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Quantitative assessment of colorectal morphology: Implications for robotic colonoscopy

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ABSTRACT

This paper presents a method of characterizing the distribution of colorectal morphometrics. It uses three-dimensional region growing and topological thinning algorithms to determine and visualize the luminal volume and centreline of the colon, respectively. Total and segmental lengths, diameters, volumes, and tortuosity angles were then quantified. The effects of body orientations on these parameters were also examined. Variations in total length were predominately due to differences in the transverse colon and sigmoid segments, and did not significantly differ between body orientations. The diameter of the proximal colon was significantly larger than the distal colon, with the largest value at the ascending and cecum segments. The volume of the transverse colon was significantly the largest, while those of the descending colon and rectum were the smallest. The prone position showed a higher frequency of high angles and consequently found to be more torturous than the supine position. This study yielded a method for complete segmental measurements of healthy colorectal anatomy and its tortuosity. The transverse and sigmoid colons were the major determinant in tortuosity and morphometrics between body orientations. Quantitative understanding of these parameters may potentially help to facilitate colonoscopy techniques, accuracy of polyp spatial distribution detection, and design of novel endoscopic devices.

1. Introduction

Colorectal cancer (CRC) is the third most common cancer worldwide, estimated to cause 10.2% and 12.7% of the total cancer death in the UK and USA, respectively [1,2]. Currently, video-colonoscopy is the preferred screening method for the diagnosis of CRC [3,4], however, it is attended by certain clinical drawbacks such as patient discomfort, need for sedation, absence of maneuverability of the scope, and a long learning curve. In order to improve compliance to the screening programs, an imaging modality – computed tomographic colonography (CTC) – was developed for early detection of colorectal polyps and cancer [5]. Other new technologies are being evaluated and have started to emerge, e.g. computer assisted colonoscopy [6–10] and active capsule colonoscopy [11–13]. Similar to conventional colonoscopy, endoluminal navigation in these new technologies is often challenging due to the convoluted nature of the colon.

New devices, that would enable painless and safe colonoscopic procedures, could have significant impact in terms of prevention, diagnosis and treatment of colorectal disease. Thus robotics could make the difference in developing devices that have onboard locomotion or/and can pulled themselves, with no risk for stretching the colonic wall outward and causing painful cramps. The main challenge for building such devices involves understanding the segmental colorectal morphology. Although the colon anatomy is well described, less is known about the variation of colorectal morphometry in quantitative terms across the general population. Studies have shown that colonic anatomical features have a significant association with failure to achieve complete colonoscopy [14]. An understanding of the length, diameter and tortuosity of the colon is important for the performance of conventional colonoscopy; and especially for the future development of robotic colonoscopy platforms that may have sections of fixed diameter and length. Moreover, this could be used to design highly flexible robotic devices, with a particularly suited internal locomotion, and with a direct vision of the colon tissue, to solve acceptance problems and maintain quality of gold standard. Consequently, using this information, important features such as colonic elongation and distension can be extracted, and statistical assessments such as polyp spatial distribution can be understood.

Colonic length has been investigated previously using barium enema, where accurate length assessment is difficult due to the three-dimensional (3-D) intraluminal centreline. Only one study was found from the barium enema literature where the colonic diameter was

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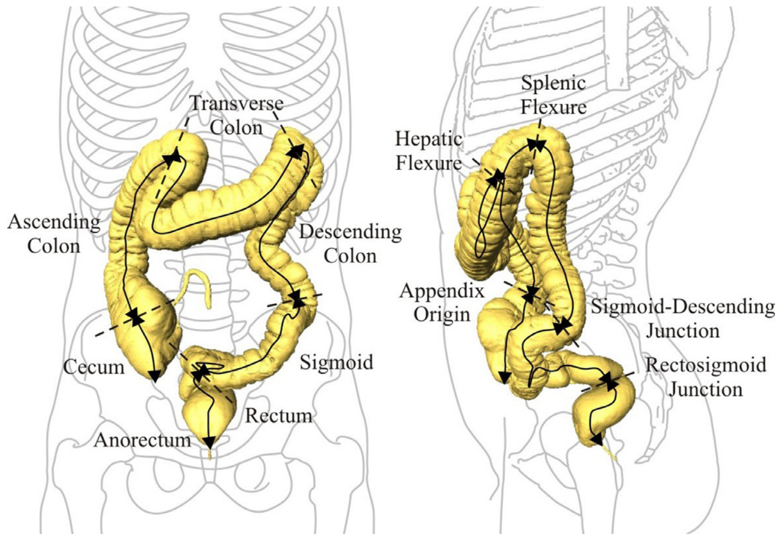

