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Phase Contrast CT Enabled Three-Material Decomposition in Spectral CT Imaging

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Abstract

Three-material decomposition is crucial for material quantification when more than two elemental materials, including a K-edge material, are presented in an image object. In principle, three-material decomposition requires a triple energy scan which cannot be directly accomplished using a conventional dual energy CT system. In this work, a new scheme to enable three-material decomposition by employing phase contrast CT was presented. When a grating interferometer is added, a conventional absorption dual energy CT system can be upgraded to a phase contrast dual energy CT system which provides an additional phase signal related to the real part of the refractive index of an image object, along with the absorption signal under two different x-ray spectra. In this work, a three-material decomposition method was proposed for the aforementioned dual energy phase contrast CT system. Physical experimental studies were performed on a benchtop x-ray Talbot-Lau interferometer system to validate the proposed method. A physical phantom, containing calcium and iodine inserts of known concentrations, was used as the image object. A rotation-rotation dual energy phase contrast CT scan was performed under 40 and 80 kVp tube potentials. For each view angle, a phase stepping procedure with five phase steps was performed. After the phase retrieval procedure and image reconstruction using the standard filtered-back projection, the solutions were decomposed into the calcium, iodine and water bases based on the proposed decomposition method. For all the solutions, the relative quantification errors of the concentrations were within 10%.

1. INTRODUCTION

Multi-energy x-ray computed tomography (CT), also known as spectral CT imaging, has been widely used in security CT scans for threat detection and in medical CT to provide the needed elemental material differentiations when two materials show the same CT numbers under a single CT scan. However, in practice, when the material is composed of more than two elemental materials, the decomposition of images into two material bases may not be sufficient to provide elemental material differentiation.¹ In this case, a three-material decomposition is deemed critical for quantification purpose. For conventional dual energy spectral imaging methods, an empirical volume conservation or mass conservation constraint has been introduced to perform three-material decomposition.² However, these conservation principles cannot be guaranteed in a real world scenario so that the methods based on them

do not always produce robust results. In order for a robust three material decomposition, hardware based methods have been implemented. Such methods include measurements using three different x-ray spectra,³ using dual-source-dual-detector system with twin-beam configuration⁴ and using photon-counting detectors (more than two energy bins),^{5,6} etc.

In this work, we presented a new scheme to enable reliable three-material decomposition from three different measurements. However, these three different measurements are not obtained from three different x-ray spectra, but from only two different spectra. To achieve this, we incorporated a grating-inteferometer into a conventional dual energy CT scan. The dual energy CT scan can be accomplished by either employing energy-integrating detectors (EIDs) with dual spectral measurements or photon-counting detectors (PCDs) with two energy bins. When the interferometer is introduced, the phase contrast CT acquisition provides a different physical measurement of electron density, along with the conventional dual energy absorption measurements, to enable reliable and accurate three-material decomposition.

2. METHODS

2.1 Theoretical foundation for phase contrast CT enabled three-material decomposition

In the diagnostic range (10 keV - 140 keV), if a material with a K-edge is presented in an image object, the energy dependent linear attenuation coefficient of the material can be decomposed into three bases¹

$$\mu(E) = a_{PE}\mu_{PE}(E) + a_{CS}\mu_{CS}(E) + a_K\mu_K(E), \quad (1)$$

where a and μ represent the decomposition coefficients and energy dependent linear attenuation coefficients of the three physical bases. Here PE represents the photoelectric effect; CS represents the Compton scattering (CS); K represents the photoelectric effect with K-edge]. Meanwhile, the attenuation coefficient can also be decomposed into three material bases, such as water, calcium and the K-edge material,⁷

$$\mu(E) = a_{\text{water}}\mu_{\text{water}}(E) + a_{\text{calcium}}\mu_{\text{calcium}}(E) + a_K\mu_K(E) \quad (2)$$

As one can tell from Eqs. (1–2), in order to determine the three decomposition coefficients for quantification purpose, measurements based on a minimum of three different spectra are required. The information provided by dual-energy systems is not adequate for a three-material decomposition.

When a grating inteferometer is added to a system, additional information regarding the refractive index of the material can be extracted. Assume that the refractive index is written as $n = 1 - \delta + i\beta$, then δ is related to the electron density as⁸

$$\delta(E) = \rho_e \times \frac{r_0 \hbar^2 c^2}{2\pi E^2}, \quad (3)$$

where $r_0 = 2.82 \times 10^{-15}\text{m}$ is the classical radius of the electron, $\hbar$ is the reduced Planck constant and c is the speed of the light. Meanwhile, it can be proved that if a material is

decomposed into three basis materials as shown in Eq. (2), its electron density can also be related to the electron densities of the basis materials as

$$\rho_e = \sum_i a_i \rho_{e,i}, \quad (4)$$

As a result, one can easily derive that $\delta(E) = \sum_i a_i \delta_i(E)$. The equation indicates that the decomposition of the attenuation coefficients and the the decomposition of δ share the same coefficients.

