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FULL PAPER

Application of gray level mapping in computed tomographic colonography: a pilot study to compare with traditional surface rendering method for identification and differentiation of endoluminal lesions

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Objective: In traditional surface rendering (SR) computed tomographic endoscopy, only the shape of endoluminal lesion is depicted without gray-level information unless the volume rendering technique is used. However, volume rendering technique is relatively slow and complex in terms of computation time and parameter setting. We use computed tomographic colonography (CTC) images as examples and report a new visualization technique by three-dimensional gray level mapping (GM) to better identify and differentiate endoluminal lesions.

Methods: There are 33 various endoluminal cases from 30 patients evaluated in this clinical study. These cases were segmented using gray-level threshold. The marching cube algorithm was used to detect isosurfaces in volumetric data sets. GM is applied using the surface gray level of CTC. Radiologists conducted the clinical evaluation of the SR and GM images. The Wilcoxon signed-rank test was used for data analysis.

Results: Clinical evaluation confirms GM is significantly superior to SR in terms of gray-level pattern and spatial shape presentation of endoluminal cases ($p < 0.01$) and improves the confidence of identification and clinical classification of endoluminal lesions significantly ($p < 0.01$). The specificity and diagnostic accuracy of GM is significantly better than those of SR in diagnostic performance evaluation ($p < 0.01$).

Conclusion: GM can reduce confusion in three-dimensional CTC and well correlate CTC with sectional images by the location as well as gray-level value. Hence, GM increases identification and differentiation of endoluminal lesions, and facilitates diagnostic process.

Advances in knowledge: GM significantly improves the traditional SR method by providing reliable gray-level information for the surface points and is helpful in identification and differentiation of endoluminal lesions according to their shape and density.

INTRODUCTION

Endoluminal lesions are common medical problems. They involve the gastrointestinal (oesophageal, stomach and colon cancer), genitourinary (uroepithelial and endometrial tumours), respiratory (lung cancer, tracheal and bronchogenic tumour) and vascular (coronary arteries disease, thrombovascular disease) systems. Endoscopic examination is essential for the diagnosis and treatment of endoluminal lesions. However, there are

many limitations associated with the traditional optical endoscopy (OE). First, OE cannot see through the endoluminal lesions, thus prohibiting evaluation of the nature of the lesion beneath its surface and its extraluminal extension. Second, OE cannot pass through the stenotic area. Distal lesion cannot be visualized. Third, OE is uncomfortable for patients and risk of complication including perforation, haemorrhage, infection and death.^{1,2}

Computed tomographic endoscopy (CTE) is an important computer-based alternative to traditional endoscopy. CTE is complementary to the real endoscope by providing earlier screening, allowing the visualization of some more additional anatomical features hidden behind the stenotic area or beneath the lesion surface, and surgical planning.

The traditional rendering technique used in CTE is surface rendering (SR), which has limitations. SR converts the volume of data into a simplified, binary form. For the purpose of surface estimation, voxels are usually assumed to be composed of a single tissue type, and gray-scale information is used only for local subpixel surface estimation; thus, a large portion of the available data is not represented in the image.³ No gray-level information (a range of CT number of a voxel in this study) of the surface in the endoluminal colon lesion, such as tumour, stool, fat or fluid contents, is displayed. Radiologists face great difficulty in differentiation between various intraluminal and/or extraluminal lesions using only traditional SR.⁴ Faecal material often looks like colonic tumour using the technique along without faecal tagging.⁴

Three-dimensional (3D) translucency volume rendering was used in computed tomographic colonography (CTC) to distinguish between true and false polyps. Such 3D rendering is more complex and needs evaluation because it requires the introduction of a transparency function needed to be set by the user. This function assigns blue, green, red and white colour channels, respectively, to areas of increasing attenuation.⁵ In brief, volume rendering technique is relatively slow and complex in terms of computation time and parameter setting.

