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Computer-Aided Detection of Colorectal Lesions with Super-Resolution CT Colonography: Pilot Evaluation

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Abstract

Reliable computer-aided detection (CAdE) of small polyps and flat lesions is limited by the relatively low image resolution of computed tomographic colonography (CTC). We developed a sinogram-based super-resolution (SR) method to enhance the images of lesion candidates detected by CAdE. First, CAdE is used to detect lesion candidates at high sensitivity from conventional CTC images. Next, the signal patterns of the lesion candidates are enhanced in sinogram domain by use of non-uniform compressive sampling and iterative reconstruction to produce SR images of the lesion candidates. For pilot evaluation, an anthropomorphic phantom including simulated lesions was filled partially with fecal tagging and scanned by use of a CT scanner. A fully automated CAdE scheme was used to detect lesion candidates in the images reconstructed at conventional 0.61-mm and at 0.10-mm SR image resolution. The proof-of-concept results indicate that the SR method has potential to reduce the number of FP CAdE detections below that obtainable with the conventional CTC imaging technology.

Keywords

Iterative reconstruction; super-resolution; domain decomposition; computer-aided detection; virtual colonoscopy

1 Introduction

Although computed tomographic colonography (CTC) is able to detect large advanced polyps at high sensitivity [1], the detection of small polyps 6 – 9 mm and flat lesions has been shown to be more challenging [2]. In principle, computer-aided detection (CAdE) systems may be able to detect such lesions at high sensitivity, but the presence of poorly tagged stool and thin layers of fecal tagging that imitate the shape and radiodensity of lesions makes it challenging to differentiate the detections of true lesions reliably from false positives (Fig. 1) [3]. Therefore, even if CAdE can yield high detection sensitivity, the number of associated FP CAdE detections is too high for routine clinical practice.

In this study, we considered the reconstruction of super-resolution (SR) images for improving the conspicuity of subtle lesions and for identifying partial-volume artifacts that imitate lesions. The enhanced detail provided by the SR images could be used to improve the detection accuracy of CAdE beyond that obtainable with conventional CTC.

2 Methods

2.1 Super-Resolution CTC (SR-CTC)

To calculate SR images, we use model-based iterative CT image reconstruction (IRT) [4]. The reconstruction problem can be formulated as

$$\hat{f} = \operatorname{argmin}_f E_f(g, f) + \alpha E_r(f), \quad (1)$$

where $E_f(g, f)$ is a data fidelity term between image f and sinogram g , $E_r(f)$ is a regularization term, and α is the weighting term. The data fidelity term can be formulated as

$$E_f(g, f) = \|g - H f\|^2 = \sum_j |g_j - H f|^2, \quad (2)$$

where H is the system matrix. The general form of the regularization term can be formulated as the L_p norm

$$E_r(f) = \|L f\|^p = \sum_i |L f_i|^p. \quad (3)$$

With $L = \nabla$ and $p = 1$, Eq. (3) becomes a total-variation regularizer that suppresses noise and preserves edges in the reconstructed images. To minimize the energy functional of Eq. (1), a lagged diffusivity fixed-point method is used for iterative approximation of the cost by a weighted quadratic cost and by solving for the resulting linear normal equations using pre-conditioned conjugated gradient iterations [5].

To reconstruct SR images, we combine Eq. (1) with fractional super-sampling of the sinogram space, where each simulated ray for a single detector is over-sampled with a bundle of casted virtual rays. By collection of the variables into a vector-matrix equation, the SR images can be calculated as the solution of Eq. (1).

The IRT method is computationally demanding, but the computation time is reduced by parallelization of the ray projections and by use of a fast non-iterative version of Siddon's radiological ray-tracing algorithm [6].

2.2 Computer-Aided Detection (CADe) System

Figure 2 presents an overview of the steps of the fully automated CAdE system. The input CTC images are interpolated to isotropic resolution, and a thick region encompassing the region of colon surface is extracted from the CTC images [7]. Lesion candidates are detected by use of volumetric shape features [8]. Level-set segmentation is used for extracting the regions of detected lesion candidates [9]. For false-positive (FP) reduction, several advanced texture and shape features are calculated from the regions of lesion candidates [10]. Based on the features, a random-forest classifier is used to calculate the lesion-likelihood of each lesion candidate. The lesion candidates that yield the highest likelihood represent the final output of the CAdE system [11].

2.3 Application of SR-CTC to CAdE

A complete SR image reconstruction of the input CTC image data would be computationally demanding and would require large amounts of memory. Because the CAdE system can already detect 99 – 100% of all visible lesions on conventional CTC images (with a large number of FP detections) [12], we can reduce the computational demands of the SR-CTC scheme substantially by performing iterative reconstruction only for regions of interest (ROIs) that contain the initially detected lesion candidates. The other regions of CTC images need not to be considered.

Figure 3 shows an overview of the proposed detection scheme. First, the CTC images are reconstructed from original sinograms by use of the filtered back-projection (FBP) method at conventional CTC image resolution, and the CAdE is used to detect the regions of initial lesion candidates from the reconstructed images.

