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Predicting Polyp Location on Optical Colonoscopy from CT Colonography by Minimal-energy Curve Modeling of the Colonoscope Path

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Abstract

The ability to accurately locate a polyp found on computed tomographic colonography (CTC) at subsequent optical colonoscopy (OC) is an important task in colorectal cancer screening. We present a method to more accurately match polyp locations at CTC and OC. A colonoscope was modeled as a flexible tube with negligible stretch and minimal strain. The path of the colonoscope was estimated using a minimal-energy curve method. The energy function was defined and optimized by a subdivision scheme. The prediction of polyp locations at OC from CTC was converted to an optimization problem. The prediction performance was evaluated on 134 polyps by comparing the predicted with the true polyp locations at OC. The method can accurately predict polyp locations at OC to within ± 0.5 colonoscope mark (5 cm) for more than 58% of polyps and to within ± 1 colonoscope mark (10 cm) for more than 96% of polyps, significantly improving upon previously published methods. This method can be easily incorporated into routine OC practice and allow the colonoscopist to begin the examination by targeting locations of potential polyps found at CTC.

Index Terms

CT colonography; optical colonoscopy; colonic polyps; minimal-energy curve

I. Introduction

1.1 Motivation

According to the American Cancer Society, colorectal cancer is the second leading cause of cancer-related deaths in the United States [1]. Nearly all colon cancers begin as noncancerous (benign) polyps, which slowly develop into cancer [2]. Therefore, detection and removal of colonic polyps in their early stages of development can effectively decrease the incidence of colon cancer. Computed tomographic colonography (CTC) and optical colonoscopy (OC) are two techniques to detect colonic polyps [3, 4]. The minimally invasive CTC has shown several advantages over OC and has emerged as a promising and increasingly accepted strategy for colorectal cancer screening.

CTC, also known as virtual colonoscopy (VC), uses low radiation dose CT scanning to obtain a view of the interior surface of the colon. As for any CT scan, the patient lies on a table that moves through a large round machine with rotating scanners. Before the test, the patient takes a bowel preparation that cleanses the colon of any stool. A small tube is inserted into the rectum and either air or carbon dioxide is infused into the colon to expand it slightly, eliminating wrinkles and making it easier to see polyps. Finally, a visualization or fly-through is generated to allow a physician to inspect the colon to identify any abnormalities as if performing a normal colonoscopy. If polyps or other suspicious areas are found during CTC, follow-up OC is necessary to remove polyps or biopsy potential cancers. In some settings, radiologists and colonoscopists work together to schedule a follow-up OC on the same day as the CTC to avoid a second colon cleansing preparation.

OC is a more invasive procedure that enables colonoscopists to visualize the appearance of the inside of the colon through a long flexible colonoscope inserted into the rectum. The tip of the colonoscope has a light and a video camera. Using the colonoscope, the physician can visualize the inner colon lining through images transmitted from the camera to a television monitor. This technique has the advantage that any polyps (or other abnormalities) discovered may be treated or removed as part of the same procedure. Colonoscopy is widely recognized as the reference method for examination of the large intestine.

The colon is divided into six colonic segments (rectum, sigmoid colon, descending colon, transverse colon, ascending colon and cecum) and has two bends (flexures). The hepatic flexure is where the ascending colon joins the transverse colon and the splenic flexure is where the transverse colon merges into the descending colon (Figure 1). Polyp locations at CTC and OC are reported clinically as the anus to polyp distance along the colon centerline and colonoscope, respectively.

In clinical practice, polyps of sufficient size (6 mm or larger) identified by CTC must be located and removed at OC [5, 6]. In performing this task, the colonoscopist searches for the polyp using the information supplied by CTC. Precise description of a polyp's location supplied by CTC to the colonoscopist can minimize anesthetic time and unproductive colonic examination. Therefore, developing a mapping between the polyp's locations calculated at CTC and OC may simplify polyp identification during OC examination and improve overall patient care.

However, it is nontrivial to match polyp locations between CTC and OC. The location of a polyp at CTC is typically expressed in two ways: (1) the colonic segment in which the polyp is located and (2) the anus-to-polyp length measured along the colon centerline. For (1), an experienced colonoscopist may approximately determine the colonic segment in which the tip of colonoscope is located by the length introduced into the rectum. However, given the variability of the colon in terms of length, path, and looping, the use of colonic segments for polyp localization is limited because of uncertainties in colonic segment boundaries, particularly at OC [7]. For (2), for the same patient, total colon length at CTC and OC examinations have large differences primarily due to telescoping and foreshortening at OC. In general, the total colon length computed at CTC is approximately 84% longer than that measured at OC [8], which substantially increases the difficulty to correlate the polyp locations on CTC and OC using the absolute anus-to-polyp lengths.

