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A Novel Colon Wall Flattening Model for Computed Tomographic Colonography: Method and Validation

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Abstract

Computed tomographic colonography (CTC) has been developed for screening of colon cancer. Flattening the three-dimensional (3D) colon wall into two-dimensional (2D) image is believed to (1) provide supplementary information to the endoscopic views and further (2) facilitate colon registration, taniae coli (TC) detection, and haustral fold segmentation. Though the previously-used conformal mapping-based flattening methods can preserve the angular geometry, they have the limitations in providing accurate information of the 3D inner colon wall due to the lack of undulating topography. In this paper, we present a novel colon-wall flattening method using a strategy of 2.5D approach. Coupling with the conformal flattening model, the presented new approach builds an elevation distance map to depict the neighborhood characteristics of the inner colon wall. We validated the new method via two CTC applications: TC detection and haustral fold segmentation. Experimental results demonstrated the effectiveness of our strategy for CTC studies.

Keywords

Conformal mapping; 2.5D representation; colon wall; medical imaging; computed tomographic colonography

Introduction

According to the recent statistics from American Cancer Society (ACS) [1], colorectal cancer ranks the third most common occurrence of both cancer deaths and new cancer cases for both men and women in the United States. Early detection and removal of colonic polyps prior to their malignant transformation can effectively decrease the incidence of colon cancer [2]. As a new minimally-invasive screening technique, computed tomographic colonography (CTC) has shown several advantages over the traditional optical colonoscopy (OC). And a plenty of evidence suggests that CTC is an acceptable alternative to OC, particularly in the group of patients who are either unwilling or unable to undergo OC [3].

In order to better depict the internal structure of the colon, traditional paradigm employs CTC to achieve the tasks of screening and diagnosis. It utilizes endoscopic views to visualize the colon wall [4][5]. It has been successfully demonstrated to be more convenient and efficient than the OC [6]. However, due to the length and winding of the colon structure, inspecting the entire inner wall of the colon or colon mucosa is still time consuming and prone to cause errors by current CTC technologies [7]. Moreover, the field-of-view (FOV) of the endoscopic views has limited, and incomplete examinations occur frequently.

Flattening the three-dimensional (3D) patient-specific colon wall into two-dimensional (2D) image is believed to increase the FOV and provide supplementary information to the endoscopic views [8]-[19]. It is also believed to provide an efficient visualization tool for polyp detection, in which the entire colon mucosa is dissected and flattened on a 2D plane. The flattened colon can be efficiently volume rendered to produce an electronic biopsy image for computer aided detection (CAD) of polyps [15]. Therefore, various flattening techniques [8]-[21] have been studied, in which the conformal mapping algorithm [15][19] showed advantages in generating 2D colon wall image with minimal distortion by preserving all the angles. An overview of colon flattening or unfolding approaches has been listed in Table 1. Conformal mapping algorithm aims at preserving the local shape on the flattened colon surface. Hence it is highly recommended for that the colon polyps usually have a semi-ellipsoidal shape which we want to preserve.

However, 2D flattening is capable of grasp the whole plate view at the cost of losing or distorting fine details, e.g., the relative height information among neighborhood of colon structure. In contrast, we added the new information of height variations to the previous presented flattening model (2D) to make it more intuitive. For polyp diagnosis, the height variations of colon structure are usually of much value for judging the abnormality of tissue. Hence, we developed a novel colon wall flattening method which will best describe not only the whole map of colon structure but also fine details of neighborhood of the components on the colon wall. For our purposes, a simple way to understand the new model is to see them as a 2.5D model.

The remainder of this paper is organized as follows. The new colon flatten methodology is presented in Section 2. To validate the model, two application scenarios are presented in section 3. In Section 4, discussions and conclusion about the new model are given.