Adequate interpretation of CTE requires a combination of 3D (endoluminal) views and two-dimensional (2D) views (axial images and multiplanar reformats). Seamless interaction between 2D images and 3D endoscopic fly-through techniques may be the best approach of data interpretation. Some proponents advocated a primary 3D read with 2D images evaluation for problem solving,⁶ whereas others used a primary 2D read with 3D fly through for problem solving.⁷ No technique has yet proved to be superior to any other consistently, and differences are seen regionally.⁸ Traditional SR 3D technique reflects only spatial shape but no gray-level information. The correlation of 2D images and 3D views is not sure in this condition, especially for two close points.

As most physicians and radiologists are familiar with the gray-level pattern of CT, in this article, we use CTC as an example and apply a new visualization technique to reduce the shortcoming of routine SR of CTC images and increase identification as well as differentiation of endoluminal lesions.

METHODS AND MATERIALS

The retrospective study of prospectively acquired data was approved by our institutional review board. All patients consented to the CT study, operation and pathological examination for suspicious colon lesions. They agreed to receive CT colonoscopy for better staging of lesions and diagnostic purpose.

Data acquisition

A spiral CT scan of the patient's abdomen was performed after the entire colon was distended with room air and tagging agent used beforehand. Because most patients had received colonoscopy and received CT scans for tumour staging, prone- and supine-position helical CT scans were performed 30 s later after intravenous contrast administration. With the advance of multiple-slices CT, the slice thickness of volume data can be reconstructed to 1.25 mm. All scans were performed using a 64-slice GE Light-Speed VCT® scanner (GE HealthCare, Milwaukee, WI).

Segmentation

One expert (S-JC) selected the value of the gray-level threshold suggested by the system based on some preset (default) values derived from the experts' past experience. Colon air is within a narrow range of the CT number. In theory, it is -1000 Hounsfield units (HUs). It is quite different from those of other soft tissues and not enhanced. The preset values for colon air segmentation in our study are also very close. Besides, the segmentation results are colour mapped in the 2D axial images and can be checked by the user to reassure that the soft tissues of the abdomen and air distended colon can be correctly segmented.

Finding the surface point of the object and surface rendering

The marching cube is an algorithm for detecting isosurfaces in volumetric data sets. It has been used to find the surface points of the colon in many CTC applications.⁹ The basic notion is that a voxel (cube) can be defined by the pixel values at the eight corners of the cube. The surface intersects those cube edges where one vertex is outside the surface (one) and the other is inside the surface (zero). Because of two different symmetries of the cube, there are 15 patterns in ways how a surface can intersect the cube (Figure 1).¹⁰ By determining which edges of the cube are intersected by the isosurface, we can create triangular patches which divide the cube between regions within the isosurface and regions outside. By connecting the patches from all cubes on the isosurface boundary, we get a surface representation.¹¹ For the comparison of below gray level mapping (GM) of the same surface points, we did not apply special filters to remove noise, detail and smooth SR images as usual commercial package did.

The GM method: gray level mapping of the surface points

In order to reveal the gray level of the surface point of an endoluminal lesion for better 2D correlation and differentiation, the gray level of each vertex of the object surface computed through the marching cube algorithm is assigned to the gray level of the nearest voxel inside the surface. Consequently, the radiologists can visualize not only the shape of the object but also the density of the object simultaneously for a more precise diagnosis. The GM algorithm is applied to CTC images and is compared with SR of CTC. The visual effects of these are evaluated from the clinical point of view in below paragraph.

Clinical evaluation

From March 2010 to May 2013, 33 various endoluminal cases were evaluated in this study from 30 patients (13 males and 17

Figure 1. The concept of the marching cube algorithm: 15 patterns of surface intersections of a cube.

females, with ages ranging from 31 to 90 years), consisting of 16 cases of potential malignancies (including polyps or cancers proved by colonoscopic biopsy) and 17 cases of other benign conditions (stool, fluid retention, calcification/tagging agent or ileocaecal valves). Two radiologists (C-CH and S-CH) with more than 10 years' experience in reading abdominal CT were invited for the retrospective evaluation. They were asked to read first the SR images, then the GM and original CT images sequentially case by case. Both radiologists were blinded to the other's results. Three evaluation criteria were used for the evaluation of the SR and GM images, respectively: (1) spatial shape (whether the viewer can easily recognize the shape of the object), (2) gray-level pattern (whether the viewer can easily know the gray-level pattern of the object surface) and (3) the correlation between the 3D surface presentation and the original 2D CT images for lesion identification and classification (benignity and potential malignancy). A three-point scale was used for the evaluation: Score 1, poor; Score 2, fair; and Score 3, excellent.