1.2 Literature methods

A previous study [8] has shown that a polyp's normalized distance along the colon centerline (NDACC) derived from CTC along with colon length reporting at OC can be utilized to predict the polyp's location at OC. The predicted polyp location at OC, anus-to-polyp length C_{a-to-p}^{oc} is computed as:

$$C_{a-to-p}^{oc} = \frac{C_{a-to-p}^{ctc}}{C_{a-to-c}^{ctc}} \times C_{a-to-c}^{oc}, \quad (1)$$

where C_{a-to-p}^{ctc} is the anus-to-polyp length at CTC, C_{a-to-c}^{ctc} is the anus-to-cecum length at CTC (total length of the colon centerline at CTC), and C_{a-to-c}^{oc} is the anus-to-cecum length at OC (total length of the colonoscope traveling from anus to the cecum at OC). The NDACC can be incorporated into the CTC report.

Instead of using normalized distance, Duncan et al. [9] proposed using absolute CTC distance with correction factors to predict polyp's location at OC:

$$C_{a-to-p}^{oc} = \begin{cases} C_{a-to-p}^{ctc} \times 0.78 & \text{for } C_{a-to-p}^{ctc} < C_{a-to-sf}^{ctc} \\ C_{a-to-p}^{ctc} \times 0.59 & \text{for } C_{a-to-p}^{ctc} \geq C_{a-to-sf}^{ctc} \end{cases}, \quad (2)$$

where $C_{a-to-sf}^{ctc}$ is the anus-to-splenic flexure length at CTC. That is, with the splenic flexure as a dividing point, for right-sided polyps the anus-to-polyp length at CTC would be "corrected" by multiplying by 0.59 and for left-sided polyps by 0.78.

In OC examination, the anus-to-cecum length is typically measured with the colonoscope in its "straightest" configuration since loops and redundancy should be avoided to generate an accurate, reproducible measurement and to reduce the discomfort to the patient. In addition, the colonoscope path is straighter than the CTC colon centerline due to its mechanical properties, such as stiffness and limited bending ability. Thus, we assumed this straightened and smoother colonoscope can be represented by a B-spline curve [10]. A 5th degree B-spline curve is utilized to simulate the anus-to-cecum OC path and polyp's location at CTC colon centerline is then converted to the B-spline as its predicted location at OC.

In [10], the control points for B-spline are uniformly distributed along the CTC colon centerline and the number of control points is determined by using training data. However, the colonoscope path is variable in different colonic segments [11]. The colonoscope path differs greatly from the CTC colon centerline path in the sigmoid and transverse colons since these two segments are highly mobile and flexible. The rectum, descending and ascending colons and cecum are relatively fixed and their colonoscope paths are less variable. Therefore, in this paper, we expanded our previous work to more accurately model the colonoscope path on the colon. First, a minimal-energy curve is used to represent the colonoscope path from anus to cecum with minimal force for an accurate, reproducible measurement. A colonoscope path with minimal force avoids loops and redundancy during the OC procedure, thereby reducing patient discomfort. An energy function is defined and the correlation of polyp locations at CTC and OC is converted to an optimization problem. Second, the control points for B-spline curve fitting are determined adaptively during energy minimization instead of uniformly sampling along the CTC centerline. Third, anatomical landmarks of colon such as rectum-sigmoid junction, sigmoid-descending junction, splenic and hepatic flexures are computed and utilized for polyp correlation. Fourth, unlike the NDACC and B-spline method in [10] which fits a curve to the entire colon since it assumes the colonoscope affects the entire colon, in the new method, the curve is fit only from anus to polyp to predict anus-to-polyp length at OC. This part of the method is more relevant to the clinical situation since the colonoscope only affects the colon from the anus to the polyp.

The paper is organized as follows. The methods for predicting polyp locations at OC from CTC are described in Section 2. We describe our experiment in Section 3 and demonstrate the prediction performance in Section 4. Our concluding remarks are stated in Section 5.

II. METHODS

2.1 Characteristics of OC and overview of methods

The OC examination is quite different from CTC regarding its effects on the morphology of the colon. Therefore, given a polyp's location at CTC, we must take into account the characteristics of OC to predict the polyp's location at OC.

First, the difference between the actual path of the colonoscope and colon CTC centerline largely depends on the colonic segment to be examined:

- The sigmoid colon is highly mobile with variable looping and length on CTC images and thus is greatly straightened and shortened after the colonoscope passes through it.
- Unlike the flexible sigmoid colon, the descending colon is relatively fixed to the posterior abdominal wall. There, the colonoscope path is relatively straight and close to the CTC centerline.
- The transverse colon is highly mobile and flexible. The splenic and hepatic flexures at either end of the transverse colon are fixed to the posterior wall of the abdominal cavity. This anatomy forces the transverse colon colonoscope path to form an arc.