Method

Overview of the pipeline of 2.5D colon flattening model

For the acquired CTC datasets, the first task is to segment the data volume and extract the colon wall as a volumetric mucosa (VM). This is achieved by a statistical maximum *a posteriori* expectation-maximization (MAP-EM) algorithm [22][23]. Considering the use of positive-contrast tagging agents to opacify the residual fecal for differentiation of the materials from the colon wall, partial volume effects (PVE) became severe and the thickness of the VM varied noticeably. Because there exists the PVE in the CTC scans which make the surface of the colon wall more implicit, a level set-based shrinkage method will help to evolve an approximated surface to reflect the mucosa surface of the colon [24]. In order to extract a polygonal mesh of an iso-surface from the 3D approximated surface consisting of voxels, a marching cube process is introduced into the pipeline. Consequently, a more vividly described colon inner wall will be presented. In order to build a bridge connecting the 3D wall with the 2.5D morphological map, a cylinder model of the inner wall will be exploited and a distance map will be created according to the shortest distance map measured between the voxelized points and the given cylindrical surface. Hence, the 2.5D map of the colon wall will exhibit geometric features which particularly conserve the original angle and the morphological shape to full extent. Figure 1 illustrates the whole pipeline of the 2.5D flattening model.

Level set-based shrinkage to initialize the layer of colon wall (shrinkage)

The starting layer (SL) of the VM is of much importance to describe the contour of the colon wall. We introduce the level set method [25] to retrieve an optimal SL, from which we build the distance transform to distinguish different topological structures. Compared with other methods, our shrinkage approach from the segmented VM is able to combine region-based information and edge-based information together, making full use of the global information and local information simultaneously and also controlling the geometric property of the level set function easily. Straightforwardly, the final layer should reside between the outermost and innermost layers, where the variation of CT intensities across the different layers remains relatively stable. Furthermore, the gradient of image intensity is used to construct the stopping criteria to stop the curve evolution by

$$\phi_t = \delta(\phi) \cdot \frac{\lambda}{1 + \|\nabla I\|} \{ \alpha_0 A + \alpha_1 B + \alpha_2 C + \alpha_3 \text{div}(\nabla \phi / \|\nabla \phi\|) \} \quad (1)$$

where ϕ is the Lipschitz function, δ is the Dirac delta function, and I represents the image intensity. A , B and C represent the square of the variance of the mean intensity values of voxels in the whole image, the narrow band and the local neighborhood, respectively. The notations λ , α_0 , α_1 , α_2 and α_3 are constants, where are used to control the influence of each term, and ∇ represents the gradient operator. The $\text{div}(\cdot)$ is the curvature of the Lipschitz function, which controls the smoothness of the zero level set surface.

Once the above evolution procedure stops (when Eq. (1) converges), the resulting zero level set surface, where $\phi_t=0$, indicates the optimal layer between the outermost and innermost layers where the variation of CT intensities changes slightly across different layers. As a

result, we will get a series of voxels which represent the SL of the colon wall. Figure 2 illustrates the colon mesh after the marching cube process.

Building distance map with a cylinder model

To build a reliable cylinder model, relying on which we calculate the distance map (as shown in Fig. 3), we need to perform two things: (1) determining the centerline (also known as medial or symmetric axis) inside the colon lumen; and (2) building a radial varying cylinder, which is inscribed within the inner wall of the colon. Several methods have been reported for centerline extraction for medical imaging, for example [26][27]. Combined with the Fast Marching technique [28], an energy minimization formula is given as follows [26],

$$E_{\text{medial-Axis}}(C) = \int_{0=C^{-1}(p_0)}^{L=C^{-1}(p_1)} F(C(s)) ds \quad (2)$$

where $F(\cdot)$ is a cost function, and $C=C(s)$ (s being arc length) is the path (traced from two points p_0 and p_1) along which we look for the centerline. What we need to do is to minimize the energy function $E(\cdot)$. In this study, we employed a method to solve a nonlinear hyperbolic partial differential equation [29]. Let $|\nabla T(x)|=F(x)$, then we have:

$$T(x) = \min_{C \in \Gamma(p_0, x)} \left(\int_{0=C^{-1}(p_0)}^{\bar{s}=C^{-1}(x)} F(C(s)) ds \right) \quad (3)$$

where $\Gamma(p_0, x)$ is the set of all paths from p_0 to x . Since the scalar field $T(x)$ represents weighted geodesic distance to point p_0 , the weighted geodesic paths are orthogonal to level sets of $T(x)$. Once the field of weighted geodesic distances has been found, the weighted geodesic path of interest is calculated by constructing a path from P_1 oriented as $\nabla T(x)$ in every point. The medial axis is a set of points, $C(p), p \in \Omega$, where Ω stands for the colon object. Then the shortest distance between the points on the medial axis and the vertices on the colon surface ($\partial\Omega$) can be expressed as:

