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A comparison of material decomposition techniques for dual-energy CT colonography

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Abstract

In recent years, dual-energy computed tomography (DECT) has been widely used in the clinical routine due to improved diagnostics capability from additional spectral information. One promising application for DECT is CT colonography (CTC) in combination with computer-aided diagnosis (CAD) for detection of lesions and polyps. While CAD has demonstrated in the past that it is able to detect small polyps, its performance is highly dependent on the quality of the input data. The presence of artifacts such as beam-hardening and noise in ultra-low-dose CTC may severely degrade detection performances of small polyps. In this work, we investigate and compare virtual monochromatic images, generated by image-based decomposition and projection-based decomposition, with respect to CAD performance. In the image-based method, reconstructed images are firstly decomposed into water and iodine before the virtual monochromatic images are calculated. On the contrary, in the projection-based method, the projection data are first decomposed before calculation of virtual monochromatic projection and reconstruction. Both material decomposition methods are evaluated with regards to the accuracy of iodine detection. Further, the performance of the virtual monochromatic images is qualitatively and quantitatively assessed. Preliminary results show that the projection-based method does not only have a more accurate detection of iodine, but also delivers virtual monochromatic images with reduced beam hardening artifacts in comparison with the image-based method. With regards to the CAD performance, the projection-based method yields an improved detection performance of polyps in comparison with that of the image-based method.

Keywords

Dual-Energy CT; CT Colonography; Computer-Aided Design; Material Decomposition

1. INTRODUCTION

The idea of using dual energy computed tomography (DECT) is inspired by the principle that the attenuation of X-ray photons is material and energy dependent. By scanning the same object at two different spectra, material decomposition can be done on the images, and hence the composition of the underlying material in the object can be known [1]. As DECT enables the differentiation of materials, many clinically relevant imaging applications with high diagnostic accuracy have been developed and reported. This includes the detection of calcified plaques [2], the differentiation between acid-containing urinary stones and non-uric acid [3], and bone marrow edema assessment [4]. One application for DECT is CT colonography (CTC). In this clinical examination, patients are administered with contrast agents and then scanned with two different x-ray spectra (typically 80 kVp and 140 kVp) [5]. From these two x-ray spectra, a virtual unenhanced image can be produced. The combination of the contrast-agent enhanced and virtual unenhanced images is able to assist the detection of polyps, especially the ones obscured by residual fecal material in the colon. Further, CTC with the combination of computer-aided diagnosis (CAD) [6] may help detect small polyps [7], which are otherwise difficult to detect. While CAD has been reported to be able to detect lesions with high sensitivity [8–9], the success of this technique depends highly on the quality of the input image. The presence of artifacts such as beam-hardening artifacts is known to severely affect the detection performance [10].

In this work, we compare two different techniques for material decomposition. Further, by using results from the material decomposition, we generate virtual monochromatic images (VMIs) to reduce the appearance of beam-hardening artifacts, and we subjectively and objectively assess the quality of the VMIs.

2. METHODS

2.1 Material Decomposition

Image-Based Decomposition—The reconstructed images from the scanner are first transformed from the Hounsfield Units (HU) scale to the original linear attenuation coefficient measurement. The transformation was done for both high- and low-energy scans. Then, the rescaled images are decomposed into two materials, water and iodine, to determine the local concentration A_i of the material.

$$\begin{bmatrix} f_{1E1} & f_{2E1} \\ f_{1E2} & f_{2E2} \end{bmatrix} * \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} L_{E1} \\ L_{E2} \end{bmatrix},$$

where

$$f_i(E) = \frac{\mu}{\rho}(E) * \rho.$$

Here, A_i is the local fraction of the material, $L_{E(i)}$ is the linear attenuation coefficient of the input images at $E(i)$, $\mu/\rho(E)$ is the mass attenuation coefficient at energy E , and ρ the density of the material.

Projection-Based Decomposition—In CT, the measurement at the detector in the presence of two known materials with two different source spectra can be written as [1]

$$\begin{aligned} I_1(A_1, A_2) &= \int S_1(E) \exp[A_1(\vec{x})f_1 + A_2(\vec{x})f_2] dE, \\ I_2(A_1, A_2) &= \int S_2(E) \exp[A_1(\vec{x})f_1 + A_2(\vec{x})f_2] dE, \end{aligned}$$

where I is the intensity measurements, $S_i(E)$ is the photon number spectra, A_i is the line integrals of the material coefficient, and f_i is the mass attenuation coefficient of the material.

In order to estimate the line integrals of the individual materials A_i , we used the maximum likelihood parameter estimation method. As it is more convenient to minimize the negative log-likelihood, we express the likelihood function as a function of parameters A , given by measurement results (m_1, m_2) as:

$$L(m_1, m_2 | I_1(A), I_2(A)) \cong \sum_{n=1}^N [I_n(A) - m_n \ln I_n(A)].$$

2.2 Virtual Monochromatic Images (VMIs)

After decomposition, VMIs at different energy levels are calculated. For the image-based decomposition, the VMIs are calculated by summing the product of the local density of the individual materials and their linear attenuation coefficients at energy E as follows:

$$L(E) = A_1 * \frac{\mu_1}{\rho_1}(E) * \rho_1 + A_2 * \frac{\mu_2}{\rho_2}(E) * \rho_2,$$

For the projection-based decomposition, the monochromatic projection data is calculated by summing the product of the line integrals of the individual materials and its mass attenuation coefficients at energy E using the following formula:

$$\mu(\vec{x}, E) = A_1(\vec{x}) * \frac{\mu_1}{\rho_1}(E) + A_2(\vec{x}) * \frac{\mu_2}{\rho_2}(E),$$

Then, the projection data is reconstructed using a conventional filtered back-projection reconstruction method.