- Similar to the descending colon, the ascending colon and cecum are fixed to the dorsal abdominal wall and thus only slightly mobile, having relatively straight paths.

This prior knowledge of the distinctive characteristics of different parts of the colon plays an important role in mapping of polyps between CTC and OC. Therefore, colon partitioning is an important step in our method. Partitioning is done by determining the anatomical landmarks of the colon, such as rectum-sigmoid junction, sigmoid-descending junction, splenic flexure and hepatic flexure.

Second, when colonoscopist is advancing the colonoscope to cecum, the highly mobile sigmoid varies a lot before and after the colonoscope passes through the sigmoid-descending junction (Figure 2). Thus, with the sigmoid-descending junction as a dividing point, two different strategies are applied for polyps distal and proximal to the sigmoid-descending junction in our method.

Finally, during colonoscopy, the colonoscopist normally first concentrates on reaching the cecum on the way in and records the total colon length at OC. Then, the colonoscopist carefully inspects the colon to find polyps on the way out and records the polyp locations at OC. Therefore, we applied a first B-spline curve fitting to simulate the colonoscope path for the entire colon and applied a second B-spline curve fitting from anus to polyp at CTC to predict polyp location at OC.

The overview of polyp mapping between CTC and OC is outlined in Figure 3. The colon centerline at CTC is first extracted and polyp location at CTC is projected to the colon centerline. Then, four anatomical landmarks along the CTC centerline are determined for colon partitioning. With the sigmoid-descending junction (SDJ) as a dividing point, two strategies are applied for distal and proximal to SDJ polyps mapping from CTC to OC.

2.2 Colon centerline extraction and colon partitioning using landmarks

We employed a subvoxel precise centerline extraction method which utilized information of the colon outer wall to determine the colon centerline [12]. Initially, segmentation of the colon is performed to obtain a subvoxel representation of the colon. The discrete segmentation is used as an initial surface for a narrow band level set segmentation to more accurately determine the location of the colon inner wall and smooth the boundary between the air and fluid-filled regions of the colon. From the level set segmentation, a subvoxel distance field is computed using the fast marching method. The centerline of a colon C^{ctc} is then computed based on the distance field. After C^{ctc} is extracted, the polyp's location on it P_p is computed by projection because the polyp is physically located on the colon surface.

Anatomical landmarks of the colon, rectum-sigmoid junction P_{rsj} , sigmoid-descending junction P_{sdj} , splenic flexure P_{sf} and hepatic flexure P_{hf} are determined from C^{ctc} . Two extreme points of C^{ctc} at z-coordinates are determined as P_{sf} (patient's left side) and P_{hf} (patient's right side). The extreme point of C^{ctc} at x-coordinates (patient's left side) is used as P_{sdj} . Finally, starting from anus, the first point with increased curvature and torsion is utilized as P_{rsj} . Figure 4(a) shows a CTC colon centerline C^{ctc} , a projected polyp found at

CTC P_p and four anatomical landmarks P_{rsj} , P_{sdj} , P_{sf} and P_{hf} . By utilizing these two junctions and flexures, we can define the colon anatomic segments automatically. These anatomical landmarks will be used as initial control points for B-spline curve fitting.

2.3 Prediction algorithm for polyps proximal to SDJ

For the polyps proximal to the SDJ, that is the anus-to-polyp length at CTC is greater than the anus-to-sigmoid-descending junction length at CTC, $C_{a-to-p}^{ctc} > C_{a-to-sdj}^{ctc}$, a two-step strategy is applied. A first B-spline curve C^{bs1} is fitted to the entire CTC centerline to simulate advancing the colonoscope into the cecum during the OC examination. Then, a second B-spline curve C^{bs2} is fitted from anus to polyp at CTC to predict polyp location at OC.

2.3.1 Entire colon B-spline curve fitting: C^{bs1} —During colonoscopy, the first and most challenging part for the colonoscopist is advancing the colonoscope to the cecum with the minimum of forces (push, pull, and torque). We assume that the colonoscope is to reach the cecum with lowest energy. Therefore, a minimal-energy curve can be thought of as representing a colonoscope path of the entire colon with minimal strain.