The proposed material decomposition method is calibration based. Assume that we have three calibration materials with known attenuation coefficients $[\mu_1(E), \mu_2(E), \mu_3(E)]$ and electron densities $[\rho_{e,1}, \rho_{e,2}, \rho_{e,3}]$. The attenuation coefficient of the unknown material is denoted as $\mu(E)$. The decomposition can be written in a mathematical form

$$\mu(E) = a_1 \mu_1(E) + a_2 \mu_2(E) + a_3 \mu_3(E). \quad (5)$$

Based on dual energy phase contrast CT, the attenuation coefficients for two spectra and the information about the refractive index can be acquired. Since they share the same decomposition coefficients, three equations can be formed

$$\mu_L = a_1 \mu_{1,L} + a_2 \mu_{2,L} + a_3 \mu_{3,L}; \quad (6)$$

$$\mu_H = a_1 \mu_{1,H} + a_2 \mu_{2,H} + a_3 \mu_{3,H}; \quad (7)$$

$$\rho_e = a_1 \rho_{e,1} + a_2 \rho_{e,2} + a_3 \rho_{e,3}, \quad (8)$$

where $\mu_{i,L/H}$ represent the attenuation coefficients of the i -th basis measured under the low energy or high energy spectrum, respectively.

The next step is to replace Eq. (8) with the measured phase signal. Since the relationship between δ and x-ray energy E solely relies on the $1/E^2$ term, the δ values for different materials under different x-ray spectra should be linearly dependent.⁹ More explicitly, the rank of the matrix

$$\begin{bmatrix} \rho_{e,1} & \rho_{e,2} & \rho_{e,3} \\ \delta_{1,L} & \delta_{2,L} & \delta_{3,L} \\ \delta_{1,H} & \delta_{2,H} & \delta_{3,H} \end{bmatrix}$$

should be one, where $\delta_{i,L/H}$ represent the δ value of the i -th basis measured under the low energy or high energy beam, respectively. In this case, Eq. (8) can be replaced by

$$\delta = a_1 \delta_1 + a_2 \delta_2 + a_3 \delta_3, \quad (9)$$

where the δ values can be the group of values measured under either the high energy or low energy spectrum.

Finally the equations can be summarized in a matrix form

$$\begin{bmatrix} \mu_{1,L} & \mu_{2,L} & \mu_{3,L} \\ \mu_{1,H} & \mu_{2,H} & \mu_{3,H} \\ \delta_1 & \delta_2 & \delta_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} \mu_L \\ \mu_H \\ \delta \end{bmatrix} \Rightarrow M \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} \mu_L \\ \mu_H \\ \delta \end{bmatrix}. \quad (10)$$

where

$$M = \begin{bmatrix} \mu_{1,L} & \mu_{2,L} & \mu_{3,L} \\ \mu_{1,H} & \mu_{2,H} & \mu_{3,H} \\ \delta_1 & \delta_2 & \delta_3 \end{bmatrix}$$

is the decomposition matrix. The solution is given as

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = M^{-1} \begin{bmatrix} \mu_L \\ \mu_H \\ \delta \end{bmatrix}. \quad (11)$$

2.2 Experimental methods

Physical experiments were performed on a benchtop-based x-ray Talbot-Lau interferometer to validate the proposed decomposition method. The system uses a medical grade rotating-anode x-ray tube with 1.0 mm nominal focal spots and an energy integrating detector (Shad-o-Box 2048) with a pixel size of 48 μm . The source grating G0 has a pitch size of 20.7 μm and a duty cycle of 35%; the phase grating G1 has a pitch size of 4.3 μm and a duty cycle of 50%. The analyzer grating G2 has a pitch size of 2.4 μm and a duty cycle of 50%. The G1 grating is a π -phase grating designed for 28 keV x-rays. The distance between G0 and G1 was set to 150 cm, and the distance between G1 and G2 was 17.5 cm. The image object was placed between G0 and G1. The distance from the x-ray source to the isocenter is 175 cm and that from the x-ray source to the detector is 212 cm.

The image object was an in-house quantification phantom, as shown in Fig. 1. The base of the phantom is made of polymethylmethacrylate (PMMA) and solutions with different calcium and iodine concentration were used as inserts. The compositions of the inserts are shown in Fig. 1(b).

