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Application of Pseudo-enhancement Correction to Virtual Monochromatic CT Colonography

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Abstract

In CT colonography, orally administered positive-contrast fecal-tagging agents are used for differentiating residual fluid and feces from true lesions. However, the presence of high-density tagging agent in the colon can introduce erroneous artifacts, such as local pseudo-enhancement and beam-hardening, on the reconstructed CT images, thereby complicating reliable detection of soft-tissue lesions. In dual-energy CT colonography, such image artifacts can be reduced by the calculation of virtual monochromatic CT images, which provide more accurate quantitative attenuation measurements than conventional single-energy CT colonography. In practice, however, virtual monochromatic images may still contain some pseudo-enhancement artifacts, and efforts to minimize radiation dose may enhance such artifacts. In this study, we evaluated the effect of image-based pseudo-enhancement post-correction on virtual monochromatic images in standard-dose and low-dose dual-energy CT colonography. The mean CT values of the virtual monochromatic standard-dose CT images of 51 polyps and those of the virtual monochromatic low-dose CT images of 20 polyps were measured without and with the pseudo-enhancement correction. Statistically significant differences were observed between uncorrected and pseudo-enhancement-corrected images of polyps covered by fecal tagging in standard-dose CT ($p < 0.001$) and in low-dose CT ($p < 0.05$). The results indicate that image-based pseudo-enhancement post-correction can be useful for optimizing the performance of image-processing applications in virtual monochromatic CT colonography.

Keywords

Dual-energy CT; Virtual monochromatic imaging; Pseudo-enhancement correction; CT colonography

1 Introduction

CT colonography (also known as virtual colonoscopy) has been recommended by the American Cancer Society as a screening option for colon cancer [1]. When performed well and interpreted by experienced radiologists, CT colonography provides a safe and accurate method for examining the complete region of the colon. However, poor bowel preparation,

suboptimal CT acquisition, and/or the presence of retained fluid and stool, may obscure or imitate polyps, thereby reducing the accuracy of CT colonography [2].

For confident detection of polyps, orally administered positive-contrast fecal-tagging agents are used in CT colonography for opacifying retained fluid and feces on the CT colonography images [3]. However, the presence of high-density fecal-tagging agent in the colon can also cause local pseudo-enhancement distortion of the CT values of adjacent soft-tissue structures on the reconstructed CT images [4]. The resulting uncertainty between the higher-than-expected CT values of pseudo-enhanced polyps and the lower-than-expected CT values of unclearly tagged fluid or feces presents significant challenges to automated image-processing algorithms, such as computer-aided detection (CAD) of polyps [2, 4, 5] and electronic cleansing of fecal-tagged materials [6]. Therefore, image-based post-correction algorithms have been developed for pseudo-enhancement correction of CT colonography images. The application of pseudo-enhancement correction has been shown to improve the detection performance of CAD and the accuracy of electronic cleansing in CT colonography [4, 6].

Dual-energy CT (DECT) [7] provides an alternative method for correcting pseudo-enhancement artifacts by the calculation of virtual monochromatic (VM) images. In principle, the VM images should be free from pseudo-enhancement and beam-hardening artifacts, and they can also provide quantitatively more accurate attenuation measurements than does single-energy CT [8, 9]. However, empirical studies have shown that VM images can still contain some pseudo-enhancement artifacts [8].

In this study, we investigated the potential benefit of the application of image-based pseudo-enhancement correction to VM images in standard-dose and low-dose DECT colonography. To perform low-dose DECT colonography without producing excessive noise on the low-energy images, the low-dose DECT images were reconstructed by use of iterative reconstruction (IRT).