Given m real values t_i , called knots, with $t_0 \leq t_1 \leq \dots \leq t_{m-1}$, a colonoscope is modeled as a B-spline curve [13] of degree n which is a parametric curve $C:[t_n, t_{m-n-1}] \rightarrow R^d$ composed of a linear combination of basis B-splines $b_{i,n}$ of degree n

$$C(t) = \sum_{i=0}^{m-n-2} P_i b_{i,n}(t), t \in [t_n, t_{m-n-1}]. \quad (3)$$

The points $P_i \in R^d$ are called control points or de Boor points. There are $m-n-1$ control points. The $m-n-1$ basis B-splines of degree n can be defined using the de Boor recursion formula

$$b_{j,0}(t) = \begin{cases} 1 & \text{if } t_j \leq t \leq t_{j+1} \\ 0 & \text{otherwise} \end{cases}, j=0, \dots, m-2$$

$$b_{j,n}(t) = \frac{t - t_j}{t_{j+n} - t_j} b_{j,n-1}(t) + \frac{t_{j+n+1} - t}{t_{j+n+1} - t_{j+1}} b_{j+1,n-1}(t), j=0, \dots, m-n-2. \quad (4)$$

In our implementation, $n=4$, with known control points $\{P_i\}$ and the number of control points $\text{num}(P)$, $m=\text{num}(P)+n+1$,
 $t = [\underbrace{0, \dots, 0}_{n-1}, \underbrace{0, 1/(m-n+1), 2/(m-n+1), \dots, 1}_{m-n+1}, \underbrace{1, \dots, 1}_{n-1}]$, and the number of points on B-spline is set as $5 \times \text{num}(P)$.

The Darboux vector [13] of a curve is defined to describe the rotational strain along the curve in terms of the Frenet frame [14] as

$$D(t) = \tau(t)T + \kappa(t)B, \quad (5)$$

where T and B are the tangent and binormal, respectively. τ and κ denote the torsion and curvature of curve. Here, we assume there is no translational strain: the colonoscope does not stretch.

For our specific application, we define the energy of curve C during colonoscopy as

$$E(C) = \frac{1}{l} \int_{t_0}^{t_{m-1}} \|D(t)\|^2 dt + \sum_{i=\{r,d,a\}} H_i \frac{1}{l} \int_{t_0}^{t_{m-1}} \|\tau(t)\|^2 dt + \frac{1}{l} \int_{t_0}^{t_{m-1}} \|\kappa(t)\|^2 dt + \sum_{i=\{r,d,a\}} H_i l \int_{t_0}^{t_{m-1}} \left\| \frac{dC(t)}{dt} \right\| dt, \quad (6)$$

where H_i is the Hausdorff distance from the CTC centerline C^{ctc} to B-spline C^{bs1} (simulated colonoscope path) at different segments. Rectum (r), descending (d), and ascending/cecum (a) segments are considered here because their positions are relatively fixed and the distance between C^{ctc} and C^{bs1} at these colonic segments are small and reliable.

The energy function consists of three terms, the bending energy (integral of the curvature squared over the curve), the twisting energy (integral of the torsion squared over the curve), and the distance between CTC centerline C^{ctc} and colonoscope path C^{bs1} . The bending and twisting energies are normalized by the curve length l . This model captures the essential property of colonoscopy. The optimization process is interpreted as the evolution of the model toward a state of minimal energy and the colonoscope path from anus to cecum is thought of as an optimal B-spline by minimizing energy E .

The minimal-energy curve C^{bs1} that represents the colonoscope path for the entire colon is optimized by curve subdivision [15]. Subdivision is normally used in the field of geometric modeling for compact representations of curves and surfaces. For example, a subdivision scheme is used for minimal-energy curves for path planning of deformable linear objects [16]. The idea is to start with a simple curve and keep refining it based on refinement rules, as long as we can lower the energy of the curve. Typically, the rules can be thought of as a weighted interpolation scheme.

In our implementation, the initial control points for C^{bs1} consist of two ends of the CTC centerline, rectum-sigmoid junction P_{rsj} , sigmoid-descending junction P_{sdj} , splenic flexure P_{sf} and hepatic flexure P_{hf} . C^{bs1} is created based on eq. (3) and its energy $E(C^{bs1})$ is computed using eq. (5). To decide which segment of C^{bs1} to subdivide in subsequent steps we consider the length of segments. S_i is defined as the curve length (segment) between consecutive control points P_i and P_{i+1} . We maintain a priority queue of lengths of all segments. The largest segment length is assigned the highest priority. The longest segment is subdivided to find a new control point on C^{ctc} . C^{bs1} and E are recomputed with the new control point. If the energy E is increased, the new control point by subdivision is discarded and we subdivide the second longest segment for a new control point. The subdivision repeats until the new energy E is decreased and thus the new control point is accepted. Then, the control points set is updated and C^{bs1} is regenerated based on eq. (3). Note, at each iteration we do not subdivide all segments simultaneously. Instead, we adaptively subdivide

one segment at a time. Here, we make use of the observation that we can locally change the curve shape to get closer to a minimal-energy curve. After C^{bs1} is regenerated, sorting and subdivision are repeated until the difference of energies between two iterations is smaller than some threshold or the length of C^{bs1} is very close to the colon length at OC. Figure 4(b)–(e) shows the different C^{bs1} during the optimization by subdivision.