For the dual energy phase contrast CT acquisition, two scans were performed with the tube potential being set at 40 kVp (mean energy of 28 keV) and 80 kVp (mean energy 51 keV). The fringe visibility of the system was approximately 0.12 for the 40 kVp x-ray beam and dropped to 0.01 for the 80 kVp beam. For both scans, data were acquired at 360 view angles. For each view angle, a phase stepping procedure with 5 phase steps was performed. The exposure level for each phase step was 30 mAs for the 40 kVp scan and 10 mAs for the 80 kVp scan.

The phase retrieval process was performed and images were reconstructed using the standard filtered back-projection method (Ramp kernel for absorption CT and Hilbert kernel

for phase CT). The reconstructed image has a pixel matrix of 512×512 , a field of view of 40 mm and the slice thickness of 1 cm. For the decomposition, inserts A, B, and C (100 mg/ml CaCl_2 , 10 mg/ml iodine and water) were used as the three basis materials. By measuring the attenuation coefficients and the phase signal for the three basis materials from the reconstructed images, the decomposition matrix M was determined and the material decomposition was performed.

3. RESULTS

The reconstructed absorption and phase CT images for the 40 kVp beam and 80 kVp beam are shown in Fig. 2. Due to the drop of the visibility under the 80 kVp beam, the corresponding phase CT image is too noisy and was not used in the decomposition. The basis materials are indicated in Fig. 2. The decomposition matrix M was measured from the reconstructed images and the values of its elements are given as

$$M = \begin{bmatrix} \mu_{1,L} & \mu_{2,L} & \mu_{3,L} \\ \mu_{1,H} & \mu_{2,H} & \mu_{3,H} \\ \delta_1 & \delta_2 & \delta_3 \end{bmatrix} = \begin{bmatrix} 0.646 & 0.535 & 0.375 \\ 0.272 & 0.307 & 0.212 \\ 0.310 \times 10^{-6} & 0.294 \times 10^{-6} & 0.294 \times 10^{-6} \end{bmatrix}. \quad (12)$$

The first two rows of M have a unit of $[\text{cm}^{-1}]$. The decomposition was performed following Eq. (11) and the results are shown in Fig. 3. Some quick qualitative analysis can be performed. For example, since insert E (6.7 mg/ml iodine) does not contain calcium, it should appear dark in the calcium basis image, which is consistent with Fig. 3(a). Also, the PMMA does not contain iodine and it appears dark in the iodine base image (Fig. 3(b)).

Quantitative measurements of the decomposition coefficients were performed and the results were summarized in Table 1. The measured concentration of insert D is 55 mg/ml CaCl_2 and 4.7 mg/ml iodine and that for insert E is 6.6 mg/ml iodine. For all the materials, the relative quantification error is less than 10%.

4. CONCLUSIONS

In this work, a new scheme was proposed to enable reliable three-material decomposition from the dual energy phase contrast CT. The proposed method was validated based on experiments using a benchtop phase contrast CT system. The relative quantification errors for the materials were within 10%.

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Figure 1.

(a) A picture of the quantification phantom. (b) A cross section of the phantom with the size and the composition being indicated. Insert D is a mixture of iodine and calcium; each milliliter of the solution contains 50 mg CaCl_2 and 5 mg iodine.

Figure 2.

Reconstructed absorption and phase CT images for the 40 kVp beam and 80 kVp beam.

Display window: $[0 \ 0.66] \text{ cm}^{-1}$ for (a) and (b); $[0 \ 0.32] \times 10^{-6}$ for (c) and (d). The three inserts used as the basis materials are marked with the arrows.

Figure 3.

Decomposition results. (a) CaCl_2 basis (100 mg/ml CaCl_2); (b) iodine basis (10 mg/ml iodine); (c) water basis. The color scales are indicated in the figure. (d) multimaterial map by overlaying the calcium basis image and the iodine basis image onto the 40 kVp absorption image.

Table 1.

Summary of the decomposition coefficients (Mean $\pm$ Std) for inserts D, E and F. The values in bold indicate the ground truth.

	calcium basis	iodine basis	water basis
insert D	0.55 ± 0.06 (0.5)	0.47 ± 0.06 (0.5)	-0.03 ± 0.04 (0)
insert E	0.02 ± 0.08 (0)	0.66 ± 0.1 (0.67)	0.32 ± 0.05 (0.33)
F (PMMA base)	-0.3 ± 0.06 (-0.33)	0.04 ± 0.07 (0)	1.44 ± 0.04 (1.53)