Next, we use a projection-driven technique to reduce the reconstruction problem to a set of ROIs that encompass the detected lesion candidates and their immediate neighborhood region [13]. In the technique, the ROIs are reprojected to the sinogram domain. By nullification of the locations of ROIs, we create a set of projections that correspond to the relevant ray-projection field excluding the ROIs. By subtraction of this background region from the data, we facilitate iterative reconstruction of the ROIs at SR by the methods of Section 2.1. The technique makes the SR computations orders of magnitude smaller than what would be required by a full algebraic reconstruction.

Finally, the reconstructed SR images are reviewed by the CAdE scheme to reduce FP detections. The output of this step determines the output of the CAdE scheme.

3 Evaluation

An anthropomorphic human-colon phantom (The Phantom Laboratory Inc., Salem, NY) was designed to imitate features observed in clinical human CTC scans (Fig. 4a). The phantom was filled partially with an iodine-based tagging agent (Oxilan, Guerbet, Bloomington, IN) and with cereal to imitate residual materials (Fig. 4b). The phantom was scanned in supine position with a dual-energy CT scanner (SOMATOM Definition Flash, Siemens Healthcare) at tube currents of 22 mA (140 kVp) and 106 mA (80 Kvp). The CT scanner reconstructed the conventional CT images of the scans by use of a conventional FBP algorithm at a 0.61-mm image resolution. Only the 140 kVp scan was used for the reconstructions — dual-energy reconstructions were not considered.

For pilot evaluation of the proposed ROI and SR methods, the raw sinogram data was downloaded from the CT scanner. To simplify the experiments, we reconstructed the complete region of transverse colon from the sinogram data at SR (Fig. 4c). The locations of lesion candidates that the CAdE system detected on conventional CTC images were mapped to the SR-CTC images.

4 Results

The reconstructed region of transverse colon contained 6 simulated lesions. There were 2 pedunculated polyps, 2 sessile polyps, and 2 flat lesions. They measured between 8 – 16 mm in largest diameter. All 6 lesions were detected correctly by the CAdE system on conventional CTC images. The use of SR did not cause CAdE to reject any of the true positives.

The CAdE system detected one FP lesion candidate on conventional CTC images (Fig. 5a). Magnification of the detected region at conventional image resolution (Fig. 5b) indicates that the detection could be a small polyp on a fold. The relatively low CT value of the detection on conventional CTC images (≈ 100 Hounsfield units (HU)) further suggests that the detection may be a soft-tissue lesion.

However, on the corresponding SR image (Fig. 5c), the detection has a relatively high radiodensity (200 HU). This indicates that the detection is caused by a small round droplet of fecal tagging on fold. Therefore, the use of SR-CT enabled the CAdE system to exclude the lesion candidate confidently as a FP detection.

Figure 6 demonstrates the difference between conventional and SR images in the virtual endoscopic rendering of a simulated 8-mm polyp. Same rendering parameters were used in both cases. It is evident that the SR-CTC image shows the bowel surface in more detail than the conventional CTC image.

5 Discussion

The limited image resolution of conventional CTC makes it challenging to differentiate subtle lesions reliably from tagged feces and their partial-volume effects. This presents a potential limit to the detection accuracy of conventional CAdE. However, enhancement of the lesion candidates by use of SR-CTC could be used to overcome this limitation.

The ROI reconstruction problem that was considered in this study is different from ROI tomography. In ROI tomography, the reconstruction is based on a local projection of the target region, whereas in this study, we assumed access to the entire projection data. Thus, the proposed method presents a practical post-acquisition approach for ROI-focused CTC.

The proposed SR method makes it possible to reconstruct images of detected ROIs at a resolution that is beyond those of the nominal resolution of the CT detector and the capabilities of conventional image reconstruction provided by the CT scanner. Thus, our approach is different from providing detected locations back to the CT scanner for performing conventional image reconstruction.

The SR-CTC may also have other uses than improvement of the standalone detection accuracy of CAdE. Several studies have shown that radiologists can incorrectly dismiss correct CAdE prompts of true lesions [14]. By providing enhanced SR-CTC images of the CAdE detections, radiologists might be able to use the CAdE prompts more effectively.

In this study, we reconstructed SR images of ROIs by use of IRT. The IRT has also several other advantages over the conventional FBP method. It can be used to reconstruct CT images at a substantially lower radiation dose than that of conventional standard-dose FBP, without impairing image quality. It can also be used to correct for beam-hardening artifacts that may appear at low radiation doses or with high concentrations of fecal-tagging agents [15].

This pilot study had several limitations. First, the proposed method was tested on an anthropomorphic phantom only. Second, the evaluation was largely anecdotal, because all true lesions were detected and there was only one false positive to be excluded by the use of SR. Therefore, it is premature to perform a formal receiver-operating characteristic (ROC) analysis for evaluating the CAdE system performance and for comparing with expert reading.

