Original Article

A quantitative validation of segmented colon in virtual colonoscopy using image moments

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ABSTRACT

Background: Evaluation of segmented colon is one of the challenges in Computed Tomography Colonography (CTC). The objective of the study was to measure the segmented colon accurately using image processing techniques.

Methods: This was a retrospective study, and the Institutional Ethical clearance was obtained for the secondary dataset. The technique was tested on 85 CTC dataset. The CTC dataset of 100–120 kVp, 100 mA, and ST (Slice Thickness) of 1.25 and 2.5 mm were used for empirical testing. The initial results of the work appear in the conference proceedings. Post colon segmentation, three distance measurement techniques, and one volumetric overlap computation were applied in Euclidian space in which the distances were measured on MPR views of the segmented and unsegmented colons and the volumetric overlap calculation between these two volumes.

Results: The key finding was that the measurements on both the segmented and the unsegmented volumes remain same without much difference noticed. This was statistically proved. The results were validated quantitatively on 2D MPR images. An accuracy of 95.265±0.4551% was achieved through volumetric overlap computation. Through paired t-test, at α = 5% statistical values were p = 0.6769, and t = 0.4169 which infer that there was no much significant difference.

Conclusion: The combination of different validation techniques was applied to check the robustness of colon segmentation method, and good results were achieved with this approach. Through quantitative validation, the results were accepted at α = 5%.
At a glance of commentary

Scientific background on the subject

CT Colonography is a new noninvasive medical imaging technology for the analysis of colon polyps using computer software. Accuracy of polyp measurement is completely dependent on the accuracy of colon segmentation. Most of the segmentation techniques are application-specific, and it is difficult to achieve a ubiquitous solution.

What this study adds to the field

Volumetric measurement of any anatomy is the tough task before the radiologist either before segmentation or thereafter. The contribution in this work helps in measuring the segmented colon more accurately in 3D space through three different approaches. This helps in accurate colon polyp analysis.

Materials and methods

The CT Colonography dataset was downloaded from The Cancer Imaging Archive (TCIA), USA [9–11]. The images were of good diagnostic quality and were acquired with the standard CTC protocol ACRIN 6664 [12]. Empirical testing includes eighty-five samples (n = 85) of good diagnostic quality images. The imaging parameters were, 8 slices MDCT images, Feet First Supine and Feet First Prone position scans, ST (Slice Thickness) = 1.25mm and 2.5mm, imageresolution = 512 × 512, ~1000 images/patient, mA = (200 – 300), 120 kVp and age = (40–80) years acquisitioned from SIEMENS Somatom™ (SIEMENS Healthcare, Erlangen, Germany). The authenticity of the images was checked through DICOM [13,14] validation framework that we had implemented.

The proposed methodology is illustrated in Fig. 1. After CT image acquisition, the 3D volume is constructed in R³ dimension from a set of images in R² and the colon is segmented and visualized with object-based visualization techniques. The statistical property of the segmented colon (moments) is calculated and analyzed in three different ways using the statistical analysis.

![Fig. 1 Illustration of the colon segmentation, distance measurement, and the validation techniques.](image-url)
Fig. 2 3D volume visualized through surface rendering technique with thick and thin slices. (A) 3.0 mm, (B) 1.5 mm, and (C) 0.75 mm. Thicker slices produce a kind of staircase effect and not the smooth transition in z-axis.

Fig. 3 A segmented colon visualized through direct volume rendering technique with variable slice thickness to demonstrate the staircase effect in the case of higher slice thickness. (A) 5.0 mm (stair case effect can be observed), (B) 3.0 mm, (C) 1.5 mm, and (D) 0.75 (there is no discontinuity in the colon boundary also). Improvement in the results can be observed when moved from thick to thin slices.

Fig. 4 The results of colon segmentation are presented systematically. (A) Unprocessed axial slice, (B) Noise reduction with adaptive smoothing, (C) Colonic segment boundary delineation, (D) DRR of unsegmented colon in Anterior to Posterior (AP) view, (E) DRR of segmented colon, (F) The volume rendered image of segmented colon and (G) The endoluminal view after segmentation.

