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Feasibility of Using the Marginal Blood Vessels as Reference Landmarks for CT Colonography

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Abstract

OBJECTIVE—The purpose of this study was to show the spatial relationship of the colonic marginal blood vessels and the teniae coli on CT colonography (CTC) and the use of the marginal blood vessels for supine-prone registration of polyps and for determination of proper connectivity of collapsed colonic segments.

MATERIALS AND METHODS—We manually labeled the marginal blood vessels on 15 CTC examinations. Colon segmentation, centerline extraction, teniae detection, and teniae identification were automatically performed. For assessment of their spatial relationships, the distances from the marginal blood vessels to the three teniae coli and to the colon were measured. Student *t* tests (paired, two-tailed) were performed to evaluate the differences among these distances. To evaluate the reliability of the marginal vessels as reference points for polyp correlation, we analyzed 20 polyps from 20 additional patients who underwent supine and prone CTC. The average difference of the circumferential polyp position on the supine and prone scans was computed. Student *t* tests (paired, two-tailed) were performed to evaluate the supine-prone differences of the distance. We performed a study on 10 CTC studies from 10 patients with collapsed colonic segments by manually tracing the marginal blood vessels near the collapsed regions to resolve the ambiguity of the colon path.

RESULTS—The average distances ($\pm$ SD) from the marginal blood vessels to the tenia mesocolica, tenia omentalis, and tenia libera were 20.1 ± 3.1 mm (95% CI, 18.5–21.6 mm), 39.5 ± 4.8 mm (37.1–42.0 mm), and 36.9 ± 4.2 mm (34.8–39.1 mm), respectively. Pairwise comparison showed that these distances to the tenia libera and tenia omentalis were significantly different

from the distance to the tenia mesocolica ($p < 0.001$). The average distance from the marginal blood vessels to the colon wall was 15.3 ± 2.0 mm (14.2–16.3 mm). For polyp localization, the average difference of the circumferential polyp position on the supine and prone scans was 9.6 ± 9.4 mm (5.5–13.7 mm) ($p = 0.15$) and expressed as a percentage of the colon circumference was $3.1\% \pm 2.0\%$ (2.3–4.0%) ($p = 0.83$). We were able to trace the marginal blood vessels for 10 collapsed colonic segments and determine the paths of the colon in these regions.

CONCLUSION—The marginal blood vessels run parallel to the colon in proximity to the tenia mesocolica and enable accurate supine-prone registration of polyps and localization of the colon path in areas of collapse. Thus, the marginal blood vessels may be used as reference landmarks complementary to the colon centerline and teniae coli.

Keywords

colon; colonic polyps; CT; CT colonography; mesentery; virtual imaging

CT colonography (CTC) is an accurate and safe method for colorectal cancer screening [1–7]. In CTC, patients undergo CT of the abdomen and pelvis after a bowel-cleansing preparation and colon insufflation. CT is performed twice, once with the patient supine and once prone, to improve sensitivity and specificity for polyp detection [8, 9]. Interpretation of CTC images is done using the 2D CT images alone or the 2D or 3D virtual endoluminal images in combination [10–12].

Among the many challenges in CTC interpretation are the proper correlation of findings on the supine and prone images and the proper interpretation of segments of colon that are collapsed in one image but not in the other. For example, it is helpful to determine if the finding is mobile or not to distinguish residual stool from polyps; stool moves with changes in patient position, but polyps (particularly nonpedunculated ones) do not. With regard to collapsed colon segments, it is important to ascertain that the segment is not collapsed on the other image and that the noncontinuous colonic segments are properly connected by either the software or user input to enable proper correlation of findings on the supine and prone images. The wide variation in colonic anatomy and length among individuals adds to these challenges [13, 14].

A number of approaches are available to address these challenges. The simplest is the visual approach, in which the radiologist tries to integrate the information from the 2D and 3D images to arrive at a mental model of the connectivity and orientation of the colon. This method has limitations because the colon can twist, increasing the difficulty of achieving an accurate mental registration [15]. It may also be fatiguing and inefficient because it adds another complex task to the interpretative process. In practice, it is often difficult visually to precisely align the supine and prone colons.