Another two gastrointestinal radiologists (C-WL and Y-RC) with 20 and 8 years' experience were invited to perform clinical performance measurements of the SR and GM images. Those 2 types of images of each case were presented side-by-side to the radiologists for direct comparison between the two rendering methods. The radiologists were asked to judge benignity or potential malignancy of each case by its 3D SR and GM CTC images alone without cross reference to the 2D images. Both radiologists were also blinded to the other's results.

The Wilcoxon signed-rank test was used for data analysis. Sensitivity, specificity and diagnostic accuracy were compared between the two display methods. Differences with p -values of <0.05 were considered significant. All statistical analyses were performed using the Statistical Package for the Social Sciences statistical software for Windows®, SPSS® v. 17 (IBM Corp., New

York, NY; formerly SPSS Inc., Chicago, IL). A probability of $p < 0.05$ was considered statistically different.

Comparing running times

Our computations were carried out on a Windows personal computer with 3.10-GHz Intel® single-core central processing unit and 4-GB random-access memory. All the algorithms were implemented using visual C++. Cases with 50, 100 and 200 image slices were used for the tests. The runtime of SR is calculated after the selection of thresholding for segmentation and the runtime of GM calculates the time period from SR to GM.

RESULTS

The comparison results of the traditional surface rendering and gray-level mapping images

A traditional SR image (Figure 2a) and the corresponding GM images of colon cancer (arrowhead) and stool (arrow) are shown in Figure 2b. Figure 3a shows a prominent fold in the SR endoluminal view. The fat density of the fold lesion (Figure 3b, cross) can be seen more clearly in GM images than in SR images (Figure 3a). The 2D CT image shows fat contents of a lipomatous colon lesion (Figure 3c). Figure 4a shows a SR endoluminal image with an area of layered and mottled appearance. The corresponding GM image shows higher density tagged fluid and faecal material of the above area (Figure 4b, arrows). A polypoid lesion is shown in SR image (Figure 5a). The calcified contents or tagging agents of the above lesion are recognized in the corresponding GM images (Figure 5b) but not in the SR images (Figure 5a).

Clinical evaluation

For easy comparison and concise expression, the preliminary reader score differences of 16 cases of potential malignancy (polyps and tumours) and 17 cases of other benign conditions (stool, fluid retention, calcifications/tagging agents and

Figure 2. The computed tomographic colonography (CTC) images of a 78-year-old female with clinical diagnosis of colon cancer. Comparison of surface rendering (SR) and gray level mapping (GM) of colon cancer on CTC. (a) SR image of the colon cancer and stool. (b) GM of the same colon cancer (arrowhead) and stool (arrow) as (a) with the same view point. (c) The correlated two-dimensional (2D) position of the cancer (cross) in the axial image. Its Hounsfield unit (HU) is 39. (d) The correlated 2D position of stool (cross) in the axial image. Its HU is 5. The heterogeneous lower HU, rough surface of the stool, and higher HU, smooth surface of the tumour, can be seen more clearly in (b) but not in (a) and correlated well with 2D images (c, d).

ileocaecal valves) by the two radiologists are shown in the Table 1. Table 2 shows the summarized results using the original scale they used. The GM algorithm results in significant better gray-level patterns of endoluminal lesions than the SR in pathologically proven potential malignancy and benign conditions (one-tailed Wilcoxon signed-rank test: $p < 0.01$). The new algorithm also gets higher scores with even better lesion shape ($p < 0.01$) compared with the routine SR method (Table 2). Moreover, the GM algorithm can correlate the spatial shape and gray level of any 3D point (as the cross of Figures 2b, 3b and 5b) well with its 2D image (the cross of Figures 2c, 3c and 5c), whereas there is no gray-level information correlation for the traditional SR method. The correlation with 2D images, lesion

identification and classification of GM method are significantly better than those of SR images ($p < 0.01$) (Table 2). The evaluation results of the two radiologists are consistent.

