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Virtual colon flattening method based on colonic outer surface

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ABSTRACT

Virtual colon flattening (VF) is a minimally invasive viewing mode used to detect colorectal polyps on the colonic inner surface in virtual colonoscopy. Compared with conventional colonoscopy, inspecting a flattened colonic inner surface is faster and results in fewer uninspected regions. Unfortunately, the deformation distortions of flattened colonic inner surface impede the performance of VF. Conventionally, the deformation distortions can be corrected by using the colonic inner surface. However, colonic curvatures and haustral folds make correcting deformation distortions using only the colonic inner surface difficult. Therefore, we propose a VF method that is based on the colonic outer surface. The proposed method includes two novel algorithms, namely, the colonic outer surface extraction algorithm and the colonic outer surface-based distortion correction algorithm. Sixty scans involving 77 annotated polyps were used for the validation. The flattened colons were independently inspected by three operators and then compared with three existing VF methods. The correct detection rates of the proposed method and the three existing methods were 79.6%, 67.1%, 71.9%, and 72.7%, respectively, and the false positives per scan were 0.16, 0.32, 0.21, and 0.26, respectively. The experimental results demonstrate that our proposed method has better performance than existing methods that are based on the colonic inner surface.

1. Introduction

Colorectal cancer is the second leading contributor to cancer-related deaths in developed countries [1]. A colorectal polyp grows into a cancerous tumor in a few years. Early detection and successful resection of precursor polyps are effective procedures to reduce the incidence of colorectal cancer [2–4]. Conventionally, virtual colonoscopy is a minimally invasive procedure used to detect colorectal polyps based on computed tomography (CT) data [5]. In virtual colonoscopy, operators inspect the colonic inner surface via a virtual camera going through the entire colon along the colon centerline. However, the virtual fly-through can only provide a limited field of view (FOV) for operators on a single projection window, resulting in time-consuming inspection and the possibility of missing polyps obscured by colonic haustral folds. Virtual colon flattening (VF) is a complementary viewing mode to virtual colonoscopy [6]. VF provides a global FOV of the entire 3D colonic inner surface for operators by virtually flattening the colonic inner surface onto a 2D image. Compared with conventional colonoscopy, inspecting on a 2D flattened image is faster and results in fewer uninspected regions [7–9]. Numerous methods have been proposed to implement VF in the last

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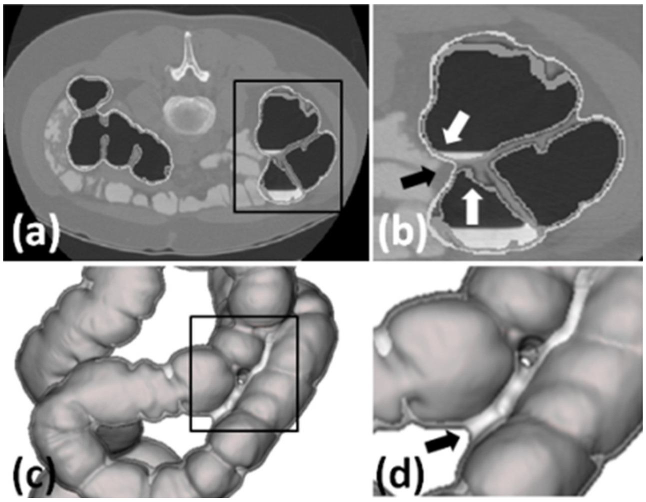

Fig. 1 – (a) Colonic outer surface plotted by white lines, and colonic inner surface plotted by gray lines. (b) The zoom-in image in the black frame of (a). Black and white arrows in (b) indicate the colonic inner and outer surfaces respectively. (c) 3D colonic wall. The colonic wall appears as a white layer surrounding the gray colonic inner surface. The colonic outer surface is the outer surface of the colonic wall. (d) The zoom-in image in the black frame of (c). The black arrow in (d) indicates where fused areas between distant colonic regions occur.

decade [6,10–17]. These methods can be divided into three categories, namely, ray casting, conformal mapping, and skeleton straightening, all of which were named according to the principal computer graphic technique used.