In response to these limitations, automated methods of registration of the supine and prone views have been developed to improve existing commercial software. In one, the teniae coli are identified and used as a circumferential coordinate system for matching polyps on and for synchronized visualization of the supine and prone views [16]. In another, conformal geometry is used to guarantee that the registration is a diffeomorphism, in which teniae coli

and colon flexure locations are also incorporated [17]. A Markov random field method is used to match the features of the endoluminal surfaces of supine and prone acquisitions [18–20]. These methods rely on features intrinsic to the colon (teniae and haustral folds) that limit the accuracy in areas of colon collapse or poorly subtracted endoluminal fluid or stool. Graph-matching methods that can register supine and prone polyps without centerline information have been developed recently [21]. Some other methods use the anus-to-polyp colon length for supine-prone registration [22, 23].

In this article, we propose the use of the colonic marginal blood vessels as a complementary additional axis for supine-prone colon registration. In this article, the term “marginal blood vessels” refers to the colonic marginal artery and vein. The marginal artery, also known as the marginal artery of Drummond, lies within the mesentery, in proximity to the colon. Because of its relationship to the mesentery, the marginal artery also lies in proximity to the tenia mesocolica, the site of attachment of the mesentery onto the wall of the colon. The vein follows a course similar to that of the artery. The marginal blood vessels may therefore serve as the origin of a circumferential coordinate system for supine-prone registration in a way similar to that of the tenia mesocolica [24]. Figure 1 shows the configuration and relationships of the colon, teniae coli, and marginal artery.

In addition, because the marginal blood vessels are extrinsic to the colon, they are not subject to being obscured in regions of colon collapse or residual endoluminal fluid or stool. This may be in part because the marginal blood vessels are not adherent to the serosa, but rather there is a plane of fat between them and the colon. Thus, the marginal blood vessels may serve as a longitudinal coordinate system (linear reference path) complementary to that of the colon centerline.

The purposes of this pilot study were to show the spatial relationship of the marginal blood vessels and the teniae coli on CTC and show the feasibility of using the marginal blood vessels for supine-prone registration of polyps and for determination of proper connectivity of collapsed colonic segments.

Materials and Methods

This study was approved by the institutional review board and was HIPAA compliant. Informed consent was waived by the institutional review board because the project was conducted with existing CTC data. The software (Vascular Editor, Biomedical Imaging Laboratory) [25] used for setting the reference standard was supplied free of charge by the developer. Free open source software (3D Slicer) [26] was used for 3D image display.

Dataset

This study used three CTC datasets, one (dataset 1) for assessing the relationship of the tenia mesocolica and the marginal blood vessels; one (dataset 2) for assessing the spatial relationship of polyps on supine and prone studies using the marginal blood vessels; and one (dataset 3) for assessing the utility of the marginal blood vessels for assisting the connection of colon segments when an intervening segment is collapsed. The three datasets are all subsets of a previously described population of 182 consecutive patients [27]. The patients

were screening patients who had positive CTC findings; 104 of the patients underwent same-day optical colonoscopy and the remainder entered a surveillance program in which patients undergo more frequent CTC evaluation rather than immediate polypectomy.

Dataset 1 contained 15 CTC studies from 15 patients (nine men, six women; average age, 56 years; range, 51–64 years), with supine scans from eight patients and prone scans from seven patients. The criterion for case selection was based on the visibility of the marginal blood vessels. Selecting the dataset was not a trivial task because the data were collected without IV contrast material administration. About one fourth of the 182 cases could not be annotated. In approximately one third of the 182 cases, at least one segment of the marginal blood vessels was not traceable. Visceral fat separates the colon from the adjacent structures, which improves the visibility of the marginal blood vessels. The cases chosen in dataset 1 had more visceral fat than others in general. However, the case selection was performed visually and did not quantify the percentage of visceral fat. The 15 CTC cases in our dataset all showed a clear path of the marginal blood vessels in most regions of the colon.

