Single-Shot Quantitative X-ray Imaging Using a Primary Modulator and Dual-Layer Detector: Simulation and Phantom Studies

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ABSTRACT

Conventional x-ray imaging provides little quantitative information due to scatter, beam hardening, and overlaying tissues. A single-shot quantitative x-ray imaging (SSQI) method was previously developed to quantify material-specific densities in x-ray imaging by combining the use of a primary modulator (PM) and dual-layer (DL) detector. The feasibility of this concept was demonstrated with simulations using an iterative patch-based method.

In this work, we propose a new algorithm pipeline for SSQI that enables accurate quantification and high computational efficiency. The DL images contain four measurements that are obtained behind the unattenuated and partially attenuated regions of the PM of each layer. Using the low-frequency property of scatter and a pre-calibrated material decomposition (MD), four unknowns (i.e., two scatter images and two material-specific images) are jointly recovered by directly solving four equations given by the four measurements.

We tested this algorithm in simulations and further demonstrated its efficacy on chest phantom experiments. Through simulation, we show that the new method for MD is robust against scatter. Its performance improves with smaller PM pitch size and smaller focal spot blur. The RMSE in material-specific images compared to ground truth reduces by 52%-84% versus without scatter correction. For our experimental study, we successfully separated soft tissue and bone. The computational time for processing each view was ~8 s without optimization. The reported results further strengthen the potential of SSQI for widespread adoption, leading to quantitative imaging not only for x-ray imaging but also for real-time image guidance or cone-beam CT.

1. PURPOSE & INTRODUCTION

Dual-energy x-ray imaging can significantly improve the utility of x-ray images by providing quantitative information, such as area density of specific materials. However, quantitative x-ray imaging suffers from a number of challenges, including factors like patient motion in double-shot methods, scatter, and beam hardening. In particular, scattered x-rays add undesired signal that biases the accuracy of quantitative analysis, for example, when using weighted subtraction of low-energy (LE) and high-energy (HE) images to generate material-specific images.

There are a number of scatter correction methods that have been proposed, including software- and hardware-based scatter estimation. We chose to use primary modulator (PM) in particular as it simultaneously captures both primary and scatter signals in every acquisition view. The PM encodes the primary signal using a checkerboard pattern with alternating semitransparent and transparent regions, whereas the scatter distribution is low frequency that are imposed on the encoded primary information and not altered by the checkerboard pattern¹. One of the main challenges for using a PM has been the beam hardening induced by the semitransparent regions, which can be corrected using dual energy imaging as it fully characterizes the attenuation caused by the modulator and object. A dual-layer (DL) detector is an ideal candidate for this task as it acquires dual-energy images in a single shot, with perfect spatial and temporal registration. In Ref ², we proposed to use SSQI to jointly estimate scatter and object material density by combining the use of a PM and DL detector. The feasibility of this idea was evaluated in a simulation study for chest x-ray imaging, where the scatter and material density were iteratively estimated for a small patch, which slid across the entire image for complete estimation.
In this work, we further optimize the SSQI algorithm pipeline and propose a deterministic method to jointly perform global scatter correction and MD. We demonstrate the potential of the new SSQI algorithm for material quantification and superior computational efficiency in simulation and phantom studies.

2. METHODS
We first evaluated the feasibility of the proposed algorithm using a digital chest phantom, which was generated by forward projecting the CT (segmented into bone, soft tissue, and lung) of a COVID-19 patient, with Poisson noise added in the projection domain. The resulting projection was decomposed into two basis materials: PMMA and Cu. The PM was a checkerboard pattern of 210 µm thick Cu with 889 µm pitch size, which were acquired with realistic blur using an x-ray focal spot size of 0.3 mm. The prototype DL detector has a top CsI scintillator thickness of 200 µm, a 1 mm Cu filter, and a bottom CsI scintillator thickness of 550 µm, with a 43×43 cm² active area. The idea was further validated by acquiring phantom images (Lungman, Kyoto Kagaku) on our tabletop system. All images were acquired with 2×2 binning for a pixel size of 300×300 µm². Figure 1 is an overview of the SSQI setup.

![Figure 1. Overview of SSQI, which contains a primary modulator for scatter removal, and a dual-layer detector for simultaneous dual-energy imaging.](image)

2.1 Simulation
A polyenergetic 120 kVp source was attenuated by the PM and the digital chest phantom. The simulated geometry had a source-detector distance of 139.5 cm, and the phantom was placed directly in front of the detector to mimic chest x-ray acquisition. The DL images obtained from SSQI were simulated as a combination of primary, scatter, and noise images (Figure 2):

\[ M_k = \int I_{\text{eff},k}(E) e^{-\mu_1(E)(L_{1,\text{PM}} + L_{1,\text{obj}})} e^{-\mu_2(E)(L_{2,\text{PM}} + L_{2,\text{obj}})} dE + S_k + N_k, \quad (1) \]

where two basis materials (PMMA, Cu; \( \mu_1, \mu_2 \)) and their corresponding line integrals for PM \( (L_{1,\text{PM}}, L_{2,\text{PM}}) \) and object \( (L_{1,\text{obj}}, L_{2,\text{obj}}) \) were used for simulation. The \( L_{k,\text{PM}} \) were assumed to be known a priori. The detector response and filtration were modeled into the effective spectrum, \( I_{\text{eff},k} \), indexed by \( k \). Low-frequency scatter images \( S_k \) were then added, where
the bottom layer scatter was slightly reduced since scatter tends to be lower energy and less penetrating than primary. A simplified Gaussian noise $N_k$ was added to DL images to add randomness to the DL projections.