2.3 Patient Data

A total of 20 patients underwent ultra-low-dose CTC scanning using Siemens SOMATOM Definition Flash (Siemens Healthcare, Erlangen, Germany) operated in dual-source mode at 80 kVp and 140 kVp. Each patient was prepared for CTC by use of reduced bowel cleansing

and orally administered fecal tagging with iodine and was scanned twice, once in supine position and once in prone position.

3. RESULTS

Figure 1 shows the decomposed images obtained from the two methods. One can see that both decomposition methods are able to detect iodine from other materials. Bone is detected in the iodine image in the image-based method, but not in the projection-based method. This suggests that the projection-based method has a better material separation capability in comparison with the image-based method.

Figure 2 shows the VMIs obtained from both decomposition methods. One can see that the VMIs at 120 keV have reduced appearance of beam hardening. Further analysis suggests that the beam hardening artifacts have a negative impact on the performance of the CAD program. Comparing the performance between the image-based and the projection-based VMI, analysis of the line profiles in Figure 2 suggests that projection-based VMI better reflects the theoretical value of soft tissue (~ 0 HU).

Figure 3 shows images in presence (uncleansed) and in absence (electronically cleansed) of iodine. The solid arrow in Figure 3(B) shows part of the iodine solution that is wrongly classified as colonic wall (soft tissue). The beam hardening artifacts were corrected in the VMIs as shown in Figure 3(C), which resulted in a correct segmentation of the colon shown in Figure 3(D).

To evaluate the potential improvement by the image reconstructions in improving CAD performance, a CAD system [10] was used to detect lesion candidates automatically from the prone VMI datasets of 6 patients, where 5 of the patients had a colonoscopy-confirmed polyp ≥ 6 mm in size. The detection sensitivity of CAD was 100% with both reconstruction methods. Furthermore, the CAD system calculated several three-dimensional image-based features from the extracted regions of lesion candidates to be used for the reduction of false positives. To evaluate the potential improvement by the image reconstruction methods, we calculated the area under receiver operating characteristic (ROC) curve for the discrimination performance of the CAD features calculated from the VMIs. Table 1 demonstrates the discrimination performance in terms of the area under the receiver operating characteristic (ROC) curve, A_z , for the mean of CT value, which is expected to be sensitive to the quality and consistency of image reconstruction. The generally higher values of the A_z with the projection-based method indicate that the use of the projection-based method makes it possible to discriminate true-positive and false-positive polyp candidates more accurately than the use of the image-based method. This also suggests that the CAD may have higher and more consistent detection performance using the VMIs from the projection-based method than from the image-based method.

4. DISCUSSION

In this work, we have shown that the material decomposition technique is capable of correctly isolating iodine from other organs such as soft tissue, fat, and bone. Further, we illustrated that the resulting VMIs are capable of reducing the severity of beam-hardening

artifacts caused by the presence of high Z-number materials such as iodine. This reduction of beam-hardening artifacts contributes to improvement of CAD performance. Comparing the two different material decomposition techniques, our results showed that the projection-based decomposition method has better material separation capability while producing higher quality VMI. Furthermore, the combination of projection-based VMI and CAD yielded better detection performance in comparison to using image-based VMI.

5. CONCLUSION

In this work, we illustrated the difference in two decomposition methods, the image-based decomposition and projection-based decomposition methods. Although the image-based decomposition is computationally faster, the projection-based decomposition yields better material decomposition results. Further, we showed that decomposed materials could be used to calculate VMIs. These images have the advantage that it is able to reduce beam-hardening artifacts, and thus improve the CAD performance, especially in creating contrast-material enhanced and unenhanced images. The combination of CAD and VMIs has the potential to improve the accuracy of automated polyps and lesions detection in CT colonography, hence effectively aid radiologists in the detection process.

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Figure 1.

The decomposed images from the image-based and projection-based methods. Both decomposition methods are able to detect iodine. However, bone is seen in the iodine image in the image-based method, whereas it is not observed in the projection-based method.

Figure 2.

An original CTC image at 80 kVp and the corresponding VMIs at 120 keV generated by use of both image-based and projection-based methods. Visually, one can see the reduction of beam-hardening artifacts (blue arrows) in the VMIs. The rightmost graphs show the profiles along the red lines on the original and the VMIs. These profiles quantitatively show that the projection-based method is less noisy and reflects the true value better than the image-based method.

Figure 3.

Axial images of uncleansed and cleansed colon using input from original images (first column) and VMI (second column). In (A), severe beam hardening can be seen around the iodine. This causes problems in the CAD segmentation of the colon resulting in the wrong classification of iodine in an electronically cleansed image as pointed by an arrow in (B). The VMI in (D) has better image quality; thus the above misclassification does not occur, as evident in (D). All images have WL of 0 and WW of 2000.

Table 1

Evaluation of the area under the ROC curve (A_z) of the CT value feature in the discrimination of true-positive and false-positive CAD detections. Higher values of the A_z indicate higher performance.

Energy of VMI (kVp)	Area under the ROC curve (A_z)	
	Image-Based VMI	Projection-Based VMI
80	0.53	0.52
100	0.51	0.65
120	0.54	0.61
140	0.50	0.66