Dataset 2 contained 40 CTC studies from 20 patients (12 men, eight women; average age, 61 years; range, 52–74 years) with both supine and prone CTC scans. The criterion for case selection was that each patient had at least one polyp 6 mm or larger measured at CTC [28]. We selected one polyp 6 mm or larger from each patient for our study. Dataset 2 had no overlap with dataset 1. Patients of dataset 2 all underwent same-day optical colonoscopy, and the polyp findings on CTC were all confirmed by optical colonoscopy.

Dataset 3 contained 10 CTC studies from 10 patients (three men, seven women; average age, 60 years; range, 51–74 years), with supine scans from four patients and prone scans from six patients. The criterion for case selection was that each CTC scan had at least one collapsed colonic segment and the marginal vessels were visible in the collapsed region. This dataset had one patient in common with dataset 1 and three patients in common with dataset 2.

Bowel Preparation

Patients consumed a clear liquid diet for 24 hours before CT. For bowel cleansing, the patients consumed one 45-mL dose of sodium phosphate preparation (Fleet 1, Fleet Pharmaceuticals). For feces and fluid tagging, the patients consumed one 250-mL dose of dilute barium sulfate (2.1% by weight) (Scan C, Lafayette Pharmaceuticals), and one 60-mL dose of diatrizoate sodium (Gastrografin, Bracco Diagnostics).

CT

CT was performed during a single breath-hold in each of the prone and supine positions using an 8-MDCT or 16-MDCT scanner (both Light Speed Series, GE Healthcare). CT parameters included 1.25-mm section collimation, 1-mm reconstruction interval, 50–75 mAs, and 120 kVp.

Experimental Procedure

Marginal blood vessel labeling, colon segmentation, centerline extraction, teniae coli detection, and teniae coli identification were performed on all 15 CTC studies in dataset 1. Figure 2 is a flowchart of our experimental procedure, showing the order of each step.

Marginal Blood Vessel Labeling

The marginal blood vessels were manually labeled using Vascular Editor software, which allows users to create, edit, and manipulate 3D vascular models [25]. One author, a postdoctoral trainee with 2 years of experience, labeled the vessel under the supervision of a senior radiologist with 17 years of experience interpreting abdominal CT and 12 years of experience interpreting CTC in a research setting. During the labeling process, we looked for the blood vessel that is parallel and in proximity to the colon. The vessel was traced along the entire length of the colon. The Vascular Editor software allows the user to arbitrarily set the size of the vessel for display purposes. The diameter of the vessel was set to be constant throughout its length. The manual labeling generally takes 30–45 minutes per case.

The marginal artery and vein are two parallel structures, and only one was labeled. It was not always possible to determine which was the artery or the vein. For the purposes of this study, the distinction between artery and vein was less important because the two lie in proximity to one another.

Colon Segmentation

Colon segmentation was performed using in-house software [29]. The method uses a modified region-growing technique to obtain regions containing air and fluid in the colon lumen. Fuzzy-connectedness segmentation was used to close gaps and holes and form a colon lumen probability map. Then level-set segmentation was applied to the probability map to obtain the colon wall.

Centerline Extraction

Centerline extraction was performed using previously published methods [30, 31] to be more robust in areas of over- and underdistention of the colon. Our method used segmentation of both the inner and outer colon walls to extract the colon centerline. In areas of poor distention, inner colon wall segmentation fails. In such situations, the outer colon wall centerline was extracted and used to fix the missing segment. The combined centerline of the inner and outer colon wall is robust for colons with variable distention.

Teniae Coli Detection

Teniae coli are three approximately 8-mm-wide longitudinal smooth muscle bands in the colon wall. They are parallel, equally distributed, and form a triple-helix structure from the appendix to the sigmoid colon [32, 33]. Each tenia is named in reference to its relationship with the bowel mesentery or omentum. The tenia mesocolica is associated with the mesentery, the tenia omentalis is associated with the omentum, and the tenia libera is not associated with either mesentery or omentum [34].

