation algorithm was set to 8.

The threshold **T** was set to be the maximum variance of components of the feature vectors, where the feature vectors were obtained by applying K-L transformation to the intensity vectors. This reflects our expectation of obtaining a minimal number of different classes from the image data [1].

In the following of this paper, we denote the air region inside the colon lumen as _AL_ and denote the tagged materials inside the colon as _TM_.
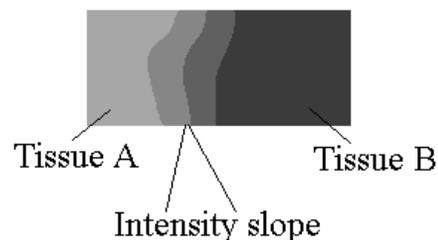

Figure 1. It shows an example that the intensity value of tissue B gradually increases to that of tissue A. The central region represents the partial volume area.

C. Extraction of Colon Lumen

The second step of the segmentation algorithm is to extract the LOC from the labeled result of the first step by assuming

that the colon lumen is separated spatially from those adjacent tissues, such as the lungs, bone and small bowel. Only those voxels associated with the LOC will be remained. Therefore, a region growing technique [1] was employed for this task. The extracted LOC consist of 4 different types of voxels: the *AL*, the partial volume from soft tissue to the air (PVSA), the *TM*, and the partial volume from soft tissue to the tagged materials (PVSTM).

D. Model of Polyp Detection

During the two steps of image segmentation, we must keep the polyp model in mind. In general, the polyp model could be built by using both the contrast features among the tissues within the colon wall and the geometry features on the wall inner surface [3]. For CT-based approach, the contrast feature is minimal; therefore, the geometry features play the major role. The critical point to the performance of polyp modeling lies in the description of the partial volume effect. The partial volume regions must be smaller than 3 mm. The geometry features of the wall inner surface are described below.

The inner contour surface of the colon lumen is modeled as a close surface within 3D Euclidean space, where the surface is assumed to have the continuous second-order differentials. The inward normal for the closed surface is determined first. Then, the continuous Gaussian curvature field is calculated for that surface. The curvature field characterizes shape variation of the surface [2]. For example, the curvature is constant value for the surface of a ball. An insufflated healthy colon wall is a smooth tube with nearly regular ring folds. There are two kinds of shapes that may be most frequently found for polyps on colon wall surface. One of them is a half-ball like hill shooting out from the colon wall towards the lumen. Another one is a small plateau grown out from a smooth surface or between two folds towards the lumen. For the first kind of shape, the Gaussian curvatures around that small hill should be larger than those of normal colon wall. For the second kind of shape, the Gaussian curvatures on that plateau should be close to zero. According to these geometry features, locations of suspected polyps can be detected by thresholding on the Gaussian curvatures. Of course, thresholds for determining the half-ball hill and plateau like polyps must be pre-set. This is usually done by several phantom experiments.

To ensure the Gaussian curvature model being able to characterize the polyps, two requirements should be met. First, the contour surface would be smooth enough as compared to the shapes of polyps. This ensures that the Gaussian curvatures of polyps have either maximal or minimal values within the curvature field. Second, the shapes of polyps would be large enough to be distinguished from noisy spots on the wall inner surface. For virtual colonoscopy, it is clinically significant to detect polyps with size of 5 mm or larger in diameter. If a convex hill or a plateau shot out from the surface with radius or height more than 3 mm, the area is highly likely a polyp. Our numerical experiments demonstrated that the Gaussian curvatures of those areas had a maximum or minimum value within the curvature field. In other words, the polyp of this kind could be detected by determining critical point of the Gaussian curvatures. To minimize missing polyps, we will retain those suspected areas for physician's assessment in the following navigation fly-through the entire colon lumen. The physician will have interactive means to quantitatively analyze those areas by the size, shape, and internal intensity distribution.

The main error in segmentation results is, as expected, due to the partial volume effect. If the partial volume layer is so thick that it is larger than 3 mm, we have the risk of missing small polyps in the segmentation results. Hence, it is technically significant to evaluate the partial volume error created by our ECT described above.

E. Evaluation Method

The conventional fiber-optical colonoscopy is currently utilized as the gold standard for validating virtual colonoscopy technologies for detecting colonic polyps of 5 mm or larger in diameter. For the electronic cleansing without physical bowel washing, the gold standard is not applicable. Instead, we acquired both supine and prone scans for each volunteer, and furthermore repeated the scans on the next day, aiming to measure the reproducibility, repeatability and robustness on the partial volume effect of the above presented ECT. The results were further subjectively judged by an experienced radiologist using a virtual colonosocpy navigation system. Four objective criteria parameters were calculated from the segmentation results to indirectly measure the ECT performance. The first two were designed to measure the segmentation error caused by the partial volume effect. The other two were utilized to demonstrate reproducibility (by the same dataset) and repeatability (by both supine and prone scans of the same volunteer) of the method. All these four parameters were calculated from the extracted colon lumen.