$$\{r_{p_j} = \min(d_{p_j}) | d_{p_j} = \sqrt{(\tilde{p}_j - \nu_i)^2}, \tilde{p}_j \in C(\tilde{p}), \nu_i \in \partial\Omega\} \quad (4)$$

where r is the radius of the cylinder model, and $\{p_j, \nu_i\}$ are recorded as pairs for further calculation. The colon inscribed cylinders are shown in Fig. 4.

This constructed cylinder model has its' own surface ($\partial\Omega''$). The Euclidean distance between the vertices on the surface of the colon wall and the surface of the cylinder model will be further calculated as follows:

$$\{D_i = \sqrt{(\nu_i - p_j)^2} - r_i, \nu_i \in \partial\Omega, p_j \in \partial\Omega''\} \quad (5)$$

where p_j is a vertex on $\partial\Omega''$ of the model surface, and ν_i is a vertex on $\partial\Omega$ of the colon surface. The set of D , named distance map, will be further introduced in the following flattening process.

Improved Flattening map model of colon wall

In recent years, a number of methods have been proposed to map the colon surface to a plane or a sphere [15][19]. For the purpose of eliminating the limitations brought by 2D flattening image, we introduced the 2.5D flatten techniques above and more details are given below. Given a colon surface Ω (as shown in Fig. 2) with boundaries γ_0 and γ_1 , we are able to perform the following tasks:

1. Compute a Harmonic function f by solving the Dirichlet problem, such that: $f \equiv 0$, $f|_{\gamma_0} \equiv 0$, $f|_{\gamma_1} \equiv 1$ and further compute the closed 1-form τ , which denotes:

$$d\tau=0, \quad \text{and} \quad \int_{\gamma_0} \tau=1 \quad (6)$$

where d is the exterior differential operator.

2. Compute a function $g: \Omega \rightarrow \mathbb{R}$, such that:

$$\delta(\tau + dg) = 0, \quad \text{and} \quad \delta = * d* \quad (7)$$

where $*$ is the Hodge star operator and $\tau + dg$ is a harmonic 1-form.

3. Let $\omega = \tau + dg$, and calculate the Hodge star of ω , which takes the form $*\omega = M^{-1}df$ and equals to the harmonic energy of $f: M = \int_{\Omega} |\nabla f|^2$.

4. Select a shortest path γ , which connects γ_0 with γ_1 , and slice Ω along γ to get $\bar{\Omega}$. Given a base vertex v_0 ($v_0 \in \Omega$), for any vertex v ($v \in \Omega$),

$$\varphi(v) = \int_{v_0}^v \omega + \sqrt{-1} * \omega, \quad (8)$$

where φ is the flattening mapping operation and $\omega + \sqrt{-1} * \omega$ is the Holomorphic 1-form.

Along the integration path which may be chosen arbitrarily on $\bar{\Omega}$, we finally got the mapping between any vertex (x, y, z) in 3D space and the new vertex (x', y', z') (**Note:** z' equals to the corresponding D_i for vertex (x, y, z)). Figure 6 (in next section) illustrates the results of 2.5D flattened results.

Applications

The new 2.5D flattening model above can be applied to the following: (1) to improve navigation experience in CTC, (2) to help detecting haustral folds on the colon wall, and (3) to find out the taniae coli line on the colon wall (see Fig. 5). In this paper, we performed two applications: haustral folds detection & segmentation and TC finding.

Haustral folds detection and segmentation

In the previously reported literature, most research efforts in the field mainly focused on haustral fold detection, rather than fold segmentation. For example, in the studies [30][31], the folds were detected by thresholding the curvatures in the 3D colon representation, while in [32], the detection task was fulfilled by using a Gabor filter on a 2D unfolded colon representation. In this exploratory investigation, a local elevation mapping (LEM) method is

proposed for the colonic fold detection and segmentation. The main idea can be characterized by **three steps**: (1) map the 2.5D mesh to a flattened gray scale image (Fig. 7), in which the intensity of each pixel is determined by its elevation value; (2) find the local maxima with a parameter named “error tolerance” (ET); and (3) exploit flood fill to get the regions, which belong to a given haustral fold.