Teniae coli detection was performed using a previously described automated method [35, 36]. The teniae were detected on 2D height map images in which the elevation of the colon surface is projected onto an unfolded flattened representation of the colon. The basis of the method is that each haustral fold is divided into three roughly equal sections by the teniae coli. By identification of the haustral fold sections, the teniae coli can be detected. The method has been validated and shown to be highly accurate [36]. However, in this dataset, minor (< 10% of total colon length) manual corrections to the teniae path were required in four of the 15 scans, particularly in areas of high curvature such as at the flexures. The correction process took 10–15 minutes per scan.

Teniae Coli Identification

The anatomic relationships between teniae and the ileocecal valve were used for teniae identification. The ileocecal valve is a sphincter situated at the junction of the small intestine and the colon. The ileocecal valve lies anterior to the tenia mesocolica and can be used to identify the tenia mesocolica [37]. The locations of the ileocecal valve were manually labeled. Then the tenia nearest to the location of the ileocecal valve was identified as the tenia mesocolica. The tenia mesocolica, tenia omentalis, and tenia libera are located clockwise in the cecum at the level of the ileocecal valve. Once the tenia mesocolica is identified, the tenia omentalis and tenia libera can be subsequently derived by their relative positions.

Analysis Methods

For each point in the centerline, the method identified one point on each tenia that was closest to the centerline point. The three points from the teniae, denoted as P_{TM} , P_{TO} , and P_{TL} , determined a cross-section of the colon. This cross-section, in theory, is perpendicular to the centerline. The nearest point in the marginal blood vessel to the centerline point was also located, denoted as P_{MV} . For measurement of the spatial relationship between the marginal blood vessel and teniae, the distances from P_{MV} to each teniae point, P_{TM} , P_{TO} , and P_{TL} , were calculated, denoted as D_{TM} , D_{TO} , and D_{TL} , respectively. The distance from the marginal blood vessel point to the colon wall was calculated as well by computing the minimal distance from P_{MV} to the cross-section, denoted as D_{colon} . The various points and distances are illustrated in Figure 3.

False-Measurement Reduction

Because the CTC images were obtained without IV contrast material administration, sometimes it was hard to see the marginal blood vessels. Thus, for some colon cross-sections, there was no corresponding labeled marginal blood vessel. In these cases, the method for distance calculation will make a false measurement using the marginal blood vessel from another part of the colon. An example is shown in Figure 3C in which the colon segment C_A does not have any corresponding labeled marginal blood vessels. In this case, the algorithm erroneously takes the marginal blood vessel near colon segment C_B as the corresponding one to segment C_A and computes the distances from the teniae points in colon segment C_A to the marginal blood vessel corresponding to segment C_B . To deal with this problem, a maximal acceptable value for the distance, D_{colon} , was defined as a threshold

Th_{MV} , which was set on the basis of the distribution of D_{colon} . We chose Th_{MV} as 25 mm empirically, which was large enough to include most of the valid distances.

Teniae can be missing in some segments of the colon, which could be caused by two factors: only two teniae present, which usually happened in the sigmoid colon where tenia omentalis and tenia libera start to merge from the lower part of the descending colon to form one single tenia near the sigmoid colon [32], or no detection of tenia in the descending colon where the haustral fold features became weak and teniae became obscure. In this case, teniae in a nearby segment of the colon could be mistakenly measured. An example of this problem is shown in Figure 3C. Therefore, to prevent false measurements from the marginal blood vessels to teniae in noncorresponding parts of the colon, the maximum acceptable distance value from the centerline was defined as a threshold, Th_{teniae} , comparable to the distance from the centerline to the colon wall. Th_{teniae} was selected as 40 mm on the basis of the distribution of the diameters of the colons. If the distance between a tenia and the marginal blood vessel was larger than the threshold, the distance measurement was eliminated.

Polyp Localization on the Basis of Marginal Blood Vessels

A potential application of the marginal blood vessels is to locate polyps more precisely on supine and prone CTC. We analyzed 20 polyps (average size, 11 mm; range, 6–26 mm; 12 sessile, 4 flat, and 4 pedunculated) from the 20 patients in dataset 2. The identification of polyp locations is described in the next section of this article.