2.3.2 Anus-to-polyp B-spline curve fitting: C^{bs2} —Given a polyp location at CTC, a second B-spline C^{bs2} is fitted just from anus to the polyp using the subset of control points from section 2.3.1. That is, only the control points located between anus and polyp are utilized for C^{bs2} fitting. Finally, the length of C^{bs2} is the predicted polyp location at OC (anus-to-polyp length at OC). Figure 4(f) shows the anus-to-polyp B-spline curve C^{bs2} .

2.4 Prediction algorithm for polyps distal to SDJ

For the polyps with $C_{a-to-p}^{ctc} \leq C_{a-to-sdj}^{ctc}$, since the scope may maximally stretch the colon (Figure 2a), all points from anus to polyp on C^{ctc} are used as control points to fit a B-spline. The length of this B-spline is the predicted polyp location at OC.

The pseudocode for polyp mapping between CTC and OC is summarized in Table 1.

III. EXPERIMENTS

The study was HIPAA-compliant and approved by our Institutional Review Board and Office of Human Subjects Research. Our experiment includes 66 patients (134 polyps) at two medical centers who underwent same-day CTC and optical colonoscopy. Patients underwent standard 24-hour colonic preparation that included a cathartic and iodinated oral contrast administration. A four-channel or eight-channel CT scanner was used (GE LightSpeed or LightSpeed Ultra, General Electric Medical Systems). The CT technique involved the use of 1.25-to-2.5-mm collimation, a table speed of 15 mm per second, a reconstruction interval of 1 mm, and scanner settings of 100 mAs and 120 kVp [4].

In CTC, image processing and interpretation were performed with the use of a commercially available CT colonographic system (Viatronix V3D Colon, version 2.1, Viatronix). Polyps were identified and their coordinates were recorded as polyp locations at CTC. The length of the colon on CTC C_{a-to-c}^{ctc} was the distance along the centerline from the anus to the cecum, which was defined as the end points of the colon centerline. The distance to the polyp at CTC C_{a-to-p}^{ctc} was defined as the distance along the colon centerline from the anus to the polyp projected on the colon centerline.

After CTC, OC was performed the same day by colonoscopists. During the OC, the anus-to-polyp length and anus-to-cecum length along the colonoscope were measured by the colonoscopist and recorded in centimeters using the markings (10 cm interval) on the colonoscope [4] on scope withdrawal. The anus-to-polyp length at OC was used as ground truth for performance evaluation. The prediction errors within 5 cm and 10 cm are defined as ± 0.5 and ± 1 colonoscope mark (10 cm) of its true location, respectively.

IV. RESULTS

Figure 5 shows an example of OC polyp location prediction for a polyp in the transverse colon. The prediction error is 3.4 cm. For comparison, the prediction errors by the NDACC and Duncan's fixed factors methods are 8.7 cm and -14.2 cm, respectively.

The differences between the true and predicted polyp locations by colonic segment (cecum, ascending colon, hepatic flexure, transverse colon, splenic flexure, descending colon, sigmoid colon, and rectum) and by entire colon are reported in Table 2. The colonic segment for each polyp was determined by the colonoscopist at the time of colonoscopy. The differences between the true and predicted polyp locations at OC using the minimal-energy curve, NDACC, and fixed factors method were -0.7 ± 5.0 cm, -5.9 ± 7.4 cm and -2.8 ± 8.8 cm, respectively. The maximum difference was found for polyps in the hepatic flexure using the minimal-energy curve method. The maximum difference was for polyps in the sigmoid colon and cecum using NDACC and fixed factors method as expected. The biases (offsets) for all segments using the minimal-energy curve method were statistically significantly lower than those of the NDACC and fixed factors methods ($p < 0.0001$, two-tailed paired Student's t test).

Correlations between true and predicted polyp locations at OC were high ($R^2 = 0.971$, 0.955 and 0.927 for minimal-energy curve, NDACC and fixed factors method, respectively) (Figure 6). The trend lines indicate the offset between true and predicted OC polyp locations by minimal-energy curve, NDACC and fixed factors method were approximately 1 cm, 8 cm and 2 cm, respectively.