The selection of the parameter ET will play a critical role on the results of the haustral fold detection and segmentation. Figure 8 illustrates the local maxima finding results by some ET values.

By iteratively examining the neighboring pixels of the initial maxima seeds and determining whether the pixel neighbors should be added to the region, our proposed algorithm above can finally output the segmented haustral folds as shown in Fig. 9.

Teniae coli extraction for colon

Teniae coli (TC) are three approximately 8-mm-wide longitudinal smooth muscle bands in the colon wall. In the previously reported literature, approaches for TC extraction can be categorized into two groups, manual drawing and automatic extraction [30][31][32]. As far as the automatic approaches to be concerned, most of the previous studies suggested to use curvature filter or Gabor filter [32] for surface analysis to get the TC lines on the colon. However, TC usually appears to be with the middle height between the haustra and the haustral folds. Fortunately, this phenomenon can be apparently found in the obtained 2.5D flattened colon (as shown in Fig. 6). Therefore, extracting the TC lines equals to finding the shortest geodesic path (FSGP) on the 2.5D flattened map. Our algorithm for TC extraction is described in Algorithm 1. In this algorithm, we can pick up four vertices along the top edge of the colon flattened mesh, which can divide the cross section into three regions with equal width (as shown in Fig. 11(b) in a later section). Equally, four vertices at the other end of the colon will be automatically chosen.

Algorithm 1: Shortest path finding for TC extraction

Given the flattened colon mesh graph

S := empty sequence

u := target

for each vertex v in Graph:

dist[v] := infinity ; //Initializations

path[v] := Flag of Undefined ; // Previous node in optimal path

end for // from source

dist[source] := 0 ; // Geodesic distance from source to source

Ω := the set of all nodes in Graph ; // All nodes in the graph

while Ω is not empty : // The main loop

// Start node in first case on the top of stack

while path[u] is Flag of Defined :

// Construct the shortest path with a stack S

insert u at the beginning of S // Push the vertex into the stack

u := path[u] // Traverse from target to source

```

end while ;
remove u from  $\Omega$  ;           //improve the efficiency
for each neighbor v of u :   // where v has not yet been removed from  $\Omega$ .
    alt := dist[u] + dist_between(u, v) ;
    if alt < dist[v]:
        dist[v] := alt ;
        path[v] := u ;
    end if
end for
end while
return S;

```

Evaluation

To evaluate the haustral fold segmentation and the TC extraction, ground truth was established from 15 patient scans by experts' drawing of the fold boundaries. According to the suggestions from experts, a haustral fold would be detected if more than 50% of its area has been detected. As we mentioned above, the ET value needs to be determined in order to get not only a higher detection rate but also a better segmentation region. Figure 10 illustrates a typical result under different ET thresholds. According to this experimental result, an average 95.2% true positive (TP) rate can be achieved at an average 6% false positive (FP) rate level, which is better than the reported (92.7%) in [24]. By further observation on Fig. 10, we also infer that the ET values with a range from 8 to 12 are uniformly effective. With respect to the accuracy of the segmentation, the coverage ratio (CR) between the regions drawn by LEM and the regions drawn by experts were measured. Compared to 86.2% in [24], an average CR 93.1% was obtained by our proposed LEM in this work, which shows a better match between the ground truth and our segmentation results.

For TC extraction, our new approach can, in most cases, draw good approximate TC lines on the colon wall, as judged by experts from hospital. As shown in Fig. 11(a), since TC lines are observed as sequences of relatively flat and narrow ridge-breaks traversing haustral folds, the experimentally obtained TCs can be measured by analyzing overlapping area ratio (OAR) between the manually drawn TCs and the TCs drawn by our FSGP method. Mathematically, the OAR is calculated by:

$$OAR = \text{count}(v_i \cap u_j) / \text{count}(v_i), i, j = 1, 2, \dots \quad (9)$$

where v_i stands for the set of vertex extracted by FSGP (see red lines in Fig. 11(b)), u_j stands for the set of vertex chosen manually by experts (see green/black area in Fig. 11(a)). Based on the experimental results, the average OAR is 95.43%, which indicates a good match between the ground truth and the FSGP extraction results. The most reason for why the algorithm cannot reach 100% is that there are probably some distortions which happened on the pathway of the TCs.