The localization method uses the fractional distance of a polyp measured along the colon cross-section perimeter, with the projection of the marginal blood vessel onto the colon wall as the origin of the measurement (Fig. 4). For illustration, in the case of a circular colon cross-section, a polyp located on the colon wall at the point of projection is at 0%. A polyp located directly across the colon from this point, half-way around the perimeter of the colon wall, is at 50%.

The projection of the marginal blood vessels onto the colon wall was determined by finding the intersection of the colon wall and the line between the marginal blood vessels and centerline of the colon cross-section. For simplification of the processing, all polyps in this study were located within the ascending, descending, and sigmoid colon and rectum, and the cross-section was approximated as the transverse plane. Cecal polyps were excluded. We manually subtracted the fluid of 18 cases (45%) and removed prominent folds of 11 cases (28%) for a more accurate measurement of the perimeter of the cross-section. The geodesic distance from the polyp to the marginal blood vessel projection point was recorded. The ratio of this geodesic distance to the length of the perimeter (circumference) of the colon, ranging from 0 to 50%, was also recorded. The geodesic distance was approximated as Euclidean distance when the polyp was close to the projection point and the colon wall between the polyp and the projection point was nonconvex. Figure 5 illustrates the marginal blood vessel-based polyp localization system. The differences between the fractional distance on the supine and prone scans were measured.

Polyp Identification

The reference standard for polyp location was optical colonoscopy performed on the same day as CTC [1]. Each polyp found at optical colonoscopy was located on 2D and 3D prone and supine CTC images by an experienced radiologist using V3D Colon software (Viatronix). To match on optical colonoscopy and CTC, polyps had to be located within the same or adjacent colonic segment and be within 50% of each other in size. With a graphical user interface, a voxel within each located polyp was marked manually by trained research assistants under the supervision of an experienced radiologist [12].

Determining the Connectivity of Collapsed Colonic Segments

Another potential application of the marginal blood vessels is to help determine the connectivity of collapsed colonic segments. Tracing the collapsed colon is one way to determine colon connectivity, but this is often very difficult to do. The marginal blood vessels are extrinsic to the colon and are not subject to being obscured in regions of colon collapse or residual endoluminal fluid or stool. Hence, tracing the marginal blood vessels may be feasible when direct colon tracing is not. In this situation, the marginal blood vessels can serve as an alternative method or as a confirmation of the results of other methods of determining the colon path when the colon is collapsed. We studied the 10 patients with collapsed colonic segments in dataset 3 for this purpose. We manually traced and labeled the marginal blood vessels near the collapsed regions to resolve the ambiguity of the colon path, using Vascular Editor software [25]. One author, a postdoctoral trainee with 2 years of experience, labeled the vessel under the supervision of a senior radiologist with 17 years of experience interpreting abdominal CT and 12 years of experience interpreting CTC in a research setting. If the marginal vessels found near two noncontinuous colonic segments were connected, then the colonic segments were considered to be properly connected.

Statistical Analysis

The distances from the marginal blood vessels to the tenia mesocolica, tenia omentalis, tenia libera, and colon were calculated and recorded. The distances were sampled with a 1.5-mm interval for the entire length of the colon. There were, on average, 109 measurements for each CTC scan and the average distances were computed. The distance between the tenia mesocolica and the projection of the marginal blood vessels on the colon wall was also computed. Then the mean value of the average distances of all 15 scans was computed. Pair-wise Student *t* tests were used to determine whether the distance from the marginal blood vessels to the tenia mesocolica was significantly less than that between the marginal blood vessels and the tenia omentalis or tenia libera. For polyp registration on the basis of marginal blood vessels, the differences between the supine and prone scans of the normalized perimeter measurement from the marginal blood vessels projection to the polyps were analyzed using a Bland-Altman plot [38]. The Bland-Altman 95% limits of agreement were calculated as average difference $\pm$ 1.96 SD of the difference. Student *t* tests (paired, two-tailed) were performed to evaluate the differences. A *p* value of less than 0.05 was considered statistically significant.