Diagnostic performance

From the performance study of another two radiologists, (C-WL and Y-RC) both SR and GM have high sensitivity (SR: 93.8–100% and GM: 100%). However, the specificity and diagnostic accuracy of the GM method are significantly better than those of SR (specificity: 82.4% vs 17.6–23.5%; accuracy: 90.9% vs 54.5–60.6%) ($p < 0.01$) (Table 3). This means that although SR and GM are very sensitive in detection of benign and potential malignant endoluminal lesions, GM is much more capable to tell the lesions apart.

Figure 3. Images of a 62-year-old male. Colonoscopy revealed swelling of the ileocaecal valve with narrowing of terminal ileum in the health examination. Comparison of surface rendering (SR) and gray level mapping (GM) of the lipomatous area on computed tomographic colonography. (a) SR of a colonic lipomatous tumour. (b) GM of the same tumour and view position (cross). (c) An axial CT image of a correlated colonic lipomatous area (cross). The cross in (b) shows low HU (-56) as fat density that cannot be seen in (a).

Runtime comparison

Table 4 shows the runtime comparison between SR and GM. The time given under SR is the time taken for the generation of

the SR data, whereas that under the GM is the additional time needed for the generation of the GM data, the gray-level value of each vertex of the triangles that form the colon surface. Once the

Figure 4. Images of a 61-year-old male with history of colonic polyps and elevated carcinoembryonic antigen. Comparison of surface rendering (SR) and gray level mapping (GM) of fluid and faecal tagging in computed tomographic colonography. (a) SR of the above image shows the colon wall and tagged fluid with no density difference. (b) The higher density nature of the tagged fluid and mottled faeces (arrows) are best observed in the GM image. (c) The original CT image. The arrow indicates the high density of fluid and faecal tagging.

Figure 5. A 60-year-old male underwent CT scan due to sigmoid colon cancer found by colonography. Computed tomographic colonography (CTC) reveals a polypoid lesion in the ascending colon. Comparison of surface rendering (SR) and gray level mapping (GM) of the polyoid lesion on CTC. (a) Traditional SR of CTC shows a polypoid lesion (arrow) in the colon. (b) GM of the polyoid lesion shows a calcification or tagging agent (cross) over the colon wall. (c) The correlated two-dimensional (2D) point in axial image (cross). Its Hounsfield unit is 362. The high density cannot be seen and correlated with the associated 2D image in (a).

data are generated, the rendering processes of both GM and SR images are carried out by the hardware's graphics processing unit and can be interactively viewed in real time. From Table 4, the additional time for the GM data generation is very fast. It is very convenient for the users to shift from SR to GM mode.

DISCUSSION

The SR method is the routine display method for virtual CT endoscope. The shortcomings of this method include difficulty in accessing the internal nature of the intraluminal lesions, poor differentiation between lesions and the lack of the gray-level information that is in the original 2D images. The purpose of the study is to reduce these shortcomings by application of the new computer graphic rendering algorithm.

Because most radiologists and physicians are familiar with the gray-level changes on ordinary abdominal CT, we opt to use them instead of colour for visualization. The GM algorithm applies the gray level to the colon surface using the gray level of the voxel inside the object that is the nearest to the surface points of the object of interest.