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References

1. Johnson C, Chen MH, Toleday A, Heiken J, Dachman A, Kuo M, et al. Accuracy of CT colonography for detection of large adenomas and cancers. *N Engl J Med*. 2008; 359:1207–1217. [PubMed: 18799557]
2. Park S, Kim S, Lee S, Bogoni L, et al. Sensitivity of CT colonography for nonpolypoid colorectal lesions interpreted by human readers and with computer-aided detection. *Am J Roentgenol*. 2009; 193:70–78. [PubMed: 19542397]
3. Näppi J, Yoshida H. Virtual tagging for laxative-free CT colonography: pilot evaluation. *Med Phys*. 2009; 36:1830–1838. [PubMed: 19544802]
4. Do, S.; Cho, S.; Karl, W.; Kalra, M.; Brady, T.; Pien, H. Accurate model-based high resolution cardiac image reconstruction in dual source CT. *IEEE International Symposium on Biomedical Imaging: From Nano to Macro*; Boston: IEEE Press; 2009. p. 330-333.
5. Do S, Karl W, Liang Z, Kalra M, Brady T, Pien H. A decomposition-based CT reconstruction formulation for reducing blooming artifacts. *Phys Med Biol*. 2011; 56:7109–7125. [PubMed: 22025109]
6. Jacobs F, Sundermann E, De Sutter B, Christiaens M, Lemahieu I. A fast algorithm to calculate the extract radiological path through a pixel or voxel space. *J Comput Inf T*. 1998; 6:89–94.
7. Näppi J, Yoshida H. Fully automated three-dimensional detection of polyps in fecal-tagging CT colonography. *Acad Radiol*. 2007; 25:287–300. [PubMed: 17307661]
8. Yoshida H, Näppi J. Three-dimensional computer-aided diagnosis scheme for detection of colonic polyps. *IEEE Trans Med Imaging*. 2001; 20:1261–1274. [PubMed: 11811826]
9. Näppi J, Frimmel H, Dachman A, Yoshida H. Computerized detection of colorectal masses in CT colonography based on fuzzy merging and wall-thickening analysis. *Med Phys*. 2004; 31:860–872. [PubMed: 15125004]
10. Näppi J, Yoshida H. Automated detection of polyps in CT colonography: evaluation of volumetric features for reduction of false positives. *Acad Radiol*. 2002; 9:386–397. [PubMed: 11942653]
11. Näppi, JJ.; Regge, D.; Yoshida, H. Comparative performance of random forest and support vector machine classifiers for detection of colorectal lesions in CT colonography. In: Yoshida, H.; Sakas, G.; Linguraru, MG., editors. *Abdominal Imaging 2011 LNCS*. Vol. 7029. Springer; Heidelberg: 2012. p. 27-34.
12. Näppi J, Yoshida H. Ranking of polyp candidates for CAD in CT colonography. *SPIE Medical Imaging 2005: Physiology, Functions, and Structure from Medical Images*. 2005; 5746:432–439.

13. Do, S.; Liang, Z.; Karl, W.; Brady, T.; Pien, H. Proc SPIE Medical Imaging: Physics of Medical Imaging. Vol. 6913. SPIE Press; 2008. A projection-driven pre-correction technique for iterative reconstruction of helical cone-beam cardiac CT images.
14. Taylor S, Robinson C, Boone D, Honeyfield L, Halligan S. Polyp characteristics correctly annotated by computer-aided detection software but ignored by reporting radiologists during CT colonography. Radiology. 2009; 253:715–723. [PubMed: 19789221]
15. Hsieh J, Molthen R, Dawson C, Johnson R. An iterative approach to the beam hardening correction in cone beam CT. Med Phys. 2000; 27:23–29. [PubMed: 10659734]

Fig. 1. Virtual endoluminal CTC views of (a) a true 20-mm flat lesion and (b) a thin layer of fecal tagging imitating a flat lesion. (c) Axial CTC image of a thin layer of fecal tagging on colon surface.

Fig. 2.

Overview of the computation steps of the CADe system. A set of initially detected lesion candidates is identified from the input CTC data, after which the final detected lesions are determined by use of machine learning methods.

Fig. 3.
Overview of the major steps of the SR-CTC detection scheme

Fig. 4.

(a) An axial image of the anthropomorphical phantom. (b) For experiments, the anthropomorphic phantom was filled partially with a tagging agent and scanned at low dose. (c) Axial image of the region of transverse colon reconstructed at SR by use of the proposed projection-driven technique.

Fig. 5.

(a) Axial CT image of CADe detections (red color) on the phantom. The arrow indicates a FP CADe detection on a fold. (b) Magnification of the indicated FP CADe detection (red circle) at a conventional 0.61-mm CTC image resolution. (c) Super-resolution image of the indicated FP CADe detection at a 0.1-mm image resolution. (a) (b)

Fig. 6. Virtual endoscopic view of a simulated 8-mm polyp. (a) Rendered at conventional 0.61-mm image resolution. (b) Rendered at 0.1-mm super-resolution.