Results

Marginal Blood Vessel Labeling Results

We were able to label a marginal blood vessel for all 15 cases in dataset 1. For the hepatic and splenic flexure regions, the labeled marginal blood vessels were less well connected compared with the ascending, transverse, and descending colon regions where the curvatures of the centerline were smaller. Noncontinuous segments of the marginal blood vessels existed in the labeling results, particularly where segments were located at bifurcations of the vessel or farther from the colon. Because we were targeting only the vessels near the colon, those bifurcations far from the colon were not labeled, and the segments were left unconnected in some cases. Figure 5 shows the labeling of marginal blood vessels and tenia coli on a pair of supine and prone CTC examinations.

Teniae Coli Detection and Identification Results

Figures 4C and 4F show the detected and identified teniae highlighted on a pair of supine and prone 3D colon surfaces. The figures show the close correspondence of the marginal blood vessels and the tenia mesocolica.

Distance Between Marginal Blood Vessels and Teniae Coli

Figure 5 presents the spatial relationship of the marginal blood vessels and teniae in 3D space and illustrates clearly that of the three teniae the marginal blood vessel is closest to the tenia mesocolica.

The average distances ($\pm$ SD) from the marginal blood vessels to the tenia mesocolica, tenia omentalis, and tenia libera were 20.1 ± 3.1 mm (95% CI, 18.5–21.6 mm), 39.5 ± 4.8 mm (37.1–42.0 mm), and 36.9 ± 4.2 mm (34.8–39.1 mm), respectively. Pair-wise Student *t* tests comparing D_{TM} and D_{TO} , and D_{TM} and D_{TL} , both yielded $p < 0.001$, indicating that the distances from the marginal blood vessels to tenia libera and tenia omentalis were significantly different from the distance to the tenia mesocolica. The distance between the tenia mesocolica and the projection of the marginal blood vessels onto the colon wall was 16.8 ± 3.7 mm (15.0–18.7 mm). Of the 15 cases, two cases had the false-measurement problem, which occurred in the splenic flexure of the colon.

Distance From Marginal Blood Vessels to Colon

The average distance from the marginal blood vessels to the colon was 15.3 ± 2.0 mm (14.2–16.3 mm).

Polyp Localization Results

For polyp localization, the average difference of the circumferential polyp position on the supine and prone scans was 9.6 ± 9.4 mm (5.5–13.7 mm) ($p = 0.15$) and expressed as a percentage of the colon circumference was $3.1\% \pm 2.0\%$ (2.3–4.0%) ($p = 0.83$). Pair-wise comparison of the fractional differences showed that these differences were not significantly different ($p = 0.83$). Figure 6 shows the Bland-Altman plot of the differences. The 95% limits-of-agreement were -7.5% , 7.2% .

Results of Connectivity of Collapsed Colon

The 10 CTC scans in dataset 3 each had one collapsed colon segment. We were able to trace and label the marginal blood vessels near 10 collapsed colonic segments. Figure 4C shows an example of how the path of the marginal blood vessels enables identification of the two colonic segments that span the collapsed gap.

Discussion

The marginal blood vessels have typically not been used or even identified on CT. On CTC, the teniae coli are usually an incidental observation on 3D virtual colonoscopy fly-through images and are not used in clinical interpretation. In this study, we identified the marginal blood vessels and the three teniae coli in 15 CTC cases. We found that the marginal blood vessels were closest to the tenia mesocolica in accordance with their known anatomic relationship to the mesentery of the colon [34, 39–41]. As indicated by the lower SDs, the distances to the tenia mesocolica were less sensitive to colon distention compared with the distances to the tenia omentalis and tenia libera, corresponding to the relative attachment and proximity of the marginal blood vessels and tenia mesocolica and lack of attachment of marginal blood vessels to tenia omentalis and tenia libera.