The Bland-Altman plots show that there is agreement between the true and predicted polyp locations at OC with considerable variance for all three methods (Figure 7). The limits of agreement were approximately ± 10 cm, ± 15 cm and ± 18 cm for minimal-energy curve, NDACC and fixed factors methods, respectively. Figure 7 shows that our minimal-energy curve method is superior to the other two methods without gross outliers.

There was no gross pattern of prediction error according to polyp location in the colon (Figure 8). Figure 9 shows that the predicted location of a polyp was within ± 5 cm (i.e., ± 0.5 colonoscope mark) of its true location for 58.2% (78/134), 26.9% (36/134) and 40.3% (54/134) of polyps using minimal-energy curve, NDACC and fixed factors method, respectively. The OC locations of polyps were within ± 10 cm (i.e., ± 1 colonoscope marks) of the predicted locations for 96.3% (129/134), 73.1% (98/134) and 76.9% (103/134) of polyps using minimal-energy curve, NDACC and fixed factors method, respectively. By using Fisher's exact test, the polyp prediction by our minimal-energy curve is significantly more accurate than the other two methods for OC intervals of both ± 5 cm and ± 10 cm ($p < 0.0001$ and $p = 0.005$, respectively).

V. DISCUSSION

Because the colonoscope path at OC is very different than the colon centerline at CTC, in previous research polyp locations at CTC were corrected by the NDACC or fixed factors to estimate polyp locations at OC. In this paper, a colonoscope is modeled as a flexible tube

with negligible stretch and minimal strain using a minimal-energy curve method. This method enabled significantly more accurate estimations of polyp locations at OC than the NDACC and fixed factors methods, to within ± 0.5 colonoscope mark for more than 58% of polyps and to within ± 1 colonoscope mark for more than 96% of polyps.

The previously published spline-based method [10] assumes the colonoscope affects the entire colon. In that method, one B-spline curve is fit to the entire colon. The polyp's location at CTC is then mapped to the B-spline to determine its predicted location at OC. In this paper, a second B-spline is fit to the colon only from the anus to the polyp to predict the anus-to-polyp length at OC. The reason for this approach is that during the OC examination, when the scope is withdrawn after full cecal intubation, because the colon is highly movable and flexible, the colon proximal to the scope reverts to its original configuration. Thus, the colonoscope only affects the colon from the anus to the polyp. This is an assumption and an important insight of our method, and led to improved results although the evaluation data are not exactly identical (96.3% vs 81.5% [10] of polyps were accurately located at OC within ± 1 colonoscope mark).

The clinical implementation of our method is straightforward and similar to that of the NDACC method. During the CTC examination, the colon centerline is automatically extracted and polyp locations (coordinates) are saved for the colonoscopist. During the OC examination, after full colonoscope insertion to the cecum, the standard first step in OC, the colonoscopist need only record the colon length. The OC colon length is then input to the minimal-energy curve method to calculate the predicted anus-to-polyp length at OC. The clinical implementation of our method could be further simplified by creating a lookup table. This lookup table is generated after CTC examination for a range of typical OC colon length values. Then, for a given polyp found at CTC, the colonoscopist can easily read from the table the predicted anus-to-polyp length at OC for a given colon length, avoiding the need for sophisticated computer processing using the CTC colon geometry while the patient is being examined. Table 3 shows an example lookup table of a polyp calculated using the minimal-energy curve method. The anus-to-cecum total colon length and the anus-to-polyp length at CTC are 165.09 cm and 90.9 cm, respectively. The anus-to-cecum total colon length and the anus-to-polyp length at OC are 90 cm and 58 cm, respectively. The predicted polyp location at OC on the lookup table is 56.8 cm. The prediction error is -1.2 cm. For polyps not found using the minimal-energy curve method, the colonoscopist can revert to the current less precise practice of searching for the polyp within ± 1 colonic segment.

Compared to other colonic segments, the sigmoid colon is highly mobile and tortuous and it is greatly shortened and straightened by the colonoscope. Therefore, OC distance measurements in the sigmoid colon are less linear than their values at CTC, leading to inaccuracies in the predicted polyp location at OC by methods such as NDACC that do not take this nonlinearity into account. That is, maximum average difference (about 11 cm) between the true and predicted polyp locations at OC was observed for polyps in the sigmoid colon for NDACC (Table 2). However, average prediction error was reduced to 1.4 cm by using the non-linear minimal-energy curve method.

OC measurements were reported with less precision than CTC measurements. That is because the colonoscopes used in this study had markers every 10 cm along the outer sheath that allowed visual estimation of insertion distance. Using these markers, the colonoscopists rounded the majority of OC distance measurements to the nearest 5 cm, restricting the accuracy of measurements to ± 2.5 cm. Future studies may ensure that OC measurements are recorded with higher precision, such as using the latest-generation colonoscopes that have markings every 5 cm instead of every 10 cm. More precise OC measurements are likely to improve the polyp correlation between OC and CTC.