With this new algorithm, not only the 3D shape of the object dose is preserved but also the gray-level pattern observed on its surface (Figures 2–5). We summarize and illustrate the new presentations of some target endoluminal lesions that are not ever observed in traditional 3D CTC images. *Tumour*: increased densities of the tumour (Figure 2b) due to contrast enhancement can be seen on GM CTC but not on SR images (Figure 2a). *Stool*: the shaggy appearance and heterogeneous lower surface densities of the stool due to no contrast enhancement can only be visualized in GM images (Figure 2b). *Fat*: if there are fat contents inside the protruding luminal area, they can only be observed in GM images (Figure 3b). *Calcifications or tagging agents*: they can only be observed in GM images (Figure 54b). *Fluid*: homogeneous low-density nature of fluid or high-density nature of tagged fluid and mottled faeces is best observed in the GM image (Figure 4b).

In consideration of the combination and correlation of 3D CTC and 2D views, the GM algorithm provides 3D view of surface points and their gray-level distribution simultaneously. The user can correlate the 2D images not only by spatial shape but also by the gray level. The crosses of Figure 3b,c show an example of the corresponding points with fat density in 2D and 3D images. The CT numbers of them show the same value of -56 . The shape and gray-level information helps identification of the corresponding points between the 2D and 3D images. The CT numbers reassure the above correspondence. We can correlate and identify smooth enhanced tumours, rough hypodense stool, calcifications, tagging agents and fluid by the same approach (Figures 2, 4 and 5). Compared with volume rendering or colour mapping of CTC, the GM method correlates the 2D images directly and natively. Based on our experiments, the radiologists whose major are abdominal CT can easily adapt to this new mapping since the mapping density is the same as what it is in 2D image.

GM is also better than SR to identify faecal and fluid tagging which will improve polyp detection and become the prerequisite of CTC.^{12,13} Figure 4 shows SR and GM of faecal and fluid tagging. The hyperdense aspect of residual stool and fluid remaining in the colon can be observed in the GM images (Figure 4b, arrows) but not in the SR images (Figure 4a).

To evaluate the response to GM CTC images of different radiologists, two radiologists conducted the clinical application, respectively. The SR and GM images are evaluated from the aspects of the spatial shape, gray-level pattern and correlation with the original CT images. Both the radiologists agree that only GM images can show the gray-level pattern of lesions. The spatial effect of the GM image is preserved and even better than that of SR while displaying the gray-level pattern at the same time. Most importantly, GM images are statistically better than SR in correlation with the original 2D image in a point-by-point fashion by the location and gray-level value. The GM will much facilitate clinical judgement of endoluminal lesions. The clinical

Table 1. Preliminary reader score differences of computed tomographic colonography:surface rendering (SR) vs gray level mapping (GM)

Group name	Parameter	SR superior	SR and GM equal	GM superior
Intraluminal calcification/tagging agent	Surface shape		++	
				**
	Gray-level pattern			++
				**
	2D correlation classification			++
				**
Fluid faeces	Surface shape		+++	
			*	**
	Gray-level pattern			+++
			*	**
	2D correlation classification		+	++
			*	**
Ileocaecal valve	Surface shape		+	+++
			*	***
	Gray-level pattern			++++
			*	***
	2D correlation classification		+	+++
			*	***
Stool	Surface shape		++++	++++

	Gray-level pattern		+	+++++

	2D correlation classification		+++	++++

Polyp	Surface shape		+++++	++
			*	*****
	Gray-level pattern			+++++
			*	*****
	2D correlation classification		+++	+++
			*	*****
Tumour	Surface shape		++	+++++

	Gray-level pattern			+++++

	2D correlation classification		+	+++++

2D, two-dimensional.

Each cross or star represents a case rated by a radiologist. The crosses in the upper subrow and stars in the lower subrow indicate the evaluation results of two different radiologists.

application study shows consistent and statistically better results of GM images than the traditional SR method in all the application aspects.