Ray casting is based on the ray tracing algorithm [18]. The key step in ray casting is to generate sampling rays that are uniform, non-intersecting, and approximately orthogonal to the colon centerline. The 3D colonic inner surface can be mapped into a 2D image via ray projection by using sampling rays. Wang et al. [6] proposed a method that uses electric field lines as sampling rays. Bartroli et al. [10] utilized the distance field to generate sampling rays. Conformal mapping is based on a mathematical concept [12]. Conformal mapping is angle preserving when mapping a 3D structure to a 2D image. Hong et al. [11] presented a conformal-mapping method based on a harmonic 1-form. Qiu et al. [13] proposed to use discrete Ricci flow to realize conformal mapping because the computation of discrete Ricci flow can be fully parallelized and efficiently accelerated by a graphics processing unit. Zeng et al. [14] introduced the usage of quasi-conformal mapping, which can achieve supine and prone colon registration for the same patient case. Gurijala et al. proposed to use heat diffusion Riemannian metric to fulfill conformal mapping, which is robust to topological noise [17]. Skeleton straightening takes advantage of the mesh skinning algorithm, which is widely used in computer animation. In this technique, the colonic inner surface is regarded as a skin layer and the colon centerline is used as the skeleton. Further, Sudarsky et al. [15] presented a general three-step skeleton-straightening method. Yao et al. [16] described a reversible projection skeleton-straightening method that can revert a 2D flattened image to the 3D original structure.

The applications of existing VF methods are often hindered by distortions of colonic anatomies when deformed from a 3D structure to a 2D image. To alleviate deformation distortions, many existing methods use the colonic inner surface as the basis for distortion correction. However, the colonic inner surface is not a reliable tool for distortion correction because of its colonic haustral folds. Various colonic haustral folds make the surface of colonic inner surface rough, leading to unacceptable distortions. For example, ray casting and conformal mapping are usually vulnerable to over- and under-sampling, which might cause shrinking and exaggeration of the colonic inner surface on the 2D image. In skeleton straightening, colonic haustral folds can negatively affect the shape of the flattened colonic inner surface.

This study proposes a VF method that uses the colonic outer surface instead of the colonic inner surface to correct distortions. The proposed method contains two novel algorithms, namely, the colonic outer surface extraction (OSE) algorithm and the colonic outer surface-based distortion correction algorithm (DCA). OSE was developed to extract the colonic outer surface for distortion correction. In OSE, the level set method is used to generate a candidate colonic outer surface, and a geodesic distance map is applied to eliminate fused areas between distant colonic regions. The DCA describes how to use the colonic outer surface to correct distortions. Our method was validated on 60 scans involving 77 annotated polyps and compared with three existing methods.

2. Method

The concepts of colonic inner surface, colonic outer surface, and colonic wall are first defined to illustrate the proposed method. The colonic inner surface is the lumen–mucosa boundary, and the colonic outer surface is the tissue–serosa boundary. The colonic wall is the layer between the colonic inner surface and the colonic outer surface. The colonic inner surface is the outer surface of the colonic lumen, whereas the colonic outer surface is the outer surface of the colonic wall (see Fig. 1).

The framework of our proposed method is presented in Fig. 2. The proposed method is composed of seven steps. As shown in Fig. 2, only the last four procedures are introduced sequentially in the following section because the first three procedures can be performed by using many other existing methods.

2.1. *OSE algorithm*

In this section, the OSE algorithm is developed to extract a single-connectedness colonic outer surface. OSE consists of three steps: extract colonic wall, create geodesic distance map based on colonic lumen, detect and eliminate fused areas of colonic wall by using geodesic distance map and ball filter technique [19]. In our work, the OSE algorithm focuses on the third step on how to attain a single-connectedness colonic outer surface that is suitable for colon flattening, because the