Conclusion

A novel colon flattening model based on 2.5D approach to describing the structure of colon wall has been presented. The associated implementation includes (1) one algorithm for detection of an accurate PV layer of the colon wall via a MAP-EM tissue mixture image segmentation; (2) one algorithm for level set-based shrinkage to generate a good approximate mucosa surface, representing the inner surface of the colon wall; (3) one algorithm for description of the undulation of the inner colon wall; (4) one algorithm for the elevation distance map, which is introduced to depict the neighborhood characteristics of the inner colon wall. Coupling with the conformal flattening method, the proposed approach provides a new vision for colon analysis in CTC studies. We have shown the effectiveness of our 2.5D approach on segmenting the haustral folds and detecting the three TCs. This newly proposed model shall further advance computer aided detection and diagnosis in CTC studies.

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Fig. 1.
The pipeline of the new method.

Fig. 2.
The SL mesh after marching cube.

Fig. 3.
The cylinder model.

Fig. 4.
Illustration of the cylinder model of the colon (different colors stand for the varying distance).

Fig. 5.
Illustration of teniae coli, haustra and haustral folds

Fig. 6.
The 2.5D effects of the flattening model.

Fig. 7.
The mapped gray scale image of the colon wall.

Fig.8.

Local maxima with different ET thresholds: (a) ET = 5; (b) ET = 15; (c) ET = 25; (d) ET = 35; (e) ET = 45.

Fig. 9.
Illustration of the segmented haustral folds.

Fig. 10.
The curve of the TP rate and the FP rate with different ET levels.

Fig. 11. Manual and automatic results on TC segmentation: (a) The manually drawn TCs by experts. (b) The result of TC extraction by the proposed automatic method.

Table 1

Overview of some typical colon flattening or unfolding approaches.

Authors	Technique	Strengths	Possible Limitations
Paik DS <i>et al.</i> [12]	<i>Sampling the solid angle of the camera, and mapping it onto a cylinder.</i>	<i>Straightforward</i>	<i>2D. It may cause distortions in shape.</i>
Haker S <i>et al.</i> [11]	<i>Employing certain angle-preserving mappings.</i>	<i>Presented a surface scan of the entire colon.</i>	<i>2D. It requires a highly accurate and smooth surface mesh for a good mean-curvature calculation.</i>
Bartroff AV <i>et al.</i> [13]	<i>Moving a camera along the central path of the colon (angle preserved).</i>	<i>Frame by frame, and intuitive.</i>	<i>2D. It does not provide a complete overview of the colon.</i>
Wang Z <i>et al.</i> [14]	<i>Exploring a volume-based flattening strategy.</i>	<i>Volume-based. It considered the partial volume (PV) effect and preserves the original image intensity distribution.</i>	<i>The distance-based mapping may not be accurate enough for detection of small polyps.</i>
Hong W <i>et al.</i> [15]	<i>Utilizing conformal structure to flatten the colon wall onto a planar image. (angle preserved).</i>	<i>Minimized the global distortion.</i>	<i>The de-noise algorithm cannot always get genus 0 surface.</i>
Williams D <i>et al.</i> [16]	<i>Volumetric Curved Planar</i>	<i>Using volume rendering for hollow regions and standard CPR for the surrounding tissue.</i>	<i>Curved Planar Reformation CPR and volume rendering are tightly coupled.</i>
Jin M <i>et al.</i> [21]	<i>Discrete Ricci Flow</i>	<i>Minimized the global distortion, which means the local shape is well preserved.</i>	<i>The gradient descending algorithm is not invariant by calculating the first order derivative.</i>
Zeng W <i>et al.</i> [18]	<i>Using Quasi-Conformal Mapping</i>	<i>Exploited the texture information.</i>	<i>The quasi-conformal mapping deforms the circles to ellipses.</i>
Yao J <i>et al.</i> [17]	<i>Using local projections.</i>	<i>Preserved not only the topology of the original surface, but also the vertex resolution.</i>	<i>The polyp and haustral folds size will be deformed by a constant angle sampling.</i>