Fig. 1. Schematic representation of the colonic segments and landmarks in anterior and lateral views; the dashed line represents the anatomical landmark position. All measurements were recorded for the six segments (rectum, sigmoid, descending, transverse, ascending, and cecum) using the automated centreline along the axis of the colonic lumen, solid arrow lines.

estimated, in this case for Japanese men and women [15]. It is of note that in these studies the colon contains a significant volume of barium which may also influence the accuracy of measurements. Several barium enema and intraoperative laparotomy studies have investigated how various colonic parameters and gender might predict the degree of difficulty during colonoscopic examinations [16–18], but did not aim to determine the morphology and tortuosity of the colon. One study described the intestinal length as a whole in cadavers did not provide the length of the colonic segments used clinically [19]. Fig. 1 shows the 3-D geometry of the lumen and its anatomical segments. Several CTC studies reported the length measurements for the colorectal anatomy [20,21] and its correlation with difficult or incomplete examinations [22,23]. The high resolution of CTC technology, combined with regular CO2 insufflation and automated digital analyses, make this technology a far more accurate tool for assessing the anatomy of the colon when compared to other methods such as barium enema. However, little is known about the complete colon length, intra-colon segmental lengths, diameters, volume, and tortuosity angle of colorectal anatomy in a healthy population.

The aim of our investigation was to describe a method to quantitatively measure the luminal length, diameter, volume, and shape of the colon within an asymptomatic population undergoing primary CTC examinations. We also determined whether a correlation exists between these factors, and between scans taken in supine and prone orientations. These descriptors may have implications for conventional colonoscopy and CT colonography training and performance. Furthermore, they provide a quantitative description of the colonic environment that can be used for development of new colonoscopy devices, from incremental advances to current colonoscope technology to next-generation robotic systems [24]. An understanding of the diameter and tortuosity of the colon is particularly relevant for the future of these systems.

2. Materials and methods

2.1. Patient preparation and data acquisition

A single medically qualified researcher, under supervision of a consultant radiologist, searched the publically available TCIA (http://cancerimagingarchive.net/, sponsored by the Cancer Imaging Program, DCTD/NCI/NIH) retrospectively and selected clinical studies that demonstrated reportedly healthy colons in both prone and supine positions (no patients were excluded from this population). In total, 24 patient studies were selected at random: 12 men and 12 women. The average age of the sample was 54.8 $\pm$ 4.7 years ranging from 50 to 65.

The complete imaging methodology has been described previously [25]. Briefly, all patients had undergone standard 24-hour colonic preparation with stool tagging following by the oral administration of 90 mL of sodium phosphate (Phospho-soda, Fleet Pharmaceuticals) and bisacodyl tablets (10 mg) to reduce the presence of any residual stool or fluid. The final step was to ingest a 6-oz (177 mL) glass of liquid containing at least 5 mL and up to 60 mL of water-soluble iodinated oral contrast material (diatrizoate meglumine and sodium diatrizoate, Gastroview, Mallinckrodt Imaging) the night before the examination to label any residual colonic fluid. All examinations were performed using at least a 16-channel helical CT scanner with 0.8 mm collimation, 1 mm reconstruction interval, matrix 512$\times$512, 50 effective mAs, peak voltage of 120 kV, and B30f convolution kernel. Data were obtained in the supine and prone positions; 1 mg of glucagon was administered subcutaneously 7–15 min before the CT examination unless contraindicated or refused by the patient. Colonic distention was achieved with an automated carbon dioxide insufflator (PROTOCO2L, E-Z-EM).

2.2. Image segmentation and centreline

We developed a multistage algorithm to process the CT data and generate a 3-D volumetric polygon mesh, with an associated centreline, to be used in a quantitative description of the colon morphology. The first stage employs clinical visualization software (Amira, FRI Visualization Sciences Group, USA) to identify low attenuation voxels that represent gas in the colon lumen using a 3-D region growing algorithm [26]. An intensity based threshold of less than -800HU was experimentally determined for each dataset (grey-level histogram of the abdominal CT dataset) to segment the lumen's details. Increasing this threshold allows more details of the lumen interior to be visualized, however, too high threshold may result in erroneous inclusion of the surrounding tissue. Because the colon is not the only gas-filled organ, user-defined seed points were placed in the lumen to spatially isolate the colon. If the value of the connected voxels were less than the intensity threshold, they were included in the region. This algorithm stopped when no more voxels remain in the collected neighbours. Two datasets required additional user