2 Methods

2.1 Virtual Monochromatic (VM) CT Colonography

In DECT colonography, two CT colonography scans are acquired per scan position simultaneously at 140 kVp and 80 kVp energy levels. Given two basis materials, such as water and iodine, the CT values can be expressed as a linear combination of water and iodine as [9]

$$\begin{aligned} x_1 &= a + f_1 \times c, \\ x_2 &= a + f_2 \times c, \end{aligned} \quad (1)$$

where x_1 and x_2 are the observed low-energy (80 kVp) and high-energy (140 kVp) CT values, a is the water density, c is iodine concentration, and f_1 and f_2 are calibration measurements with iodine. The unknown parameters a and c can be calculated by solving of the equations based on the CT values acquired at the different energy levels.

The basis material images can be used to calculate VM images (Fig. 1). A CT value x_E of a VM image can be calculated by

$$x_E = a + c \times g(E), \quad (2)$$

where $g(E)$ is the mass attenuation coefficient derived from tabulated data at the desired VM energy E [10].

2.2 Image-Based Pseudo-enhancement Correction

Pseudo-enhancement correction can be performed retrospectively on reconstructed CT images by use of an image-based method [4]. In this method, the effect of pseudo-enhancement on a voxel p of an observed CT image is modeled as

$$v_p = \hat{v}_p + v_p^{\text{PEH}}, \quad (3)$$

where $\hat{v}_p$ is the true radio-density of the underlying material and v_p^{PEH} is the effect of pseudo-enhancement at p . To estimate v_p^{PEH} , we assume that the adjacent voxels of p are distributing some amount of pseudo-enhancement on p . The initial pseudo-enhancement energy emitted by nearby voxels q (and possibly by p itself to its surrounding voxels) is estimated as

$$r^0(p) = \sum_q \frac{C}{\sqrt{2\pi}\sigma_1(v_p)} \exp\left(-\frac{1}{2}\left(\frac{D(p,q)}{\sigma_1(v_q)}\right)^2\right), \quad (4)$$

where $\sigma_1(v_q)$ is a parameter function, $D(p, q)$ is the distance between voxels q and p , and C is a scaling constant. The CT value of p is updated according to $v_p^1 = v_p - r^0(p)$, and the process is repeated by estimation of the total distributed energy at iteration n as

$$r^n(p) = \sum_q \frac{r^{n-1}(q)}{\sqrt{2\pi}\sigma_2(r^{n-1}(q))} \exp\left(-\frac{1}{2}\left(\frac{D(p,q)}{\sigma_2(r^{n-1}(q))}\right)^2\right), \quad (5)$$

where $\sigma_2(r^{n-1}(q))$ is a second parameter function. The iteration over Eq. (5) ends when the distributed energy becomes negligible. Therefore, the final corrected value of p is calculated as

$$\hat{v}_p = v_p - v_p^{\text{PEH}} \approx v_p - \sum_{i=0}^n r^i(p). \quad (6)$$

3 Materials and Evaluation

Standard-dose and low-dose CT scans of 19 and 12 patients, respectively, were acquired by use of a DECT scanner (SOMATOM Definition Flash, Siemens) in supine and prone

positions. The CT slice thickness varied between 0.6 mm and 0.7 mm. For standard-dose DECT, the tube current was 82–159 mA at 140 kVp and 379–549 mA at 80 kVp. The standard-dose CT images were reconstructed by use of the filtered back-projection method. For low-dose DECT, the tube current was 25–36 mA at 140 kVp and 61–115 mA at 80 kVp. The CT images were reconstructed by use of the sinogram-affirmed iterative reconstruction method [11].

In total, there were 71 colonoscopy-confirmed polyps measuring 5–20 mm in their largest diameter, where the locations and sizes of the polyps on CT colonography images had been established by an expert radiologist. There were 51 polyps on the standard-dose DECT cases and 20 polyps on the low-dose DECT cases. The polyps were separated into two groups based on the presence of fecal tagging on their site: group “None” included polyps that were not affected by fecal tagging, and group “Covered” included polyps that were covered by fecal tagging. Figure 2 shows examples of polyps in the two groups.