For polyp localization on the basis of the marginal blood vessels, the differences between supine and prone fractional distance measurements for 20 polyps (including four [20%] pedunculated polyps) were smaller than the results reported in the study by Huang et al. [16] using teniae to locate polyps (including 12 of 45 [27%] pedunculated polyps; mean difference between supine and prone scan, was 0.13 ± 1.12 grid lines, equivalent to $1.1\% \pm 9.3\%$ of the circumferential position). This result indicates that the marginal blood vessels can serve as a circumferential coordinate system for supine-prone registration, complementary to that provided by the teniae. For determination of connectivity at sites of collapse, our study showed that the marginal blood vessels could be used to resolve the ambiguity of the collapsed colon path. Thus, the marginal blood vessels can also serve as a coordinate system that can help connect colon segments.

Colon rotation has been observed at CTC. As patients move from supine to prone positions, the ascending colon can rotate significantly [15]. An advantage of both the teniae- and marginal blood vessel-based colon coordinate systems is that they can correct for such rotations, enabling correct anatomic registration of the supine and prone colons.

Because of their location extrinsic to the colon and relative insensitivity to colon distention or collapse, the marginal blood vessel-based colon coordinate system may have an advantage over the teniae-based coordinate system in some patients or parts of the colon. For example, the teniae may be undetectable in poorly distended colons and cannot be detected in collapsed colon segments. Thus, the marginal blood vessels can serve as a longitudinal coordinate system (linear reference path) for supine-prone registration complementary to that provided by the teniae.

Presumably the distance to the colon (D_{colon}) should be not much different from the distance to the tenia mesocolica (D_M). We found D_{colon} to be about 5 mm less than D_M . This

difference is small and not likely to be clinically important. There could be several reasons for this, including twisting of the mesentery or colon or inaccuracy of teniae detection.

Proper marginal blood vessel detection was dependent on the accuracy of several steps in the image processing pipeline, including marginal blood vessel labeling, colon segmentation, centerline extraction, teniae detection, and teniae identification. In addition, because CTC is done without IV contrast material administration, marginal blood vessel detection may be difficult in certain patients.

The marginal artery of the colon is formed by branches of the colic arteries and runs along the inner perimeter of the colon. A single arterial trunk is formed by anastomosis of the colic arteries of the colon, which begins at the ileocecal junction, where it anastomoses with the ileal branches of the superior mesenteric artery (SMA), and ends where it anastomoses less freely with the superior rectal artery. The blood supply to the colon arises from the SMA and inferior mesenteric artery (IMA). The marginal artery allows communication between the SMA and IMA. The marginal artery runs parallel to the colon for its entire length [39–41]. Although the vascular pattern of the colon varies from one patient to another, the marginal artery is consistently presented [42, 43]. The marginal artery also serves as a collateral vessel, which makes it important in preserving the perfusion of the colon [44]. The venous drainage of the colon follows that of the arterial system [34].

A potential limitation of this study is that it was not always clear which vessel was the marginal artery and which was the marginal vein. Because both vessels run in the periphery of the mesentery adjacent to the colon, the distance between the artery and the vein is far less than that between the artery and the colon and the effect of increased variability of the distance measurement should be negligible. However, sometimes blood vessels other than the marginal vessels course near the colon; choosing such vessels could lead to substantial errors. Such misidentifications may be more common in patients having little visceral fat to separate the colon from adjacent structures. One approach to more accurately identify the marginal artery may be to develop optimized visualizations, such as maximum-intensity-projection images or curved multi-planar reconstructions along the direction of the colon centerline. The use of IV contrast material would also likely improve the accuracy of marginal artery identification, although IV contrast material is not typically used for CTC. The relatively long manual processing time will need to be addressed by improved automation [45].

In this study, we evaluated the feasibility but not the robustness of using the marginal blood vessels for supine-prone polyp registration and for determination of collapsed colonic segments. Robustness will need to be evaluated in a larger dataset to take into account anatomic variation. Because of the lack of IV contrast material administration and 1.0-mm section spacing, the relatively small marginal blood vessels are not always visible along their entire length and may not always work as a complete colonic coordinate system. However, because we show the feasibility of the application, it provides a rationale to reconstruct CTC images at higher resolution, (e.g., 0.5-mm spacing), in the future. Doing so would not necessarily require an increase in radiation dose to maintain signal-to-noise ratio unless the section collimation is also decreased. The reduced section spacing will likely

increase the robustness of using the marginal blood vessels as a complementary colon coordinate system. Sporadic visualization of the marginal artery may also be sufficient for error correction of supine-prone registration performed using another primary technique, such as the colon centerline. We envision that identification of the marginal blood vessels will be fully automated in the future.