The GM can reduce confusion in 3D CTC. This could eliminate the need for 2D image evaluation and help the reading process to be faster. Another two radiologists (C-WL and Y-RC) were

Table 2. Image features and classification scores of endoluminal cases on computed tomographic colonography

Class	Case number	Rated feature	SR	GM	<i>p</i> -value ^a
Potential malignancy	16	Spatial shape	2	2.56	<0.01
			2	2.94	
		Gray-level pattern	1	2.06	<0.01
			1	2	
		2D correlation classification	2	2.75	<0.01
			2	2.94	
Other benignity	17	Spatial shape	2	2.41	<0.01
			2	2.88	
		Gray-level pattern	1	2	<0.01
			1	2	
		2D correlation classification	1.88	2.59	<0.01
			1.88	2.76	

2D, two-dimensional; GM, gray level mapping; SR, surface rendering.

Potential malignancy: polyps or tumours. *Other benignity*: stool, fluid, faeces, ileocaecal valves, intraluminal calcification.

The upper subrows and the lower subrows of every rated feature represent the average score scored by two different radiologists, respectively.

^aWilcoxon signed-rank test (one-tailed).

invited to evaluate the diagnostic performance of GM CTC. The GM is also helpful in the diagnostic process. Standard reading of CTC usually involves evaluation of both 3D and 2D image sets anyway. Because GM shows much higher specificity and diagnostic accuracy than SR in our study, readers require less time to cross reference with the 2D images to make a diagnosis if there is more certainty on GM 3D images such as calcification, tagging agents, fat density, wall enhancement or shaggy, low density. This will help the reading process be faster. Besides, if the correlation between 3D and 2D images becomes necessary, the GM images can correlate with the original 2D image in a point-by-point fashion for any suspicious area of an endoluminal lesion in CTC in terms of the location and gray-level correspondence. This kind of 2D correlation is more precise and efficient than that of SR since there is no gray-level information on the SR images.

There are limitations in our study. One is that we only evaluate the gray-level information of the surface of endoluminal lesions. Exploration of the gray-level change below the surface of the endoluminal lesion and colour mapping of its possible

malignant contents warrant future study to further facilitate discrimination of lesions. Another is that shading may interfere with the subtle gray-level change on the surface. Sometimes, the complex background formed by the GM of normal colon walls will interfere with the analysis of a focal lesion.

Another limitation in clinical evaluation should also be addressed. The order of images presentation or side-by-side images comparison may lead to potential bias. Two readers are not enough to study reader variability; however, both of them conducted consistently and statistically better results of the GM images than the traditional SR method in subjective measures, specificity and diagnostic accuracy.

CONCLUSION

In this preliminary study with limited cases, study design and readers, we have demonstrated that GM images present significantly better spatial shape and surface gray-level information of endoluminal lesions than SR images. GM also shows high and comparable sensitivity as SR, but the specificity

Table 3. Diagnostic performance of surface rendering (SR) and gray level mapping (GM)

Reviewer/display method	Sensitivity (95% CI)	Specificity (95% CI)	Diagnostic accuracy	<i>p</i> -value ^a
Reader 1				
SR	100% (0.806, 1)	23.5% (0.096, 0.473)	60.6%	0.103
GM	100% (0.806, 1)	82.4% (0.590, 0.938)	90.9%	<0.001
Reader 2				
SR	93.8% (0.717, 0.989)	17.6% (0.062, 0.410)	54.5%	0.601
GM	100% (0.806, 1)	82.4% (0.590, 0.938)	90.9%	<0.001

CI, confidence interval.

^aValues represent comparison between diagnostic performance of SR and diagnostic performance of GM.

Table 4. Runtime of surface rendering (SR) and gray level mapping (GM)

Image slices	SR (s)	GM (s)
50	3.73	1.12
100	6.72	1.62
200	14.66	3.44

s, seconds.

and diagnostic accuracy of the GM method are significantly better than those of SR. GM correlates with the original 2D image more precisely and efficiently than SR, as shown in the figures portion. We conclude GM facilitates 3D CTC

interpretation, increases the identification and differentiation of benign and possibly malignant endoluminal lesions. It can be applied to CT colonoscopy as a non-invasive alternative for patients unsuitable for traditional colonoscopy, early screening, evaluation of the possible endoluminal lesions distal to the stenosis and surgical planning. It is anticipated to apply our technique to other tubular organs to facilitate clinical diagnosis and management.

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