To evaluate the effect of image-based pseudo-enhancement correction on VM images of pseudo-enhanced polyps, we calculated the VM images of standard-dose and low-dose DECT colonography data at 100 keV, 120 keV and 140 keV VM energies. A region-of-interest (ROI) was defined on each polyp as a 3-mm diameter sphere that was placed at the center of the polyp on the CT colonography images. Next, we measured the difference of the mean CT values within the ROI between the original VM images and pseudo-enhancement-corrected VM (VM-PEC) images. The statistical significance of the differences in CT values was compared by use of the paired *t*-test.

4 Results

Table 1 shows the differences of CT values between polyps in VM images and VM-PEC images. In low-dose DECT images, the means and standard deviations of the 15 polyps in group “Covered” at 100 keV, 120 keV, and 140 keV were 93.2 ± 95.9 HU, 82.0 ± 78.1 HU, and 69.6 ± 61.9 HU on VM images, respectively. On VM-PEC images, the means and standard deviations were 64.3 ± 56.6 HU, 59.8 ± 49.0 HU, and 52.1 ± 43.1 HU, respectively. The corresponding means and standard deviations of the 32 polyps in group “Covered” on standard-dose DECT images were 82.4 ± 90.3 HU, 72.0 ± 81.3 HU, and 60.5 ± 74.1 HU, respectively, and those on the VM-PEC images were 56.6 ± 71.0 HU, 52.0 ± 66.9 HU, and 45.7 ± 63.6 HU, respectively.

In both standard-dose and low-dose DECT images, significant differences were observed between VM images and VM-PEC images at all energy levels for group “Covered” in both standard-dose DECT ($p < 0.001$) and low-dose DECT ($p < 0.05$) images.

Figure 3 shows an example of the difference between VM images and VM-PEC images. The CT values of the VM-PEC image of the polyp were lower than those of the VM image at each energy.

Figure 4 shows the relationship of CT values between the VM images and VM-PEC images of each polyp for group “Covered”. The horizontal axis shows the case number and the vertical axis shows the mean CT values of VM/VM-PEC images of each polyp. The figure

indicates that the widest differences were observed between the highest CT-value measurements.

Figure 5 shows the example of group “None” in low-dose DECT images. In this case, the means and standard deviation of ROI in the polyp at original image, VM image, and VM-PEC image were -299.1 ± 404.2 HU, -299.2 ± 404.2 HU, and -307.6 ± 395.4 HU, respectively.

5 Discussion

At present, clinical CT colonography examinations are performed largely with conventional single-energy CT scanners. However, studies have indicated that the performance of automated image-processing applications, such as CAD and electronic cleansing, could be improved substantially by use of DECT colonography [12, 13].

Recently, there have been concerns about the theoretical risk of radiation-induced cancers by CT examinations [14]. In this study, we used low-dose DECT cases that have less than 1 mSv effective radiation dose per scan position. To compensate for the potential increment in image noise at low-dose scans, we used an IRT method for reconstruction of the CT colonography images. The results indicate that the application of IRT yields a feasible approach for performing low-dose DECT colonography.

Figure 4 shows how the effect of pseudo-enhancement correction is increased on the VM-PEC images as the pseudo-enhanced CT values increase to values of over 50 HU on VM images. The largest corrections were observed for polyps in the tagging group “Covered” on low-dose and standard-dose DECT images (Table 1) that are clearly pseudo-enhanced in the VM images. On the other hand, in standard-dose DECT, there is no difference in the CT values of polyps between the VM and VM-PEC images in group “None”.