Fig. 5 Object-based renderings in anterior to posterior direction used for validation. (A) An Un-segmented DRR, (B) First voxel hit of segmented colon, (B, D) Direct volume rendering of un-segmented and segmented colon, respectively.
**Calculation**

**Volume reconstruction**
Before segmenting the Volume of Interest (VOI), the 2D slices are preprocessed with contrast correction and gamma correction, and then the volume is reconstructed in 3D through linear interpolation. The Gamma correction, which decodes the stored pixel value in DICOM file to its actual displayable quantity [15], is applied. When the same image looks different in different display systems [16,17] without decoding it may lead to wrong clinical interpretation. The preprocessed image quality is compared with the image viewers’ syngo FastView™ [18] and the ImageViewer™. Due to the unequal size of the pixel in x and y direction, the linear interpolation technique is applied to create isotropic voxels. With this, a smooth transition is noticed near the surface of the structures when compared to

Fig. 6 Different object-based visualization methods (row 1 – before colon segmentation and row 2 – after colon segmentation in anterior to posterior direction). (A, E) First voxel hit, (B, F) Digitally reconstructed Radiograph, (C, G) Maximum Intensity Projection, and (D, H) Minimum Intensity Projection.

Fig. 7 Intra lumen distance measures shown on axial MPRs (row 1) and surface rendered images (row 2). (A) Distance in transverse colon. (B) In hepatic flexure and (C) In splenic flexure.
the higher ST [Fig. 2C]. The slices with higher ST are interpolated to 0.625 mm based on the size of the pixels, which are in the range (0.546875 – 0.9765625 mm). Fig. 2 shows the surface rendering of the unsegmented patient volume at variable ST. With the higher ST, a staircase effect, which does not show smooth transition of anatomies [Fig. 2A], can be observed. The images used for 3D volume reconstruction in Fig. 2 were acquired with 0.75 mm slice thickness (2000 CT images in a dataset). As it is not possible to expose the patient again to the radiation just to get the images with different slice thicknesses, for demonstration purpose we simulated this surface rendering with a variable ST by skipping the intermediate slice in Fig. 2B (reduced to 1000 slices) and 2A (reduced to 500 slices). In addition, the original number of slices can be reconstructed again as it is from these new sets of images through interpolation. Fig. 3 shows the direct volume rendering of the colon interior at variable ST. As moved towards the higher ST, the segmentation may lead to boundary leak problems [Fig. 3A] and may not give the accurate measurements. This suffices that without an interpolation technique, there are chances of inaccurate measurements of unequal voxel sizes.

Current state-of-the-art CT scanners produce the pixels of square shape. All the dataset in this study were acquired with the latest CT scanners such as SIEMENS Somatom Session™, Philips Brilliance™ and Toshiba Aquilion™. As per the DICOM conformance statement of these products, these scanners produce the pixels of square shape. Due to this, to achieve the voxel of equal size in all three directions of patient coordinate

![Fig. 8 Distance measured on DDR and first voxel hit of unsegmented and segmented volumes.](image-url)
system, the linear interpolation technique is applied (also, as only the slice thickness was different in z-axis when compared to the size of the pixel in x and y axis). However, the implementation supports the bilinear also. The testing did not include any such cases with rectangular pixels.

Colon segmentation
After preprocessing, a multi-step boundary based segmentation technique is applied for colon segmentation. It includes recognizing the colonic lumen with adaptive smoothing technique [Fig. 4B], boundary detection with canny operator [Fig. 4C], boundary delineation with Connected Component Labeling [Fig. 4C], and deciding the colonic segments using the prior information of colon distention grading [Fig. 4D] [6,19]. The relationship between the unsegmented volume [Fig. 4E] and the segmented colon [Fig. 4F] is given by Eq. (1), where $S$ is the original 3D volume ($V_0$), $S_0$ is the segmented colon ($V_S$) and $f$, $f_0$ are the voxel intensities and $c$ is the scene domain.