1. Average thickness of the partial volume layer (*ATPV*): This is the average thickness in 3D space of the partial volume layer from both air and enhanced materials to soft tissue/muscle. The partial volume layer was calculated with the help of distance field technology. For each voxel in the boundary of the LOC, the minimum distance from it across the partial volume layer was regarded as the thickness of the partial volume layer at that location.

2. Partial volume percentage (*PVP*): *PVP* = (summation of the volume of partial volume layer from air to soft tissue/muscle and the volume of partial volume layer from tagged materials to soft tissue/muscle)/(the volume of entire extracted colon lumen); where the volume was counted by the number of voxels in the region. This parameter estimates the ratio of the partial volume voxels to the entire colon lumen.

3. Mean intensities of the air lumen (*AL*) and the tagged materials (*TM*) voxels. The intensity is in HU.

4. $Diff(\ ) = \frac{|\ _s - \ _p|}{\ _s} \times 100\%$, where $\ _s$ is one of the parameters defined previously for the supine dataset and $\ _p$ is one corresponding to the prone dataset acquired from the same volunteer on the same day. The definition applies

to the two-day scans. A smaller value *Diff(a)* reflects a better reproducibility or repeatability.

III. RESULTS

A. Subjective Evaluation Results

A total of 18 datasets were acquired from five volunteers. Each volunteer had 4 datasets except for one who had only two supine datasets. The ECT took less than 10 minutes for processing a single supine or prone dataset on a SGI/Octane desktop computer. The entire LOCs of 10 datasets from volunteer 1, 2, and 3 were successfully delineated. (Volunteer 3 had only 2 supine datasets). The tagged materials were satisfactorily removed. However, there were some small artifacts remained on the areas where the boundary between the air and the tagged fluid connecting to the colon wall. Some small bowels were attached on the colon lumen for volunteer 4 who did not follow the diet instructions and took too much meal in the breakfast in one of the two days. This leads to both the stomach and small bowel fully filled with the tagged materials. The extracted LOC includes part of the stomach and a lot of small bowel volumes. For the other day's datasets, our ECT extracted successfully the colon lumens of this volunteer, resulting in 12 entire lumens. For volunteer 5, all the 4 datasets have areas where the colon lumen and the lungs have no distinguishable boundary (both regions are air-like). The possible reason may be due to the thick slice (5 mm CT collimation) on the boundary; where the slice is too thick to create a perceivable boundary for those two regions. Even though, our ECT could still remove the enhanced materials satisfactorily. But it failed to separate the volume of lungs from the colon lumen for all the 4 datasets of this volunteer. This problem was manually solved with our interactive navigation system. In all five volunteer studies, there exist spots where the walls of two closely touched colon folds were incorrectly segmented as the lumen due to the partial volume effect. This suggests that a higher image resolution is needed to achieve a smooth and connected colon lumen for navigation through the entire colon, or an interactive display system is required to correct the attachment manually. The navigation through the 18 colon lumens was rated as satisfactory by the experienced radiologist.

B. Objective Evaluation Results

The supine and prone datasets, acquired on the same day from volunteers 1, 2, and 4 respectively (i.e., six datasets, where volunteer 3 has only supine scans and the datasets of volunteer 5 need manual correction), were used to compute the parameters for repeatability test and partial volume effect measurement. The results are listed in Table 1 and Table 2, where V# means volunteer #. The computed values from the supine or prone scans in two days of the volunteer were similar to the table values. The results are very satisfactory, showing the robust performance. The reproducibility test from the same dataset was excellent, because of the fully automated process.

IV. DISCUSSION

If the bowel preparation instructions were followed, as most volunteers did, the segmentation results were very satisfactory. The enhanced colonic material voxels were classified and removed successfully except for some small artifacts near the area where air, colon wall and tagged fluid connected. These artifacts form a small artificial horizontal ring on the colon wall surface and can be easily distinguished from the colonic folds during 3D navigation. Nevertheless, if a polyp smaller than 3 mm is located on the ring, it could potentially be missed in the virtual colonoscopy examination. Further research is needed to minimize these artifacts for detecting those smaller polyps. If a segment of small bowel touches the colon and is filled with the tagged materials, this segment may be delineated with a higher probability as the colon lumen. This can be avoided by not eating any food/drink in the morning prior to CT scan. Another possible solution is to use an interactive display tool to manually correct the touched segment. The attachment of the lungs to the colon lumen can be avoided with a higher axial resolution. This may be achieved by a multi-detector array CT system. The attachment of colonic folds could be avoided by higher image resolution and improved colon insufflation.