In this paper, among the information provided at CTC, only polyp locations were used to locate polyps at OC. Other features such as polyp size and shape (e.g., sessile, pedunculated, or flat) and relationship to a haustral fold (e.g., behind a fold) will be helpful to locate polyps found at CTC. Similar polyp features at OC and CTC will increase confidence and accuracy of a proper match, especially for confusing situations where multiple polyps are located near one another.

In this paper, the only information needed at OC was the total length of colonoscope inserted to the cecum. That is the only possible information we can get from OC without use of additional hardware or intervention. Therefore, it is likely that some of the variation evident in Figures 7 and 8 is due to different colonoscopists or different stretching of the colon. While such variability in individual OC procedures is a potential limitation, our data shows that our technique works well anyway. Such variability is common to other cited work in the literature.

Future research could be aimed at reducing this variability to potentially achieve even greater accuracy of polyp location prediction. To assess such procedural variability, one might need additional hardware or intervention to collect information about the real-time colonoscope path, such as fluoroscopy or a magnetic tracker built into the colonoscope. The advantage of our approach is that such hardware, which is not widely available, is not necessary to achieve better results than those of other published methods.

Polyp mapping between CTC and OC is related to polyp registration between supine and prone scans in CTC [8, 17–21]. NDACC [8] simply used the length of colon centerlines extracted at supine and prone scans for polyp registration. Li *et al.* [17] proposed a heuristic algorithm for the colon centerline and polyp registration that employed the coordinate information of the centerline and anatomical knowledge of colon. Correlation optimized warping (COW) and canonical correlation analysis were used in [18]. Topological changes between prone and supine scans were considered in [19]. Teniae coli and quasi-conformal mapping were employed for flattened colons in [20]. Cylindrical parameterization was used to reduce the complexity of the registration task from 3-D to 2-D in [21]. However, polyp mapping between CTC and OC is much more challenging mainly because of the large topological change of the colon and the unknown colonoscope path.

In conclusion, we found that 96.3% of polyps can be accurately located at OC to within ± 1 colonoscope mark (10 cm) using the minimal-energy curve method. The minimal-energy

curve method is more accurate than the NDACC and fixed factors methods and can be easily incorporated into routine OC practice.

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Figure 1.
Colon anatomy and example of a colonoscope path during an OC examination.

Figure 2.
Sigmoid colon varies before (a) and after (b) the colonoscope passes through the sigmoid-descending junction.

Figure 3.
Flowchart of polyp mapping from CTC to OC.

Figure 4.

Examples of CTC centerline (red), polyp (green circle), projected polyp (black circle) and 4 anatomical landmarks (green squares) (a), B-spline curves for entire colon (blue) during optimization by subdivision at 1st, 2nd, 5th, and 7th (final) iterations (b)–(e), and the anus-to-polyp B-spline curve (green) (f).

Figure 5.

Examples of CTC centerline (red), polyp (black circle) and 4 anatomical landmarks (green squares) (a), B-spline curves for entire colon (blue) after 1st, 3rd, 5th, 7th, and 9th (last) iterations (a)–(e), and the final anus-to-polyp B-spline curve (green) (f). The anus-to-cecum total colon lengths at CTC and OC are 151.8 cm and 130 cm, respectively. The polyp locations at CTC and OC are 86.1 cm and 65 cm, respectively. The predicted polyp location at OC is 68.4 cm. The prediction error is 3.4 cm.

Figure 6.

Linear regression analyses of optical colonoscopy (OC) show true versus predicted distances to polyp. Predicted distances were determined from CT colonography (CTC) by minimal-energy curve (top), normalized distance along colon centerline (middle), and fixed factors method (bottom).

Figure 7.

Bland-Altman plots of optical colonoscopy (OC) true versus predicted distances to polyp using minimal-energy curve (top), NDACC (middle) and fixed factors method (bottom). Solid horizontal line is mean of differences, and dashed lines are mean $\pm$ 2 SD.

Figure 8.

Difference between true and predicted distances to polyp at optical colonoscopy (OC) versus true distance to polyp at OC using minimal-energy curve (top), NDACC (middle), and fixed factors method (bottom).

Figure 9.

Cumulative fraction of polyps with predicted location at optical colonoscopy (OC) within given distance of true location at OC computed using minimal-energy curve, NDACC and fixed factors method. Distances are expressed as absolute value of difference between true and predicted OC distances to polyp.