The results are visualized using the object based rendering methods on both the 2D and the 3D views using MPR and direct volume rendering techniques [20].

$$S = (c, f) \rightarrow S_0 = (c, f_0)$$

Measurement of segmented volume
Object based visualization methods [Fig. 6A–D] are widely used in medical imaging applications for validating the segmentation results. Examples are maximum intensity projection (MaxIP), minimum intensity projection (MinIP), first voxel hit and averaging (i.e. digitally reconstructed radiographs - DRR). These images can be generated in any direction of patient coordinate system (PCS). For example, DRR is used for registering the 2D x-ray image with the DRR image generated from 3D volume for position accuracy in the case of radiation therapy workflow. In this work, on 2D MPR, the DRR of the unsegmented colon and first voxel hit of segmented colon are used for measuring the distance in Euclidean space (Eq. (2)). The DRR and the first voxel hit images show the anatomy distribution of a 3D volume on a 2D image. This helps in measuring the segmented volume accurately in the required viewing direction. Fig. 5A shows the distribution of large intestine in AP direction on a DRR image. The evaluation of the segmented VOI is implemented on DRR in three different ways. In all the cases, the distance is measured on axial, sagittal, and coronal views. The measurement and the results were validated through qualitative analysis by an expert radiologist. Only one observer’s decision was considered, as the multiple readers’ evaluation might not have impact [2,21,22].

$$d(u, v) = \sqrt{(uX - vX)^2 + (uY - vY)^2 + (uZ - vZ)^2}$$

The first voxel hit method draws the 2D picture from the 3D volume as and when the first voxel is encountered by the projection ray and the method stops piercing the 3D volume further. With this, it just gives the boundary details of the outer surface [Fig. 6A] and not the depth information of the

![Fig. 9 Volumetric overlap computation in the subset of volume. (A) The subset of slices considered, (B) The original axial slice showing the cross-sectional segment of the colon, (C) Manually drawn contour points, and (D) Boundary points delineated through the automated colon segmentation technique.](image-url)
anatomy [Fig. 6B] when applied on unsegmented colon whereas this method gives a proper visualization of the anatomy after the segmentation [Fig. 6E]. MaxIP gives the maximum of the voxel intensity along the projection rays. In case the anatomy has higher voxel intensities (>2000HU let us say) due to bone [Fig. 6C] or metal implant or due to oral contrast medium [Fig. 6G], it always gives the higher intensity values by skipping the intensities of the tissues [Fig. 6C]. MaxIP is applicable only in case when hard structures visualization is required. MiniIP is exactly similar to MaxIP, but it projects the minimum intensity instead of maximum. As the tubular structure of colon has either air or CO₂ inside the lumen, it appears black on the MPR images (its voxel intensity is < −900 HU or 0 gray value when displayed with specific window value). The miniP method always gives voxels in the dark region due to which it is very difficult to visualize the colon on 2D MPR [Fig. 6D, H]. All these methods are equally good, but they are application specific and in this context of colon analysis, the DRR of unsegmented colon and the first voxel hit of segmented colon have given good results when compared to MaxIP and MiniP.

Measuring intra lumen distance. For the post colon segmentation, the intra lumen distance (between opposite edges) is measured on the axial segment (measures in mm are shown in tooltip in Fig. 7) using an electronic caliper. This measure is compared with the geometrical feature (width automatically calculated during CCL) of the colonic segment on the corresponding slice. This is repeated for fifty slices. A significant difference between these two measures is determined using paired t-test method. The measurements remain the same. The first row in Fig. 7 shows the distance measured on axial MPR in hepatic flexures segment of colon and the second row shows the surface rendered image with Marching cube algorithm [23]. The double-headed arrow in row 2 illustrates the opposite sides of the colon—the distension of the ascending colon.