A one-time empirical MD calibration was performed based on simulation. The DL detector responses were measured from PMMA and Cu in pairs of thickness ranging from 0 to 20 cm PMMA and 0 to 2 mm Cu, forming an empirical MD lookup table for later use.

To jointly recover scatter and MD globally, we expanded the 2 DL images into 4 by dividing each measurement into two subsets, which result from the unattenuated and partially attenuated regions of the PM. Given the low frequency nature of scatter, sub-measurements from the same layer shared the same scatter image, referred to as $S_t$ and $S_b$ for top and bottom layers, respectively. Four unknowns, $L_{1,\text{obj}}, L_{2,\text{obj}}, S_t,$ and $S_b$, can be directly recovered from the 4 sub-measurements, which were downsampled to 40×40 for faster computation (<8s to process one view without parallel computing). Figure 3 shows the pipeline of the proposed algorithm. Only scatter estimates were used for later processing due to their low-frequency nature.

The performance of scatter estimation is affected by PM pitch size and focal spot blur, where fine pitch and small focal spot blur are preferred. We further investigate the impact of these factors by changing the PM pitch size (889 and 457 µm) and the source-to-modulator distance (SMD: 23.1 and 36.2 cm). The focal spot blur reduced with larger SMD.

Figure 2. Pipeline to simulate the DL images, which include the impact of modulated pattern, scatter signals and noise. The demonstrated images are normalized to the air scan and the display ranges are as indicated.
Figure 3. Workflow of the proposed SSQI algorithm. Sparse samples of the raw scatter estimate were empirically selected using to avoid carrying over false information. A local filtration algorithm was used to efficiently process the sparse data to obtain the final scatter estimates. The estimated scatter and material specific images are compared to ground truth and showed strong agreement.

2.2 Phantom Data
Phantom measurements were performed on our tabletop system with the same source-to-detector distance as the simulation, a PM pitch size of 889 µm, and a SMD of 23.1 cm. The experimental setup is shown in Figure 4.

Figure 4. Left: the PM used for acquiring phantom images. Right: phantom setup with DL detector.
3. RESULTS

Figure 5(a) shows the MD results using the proposed SSQI algorithm and the impact of PM pitch and focal spot blur on its performance. As compared to ground truth, without the PM and scatter correction, the RMSE after MD was 11.35 mm for PMMA and 0.71 mm for Cu, leading to residual bone in the PMMA image, soft tissue in the bone image, and residual PM pattern. The proposed method removes most bias (minor errors pointed to by yellow arrows), with improved performance for smaller PM pitch and reduced focal spot blur. The soft tissue images clearly revealed the ground glass opacities (green arrows in Fig. 5(a)) caused by COVID-19 infection. The RMSE (2\textsuperscript{nd} - 4\textsuperscript{th} columns in Fig. 5(a)) was reduced to 5.72, 4.08, and 3.36 mm for PMMA and 0.18, 0.13, and 0.11 mm for Cu, respectively.

Figure 5(b) shows that the proposed SSQI successfully estimates scatter and MD jointly for phantom data. The resulting PMMA and Cu images clearly separate the soft tissue and bone. The basis material of PMMA and Cu can be also transformed into any other basis material pairs which can better represent soft tissue and bone, although the selected pair is more practical for calibration. Note that there is subtle residual checkerboard pattern seen in the decomposed material.

Fig. 5. (a) The impact of pitch size and focal blur on the MD performance of the proposed method. RMSE to ground truth improves with small pitch and small focal blur. (b) Estimated material specific images for phantom data.
images, which is mainly due to the simulated MD calibration used to perform MD on real measurements, where mismatch between the two is expected, such as spectral difference caused by the heel effect, which is not considered in the simulation. Position-specific calibration is needed to accurately account for the spectral difference caused by heel effect for MD calibration, a focus of our ongoing work.

### 4. DISCUSSION AND CONCLUSIONS

In this work, we proposed a new SSQI algorithm that jointly estimates scatter and performs MD with high accuracy and efficiency. SSQI brings quantitation to every exposure by removing several limitations (i.e., scatter, beam hardening, and motion artifact) that impede quantitative x-ray imaging. To the user, the single-shot method enables seamless transition from conventional imaging, obtaining quantitative imaging without an additional imaging protocol. Given its simplicity in implementation, SSQI can be broadly used for many clinical tasks, including radiography (chest and extremity x-ray imaging), fluoroscopy (maskless digital subtraction angiography), or even cone-beam CT (dental/head scanner).

In ongoing work, we will focus on improving our SSQI algorithm by performing region-specific calibration on measured data. In addition, we will further optimize the computational efficiency and explore its potential in dynamic imaging acquisition, such as maskless digital subtraction angiography and lung tumor tracking.

### ACKNOWLEDGEMENT

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