In conclusion, we have shown on CTC that the marginal blood vessels run parallel to the colon in proximity to the tenia mesocolica and enable accurate supine-prone registration of polyps and localization of the colon path in areas of collapse. Thus, the marginal blood vessels serve as a coordinate system complementary to the colon centerline and the three teniae coli that may be useful for improving CTC interpretation and polyp localization.

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R. M. Summers and J. Yao have patents (pending or awarded) for related automated analyses for CT colonography. R. M. Summers and J. Yao receive royalty income for a patent license from iCAD. R. M. Summers's laboratory receives research support from iCAD and received research software from Viatronix. P. J. Pickhardt is a consultant for Viatronix, Bracco, iCAD, and Check-Cap and cofounder of VirtuoCTC.

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Fig. 1.

Drawing shows colon, teniae, and marginal artery configuration. Marginal artery in upper left of figure is composed of series of anastomosing vascular arcades connecting superior mesenteric artery (SMA) and inferior mesenteric artery (IMA). Right of figure shows cross-section of colon. Anatomic relationships between marginal artery and three teniae coli (TM = tenia mesocolica, TL = tenia libera, and TO = tenia omentalis) are shown. Marginal artery lies within mesentery close to mesenteric border of colon where TM is located. Vein follows similar course with artery.

Fig. 2.

Flowchart shows experimental procedure for obtaining distances from marginal blood vessel to teniae coli and colon. CTC = CT colonography.

Fig. 3.

CT colonography (CTC) in 51-year-old woman.

A, CTC image shows labeled marginal blood vessel, three teniae coli, and centerline points. Red = marginal blood vessel, blue = tenia mesocolica, yellow = tenia omentalis, green = tenia libera, purple = centerline.

B, In zoomed image of region of ascending colon in **A**, arrows denote distances calculated: blue arrow for tenia mesocolica, yellow = tenia omentalis, green = tenia libera, and white = colon.

C, Zoomed image of region of descending colon in **A**, shows false distance measurement. Colon segment C_A does not have any corresponding labeled marginal blood vessel nearby. For prevention of invalid measurement of distances from marginal blood vessel near segment C_B to teniae points and colon wall in segment C_A (*arrow*), distance from marginal blood vessel to colon wall has to be less than threshold value.

Fig. 4.

51-year-old woman (same patient as in Fig. 3).

A–F, Supine (**A–C**) and prone (**D–F**) 3D reconstruction CT colonography (CTC) images show labeled marginal blood vessel (*red*), detected teniae coli, and segmented colon. Blue indicates tenia mesocolica, yellow indicates tenia omentalis, and green indicates tenia libera. **A** and **D** show labeled marginal blood vessel. **B** and **E** show labeled marginal blood vessel and detected teniae. **C** and **F** show labeled marginal blood vessel, teniae, and colon together. **C** shows example of CTC image with collapsed segment in sigmoid colon. Marginal blood vessel bridges region of collapse and helps determine colon connectivity there.

Fig. 5.

Illustration of marginal blood vessel-based polyp localization in 64-year-old man with 6-mm polyp.

A and B, In supine (**A**) and prone (**B**) CT colonography images, red circle indicates marginal blood vessel (MV), yellow circle indicates polyp, purple square indicates centerline of colon cross-section, white line indicates connecting MV and centerline to project MV to colon surface, and green line indicates geodesic distance from polyp to MV projection point.

Fig. 6. Bland-Altman plot shows mean and differences of polyp locations between supine and prone normalized perimeter measurements from marginal blood vessel projection (units are fraction of distance around colon perimeter). Bland-Altman 95% limits of agreement are shown as dashed lines.