Distance between field of view and colonic segments in arbitrary direction. Similar to the previous technique, the distance is measured from the field of view (image boundary) to the colonic segments on a DRR image of the unsegmented and the first voxel hit image of the segmented colon. This feature helps to locate the position of colon from the periphery of the abdomen. Different cases are shown in Fig. 8. The measurements are distance between the rectum and the descending colon [Fig. 8A1], volume boundary to the recto sigmoid junction [Fig. 8A2], beginning of CT scan area to hepatic flexure [Fig. 8A3], from volume boundary to the recto sigmoid junction in lateral direction [Fig. 8A4], from the CT couch top to the top of the transverse colon [Fig. 8A5] and from the patient skin to the front of the transverse colon [Fig. 8A6]. This technique was applied on eighty-five \( n = 85 \) CTC datasets acquired in both the supine and the prone positions. Table 1 shows the measures for ten patients. Overall 480 measurements \( \text{dof} = 479 \) were done. The measures are almost same with minor sub-millimeter variation. The distance on DRR of unsegmented volume is considered the Ground Truth \( (GT) \) and is denoted as \( x_i \). In addition, on the first voxel hit the image is represented as \( y_i \). paired t-test was applied to test the difference between \( x_i \) and \( y_i \). The mean of differences was equal to 0.0123. In the first group (i.e. \( x_i \)), \( \bar{\pi}_2 = 159.6587 \), \( \sigma^2_x = 87.0135 \), \( \text{SEM} = 3.9716 \), in group 2, \( \bar{\pi}_2 = 159.6463 \), \( \sigma^2_x = 87.1539 \). The t value at degrees of freedom \( \text{dof} = 479 \) is, \( t = 0.4169 \), the p value is 0.6769. Since \( p > 0.001 \), at \( \alpha = 5\% \), the small variation in the measures is not significant.

Computing the volume overlap between manually segmented colon and result of the automated method. In the third approach, the boundary points of manually drawn contour (GT) [Fig. 8C] and the automatically segmented colon [Fig. 8D] are compared through volumetric overlap (an example of Image moments). Since marking the boundary points is tedious for the entire volume and time-consuming, the overlap is calculated (Eq. (3)) for a subset of volume (only for 20 slices as in Fig. 9A). Certain validation techniques in medical imaging are empirically proved considering certain number of samples from the large population and the burden on the radiologist can be reduced to some extent with this approach [24–27]. Here, set A and set B represent the boundary points of the segmentation through GT and the proposed methods, respectively. This is where the computer algorithms outperform in delineating the boundary when compared to the manual methods. The mean of overlap was \( \bar{\rho} = 95.265\% \) with \( \sigma = \pm 0.4551\% \) and the accuracy of 95.265±0.4551% was achieved. Other volumetric measurement methods based on surface distance and volume difference are not applied, as they are computationally expensive for the entire volume.

\[
\text{Accuracy} = \frac{\text{AnB}}{\text{A} \cup \text{B}} \times 100
\]

In this study, all these distance measurement techniques were applied on CT Colonography images of 512 × 512 image resolution and we got only one high resolution (of 1024 × 1024 resolution) CT dataset. The smoothness of the surface of the structures was far better and we were able to measure the two ends more accurately when compared with the images of lower resolution. It is difficult to defend the better accuracy with high-resolution dataset unless the results are compared with the same patient dataset with lower resolution, let us say 512 by 512. However, the 3D visualization was more visually appealing in high resolution CT. The proposed techniques were tested in a high performance workstation (Intel Core i7® processor, Windows 2010 64 bit HE, 8 GB DDR3 RAM, and NVIDIA GPU).

**Conclusion**

Existing state-of-the-of-art segmentation techniques lack in accuracy of the results. This is an alternate method in the Euclidean space used to address the problem of accuracy in measurement. It was proved through the statistical analysis showing that the results were acceptable. This technique has to be evaluated on the bulk dataset (at least with \( n = 300 \)) to check its robustness. The measurements went wrong when the voxels of non-uniform sizes were considered and this proves that the voxel with isotropic resolution is necessary during the 3D volume reconstruction. The results cannot be compared with the existing CTC solutions as the dataset and
the segmentation techniques used are different. Instead, in an alternate approach, treated an expert radiologist’s manually measured values on the DRR of the unsegmented volumes as the ground truth and then compared with the measurements on the first voxel hit method of the segmented volumes achieved through the automated methods. This method can even be applied with the segmentation results of other anatomies based on the clinical need. Testing the method to know the difference when applied on images of different resolutions, measuring the distance between the two voxels on the physical object printed using a 3D printer, and comparing with the software results is the scope for the future work.

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Conflicts of interest
The authors declare that they have no competing interests.

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