Table 1. Estimation of partial volume error

		ATPV (mm)	*Mean Intensity* (HU)		*PVP*
			AL	*TM*	
V1	Supine	2.06	-888	857	4.9%
	Prone	1.89	-887	812	5.0%
V2	Supine	2.38	-905	891	9.2%
	Prone	2.57	-897	847	9.8%
V4	Supine	2.17	-906	872	6.9%
	Prone	2.09	-901	908	7.1%

Note: In Tab. 1, the mean intensity is in Hounsfield Unit and the *ATPV* is in millimeter. Vi means the i-th volunteer.

Table 2. Repeatability test

	Diff(.)			
	ATPV	*AL*	*TM*	*PVP*
V1	8.3%	0.11%	5.25%	2%
V2	8.0%	0.9%	4.9%	6.5%
V4	3.7%	0.6%	4.1%	2.8%

Table 2 lists the relative difference of parameters between supine and prone datasets.

The CAD concept was integrated as an intrinsic part into the ECT. When removing the air and enhanced material voxels for constructing the 3D model of the colon lumen, we considered the geometry features of the colonic surface and the polyps. The suspected areas were labeled for physician's assessment during navigation fly-through the colon model. User interactive means are desired in the navigation system for both correcting the above mentioned artifacts and identifying the polyps from the labeled suspected areas. The interactive means could be an integral part of an accurate CAD system for virtual colonoscopy.
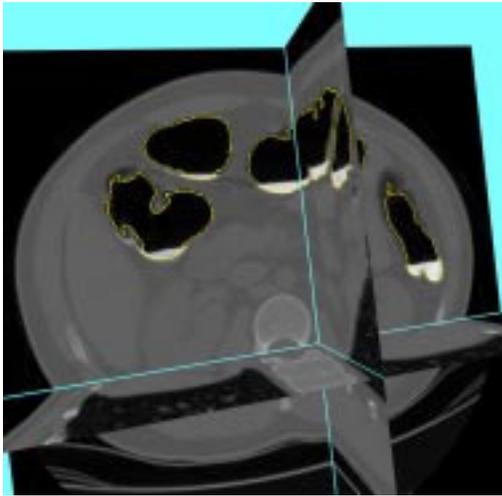
Figure 2. The pesudo 3D view of the contour (yellow line) of the extracted LOC in the CT slice images.

V. CONCLUSION

The developed ECT can detect and remove the tagged colonic materials, if the subject follows the instructions of bowel preparation.

The partial volume effect was considered in our image segmentation method. The average partial volume layer shown in Table 1 is 2.57 mm or less in thickness (i.e., the _ATPV_s are less than 3 mm). This ensures that polyps of 5 mm or larger in diameter can not be affected by the partial volume effect within the extracted colon lumen and will be correctly modeled.

All the variations of computed parameters between the supine and prone datasets in Table 2 are less than 8.3% and most of them are less than 6.5%. This demonstrates good repeatability of our segmentation method. The small variations between the consecutive scans of two days also support the repeatability of our ECT, including the bowel preparation. This statement concurs with the subjective evaluation of the experienced radiologist.

A post-processing step is desirable to minimize the artifacts occurring at the horizontal fluid edge and to remove effectively the connection of the small bowel and the colon. The reason and the probability of the overlaps between the lung and colon and between the colonic folds need to be further studied. Most importantly, this work demonstrates the feasibility of performing virtual colonoscopy without the pre-procedure of physical bowel cleansing. The CAD with interactive means built by our navigation system need further evaluation by both accuracy and efficiency criteria.

VI. REFERENCES

[1] D.Chen, Z. Liang, M. Wax, L. Li, B. Li, and A. Kaufman, "A novel approach to extract colon lumen from CT images for virtual colonoscopy," to appear in _IEEE Trans. Med. Imaging,_ 2000

[2] B. Dubrovin, A. Fomenko, and S. Novikov, _Modern Geometry Methods and Applications_, Springer-Verlag, English version, 1994

[3] Kaufman, Z. Liang, M. Wax, Dongqing Chen and Michael Wan, _System and Method for Performing Three-Dimensional Virtual Segmentation and Examination,_ US Patent Serial Number 60/125.041, 1998

[4] Z. Liang, F. Yang, M. Wax, J. Li, J. You, A. Kaufman, L. Hong, H. Li and A. Viswambharan, "Inclusion of _a priori_ information in segmentation of colon lumen for 3D virtual colonoscapy," Conf. Record IEEE NSS-MIC, Albuquerque, NM, Nov. 1997

[5] M. Wax, Z. Liang, D. Chen, B. Li, R. Chiou, A. Kaufman, and A. Viswambharan, "Electronic colon cleansing for virtual colonoscopy," The First International Symposium for Virtual Colonoscopy, Boston, MA, Nov. 1998

[6] M. Wax, A. Kaufman, Z. Liang and K. Kreeger, "Advancing virtual colonoscopy to practice," International Workshop on 3D Imaging and Virtual Endoscopy, Italy, 2000.