However, for low-dose DECT images that were reconstructed by use of an IRT algorithm, the CT values of polyps in group “None” were slightly different before and after the pseudo-enhancement correction, even though pseudo-enhancement correction is not expected when tagging is not present. Figure 5 shows an example of such a case. In this example, the local pseudo-enhancement correction is performed on a polyp, because some of the CT values within the polyp are higher than 100 HU on the CT image. In principle, the soft-tissue material of polyps should have CT values of less than 100 HU. The unusually high CT values of the polyp might reflect the use of the IRT algorithm over conventional reconstruction by filtered back-projection. This suggests that, for quantitative imaging, image-processing methods such as pseudo-enhancement correction may need to be optimized specifically for low-dose DECT which is likely to be used more often in clinical practice than standard-dose DECT.

This study had several limitations. One of the limitations was that the pseudo-enhancement correction algorithm was developed originally for single-energy CT colonography examinations performed at 140 kVp and calibrated for a different CT scanner than that used in this study. For optimal results, the method should be recalibrated for the same CT scanner and energy levels that are used for measurements. Another limitation of this study was that

we used clinical CT colonography cases with the expectation that true CT values of soft-tissue polyps should range approximately between 0 and 100 HU. Ideally, we should perform the experiments on a phantom where the undistorted CT values of colonic structures are known precisely.

The results of this study suggest that the application of pseudo-enhancement correction can be useful for optimizing the performance of CAD and electronic cleansing in virtual monochromatic DECT colonography. Thus, further studies that demonstrate the effectiveness of these methods are warranted.

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Fig. 1.
Calculation of virtual monochromatic images [9].

Fig. 2.

Examples of polyps in the two fecal-tagging groups. (a) A polyp in group “None” on low-dose DECT (140 kVp). (b), (c) Polyps in group “Covered” on low-dose DECT. (d) A polyp in group “None” on standard-dose DECT (140 kVp). (e), (f) Polyps in group “Covered” on standard-dose DECT images.

Fig. 3. Comparison of the CT value of VM images and pseudo-enhancement-corrected VM images. (a) Example of a VM image at 120 keV. The arrow indicates the location of the line samples shown in (c). (b) Example of a pseudo-enhancement-corrected image of (a). (c) The line samples of each image. (d) The enlarged image of a box shown in (c).

Fig. 4. The relationship of CT values between VM images and VM-PEC images for group "Covered". (a) 120 keV of low-dose DECT images. (b) 120 keV of standard-dose DECT images. The horizontal axis is the case number and the vertical axis shows the mean CT values of each ROI.

Fig. 5. Comparison of the CT values of original 140 kVp image and the corresponding 140 keV VM /VM-PEC images in low-dose CT colonography. (a) Original image acquisition at 140 kVp. The arrow indicates the location of polyp. (b) the 140 keV VM image of (a). (c) Pseudo-enhancement-corrected 140 keV image of (b). (d) The relationship of the CT values between images (a) and (b)/(c). Each point represents a CT value sampled from the polyp.

Table 1

Paired *t*-test results of the difference between VM images and VM-PEC images.

	Tagging group	Cases	keV	Paired differences						
				95 % Confidence interval of the difference						
				Mean	SD	Lower	Upper	t	p-value	
Low-dose DECT	None	5	100	18.9	-3.7	-3.1	41.0	2.4	0.0757	
			120	14.0	-1.2	1.6	26.3	3.1	0.0348	
			140	12.0	2.0	5.6	18.4	5.2	<0.01	
	Covered	15	100	28.9	39.3	4.6	53.1	2.6	0.0229	
			120	22.2	29.2	3.9	40.4	2.6	0.0211	
			140	17.5	18.8	4.9	30.1	3.0	<0.01	
Standard-dose DECT	None	19	100	0.9	0.9	0.1	1.7	2.3	0.0324	
			120	0.7	0.7	0.0	1.3	2.2	0.0418	
			140	0.6	0.6	0.0	1.1	2.2	0.0411	
	Covered	32	100	25.8	19.3	14.7	36.8	4.8	<0.001	
			120	20.1	14.4	11.3	28.8	4.7	<0.001	
			140	14.9	10.5	8.1	21.6	4.5	<0.001	