Table 1

Summary of procedure for polyp mapping from CTC to OC

C_{a-to-p}^{ctc} : anus-to-polyp length at CTC

$C_{a-to-sdj}^{ctc}$: anus-to-sigmoid-descending junction length at CTC

C^{ctc} : CTC colon centerline

P_i : i th point on C^{ctc} , $0 \leq i \leq N$. P_i represents the polyp, rectum-sigmoid junction, sigmoid-descending junction, splenic and hepatic flexures on C^{ctc} when $i=p, rsj, sdj, sf$ or hf .

C^{bs1}, C^{bs2} : B-spline 1 and B-spline 2

P^{bs1}, P^{bs2} : control points set for C^{bs1} and C^{bs2}

S_i : i th segment length of C^{bs1}

C_{a-to-p}^{oc} : anus-to-polyp length at OC

C_{a-to-c}^{oc} : anus-to-cecum length at OC

Input: CTC images, polyp coordinates at CTC, C_{a-to-c}^{oc} fixed thresholds t_e
and t_c

Output: C_{a-to-p}^{oc}

begin

compute $C^{ctc}, P_p, P_{rsj}, P_{sdj}, P_{sf}$ and P_{hf} ;

if $C_{a-to-p}^{ctc} \leq C_{a-to-sdj}^{ctc}$ *then*

$P^{bs1} = \{P_0 P_1 P_2 \cdots P_p\}$ and compute C^{bs1} as eqs. (3) and (4);

$C_{a-to-p}^{oc} = \text{Length}(C^{bs1})$;

endif

if $C_{a-to-p}^{ctc} > C_{a-to-sdj}^{ctc}$ *then*

initialize $P^{bs1} = \{P_0 P_1 P_2 P_3 P_{rsj} P_{sdj} P_{sf} P_{hf} P_N\}$ and compute

C^{bs1} as eqs. (3) and (4);

compute $E(C^{bs1})$ as eq. (6);

repeat

sort all segments of C^{bs1} and $Q = \{S_0 S_1 S_2 S_3 \cdots S_{s-1}\}$ with

$S_0 S_1 \cdots S_{s-1}$;

for $i=0$ to $s-1$

subdivide S_i and a new control point P' is created;

temporally update P^{bs1} and compute $C^{bs1'}$ as eqs. (3) and (4);

if $E(C^{bs1'}) < E(C^{bs1})$ *then*

discard P' ;

else

accept P' and permanently update P^{bs1} ;

compute $C^{bs1'}$

break;

endif

endfor

until $|E(C^{bs1'}) - E(C^{bs1})| < t_e$ or $|\text{Length}(C^{bs1'}) - C_{a-to-p}^{oc}| < t_c$.

$P^{bs2} = \{P_i \mid P_i \in P^{bs1} \cap 0 \leq i \leq p\}$ and compute C^{bs2} ;

$C_{a-to-p}^{oc} = \text{Length}(C^{bs2})$;

endif

end

Table 2

Mean Differences ($\pm$ SD) Between True and Predicted Polyp Locations at Optical Colonoscopy (OC) (cm) Using Three Methods.

Colon Segment	Minimal-energy Curve	NDACC	Fixed Factors	No. of Polyps
Rectum	-1.3 ± 5.1	-5.3 ± 4.5	-3.1 ± 4.7	30
Sigmoid colon	-1.4 ± 4.8	-10.9 ± 5.6	-4.9 ± 4.7	40
Descending colon	1.0 ± 3.3	-5.3 ± 8.5	1.8 ± 12.9	5
Splenic flexure	-0.4 ± 6.7	0.7 ± 12.6	0.4 ± 8.45	6
Transverse colon	-0.7 ± 5.7	-3.6 ± 6.9	-2.9 ± 9.7	13
Hepatic flexure	-3.4 ± 6.5	-5.9 ± 5.0	-0.1 ± 10.16	6
Ascending colon	1.4 ± 6.6	-1.6 ± 7.6	-0.3 ± 12.8	29
Cecum	-2.2 ± 2.4	-9.3 ± 3.8	-9.0 ± 13.9	5
All segments*	-0.7 ± 5.0	-5.9 ± 7.4	-2.8 ± 8.8	134

*
 $p < 0.0001$

Table 3

Patient-specific lookup table of predicted locations at optical colonoscopy for a polyp in the splenic flexure initially detected at CT colonography

OC Colon Length (cm)	Predicted Polyp Location at OC (cm)
60	-
70	50.7
80	55.8
90	56.8
100	59.4
110	62.7
120	67.8
130	-

Polyp location prediction calculated using the minimal-energy curve method.

- OC colon lengths less than or equal to 60 cm or greater than or equal to 130 cm are not physically possible for this patient's colon given the CTC data.