Material decomposition from unregistered dual kV data using the cOSSCIR algorithm

Benjamin M. Rizzo[a], Emil Y. Sidky[b], and Taly Gilat Schmidt[a]

[a]Department of Biomedical Engineering at Marquette University and the Medical College of Wisconsin, Milwaukee, WI, 53233

[b]Department of Radiology at The University of Chicago, Chicago, IL, 60637

ABSTRACT

Dual-kV is a spectral CT modality that is currently available clinically, which traditionally employs energy integrating detectors, and in some cases acquire spectral data that is unregistered. A spectral method developed for photon-counting detectors, the constrained one-step spectral CT image reconstruction method (cOSSCIR), is designed to perform material decomposition directly from a set of spectral measurements. As such, the spectral sinograms need not be registered. Within the framework of cOSSCIR, dual-kV data is just two-window spectral CT. Furthermore, reconstructing unregistered data, such as that acquired by fast kV switching and slow kV switching systems, provides a potential extension of sOSSCIR to reconstructing clinical data. In this investigation we demonstrate cOSSCIR on unregistered dual-kV protocols using simulations and experimental phantom studies. Our results suggest that cOSSCIR can accurately recover the basis material maps using slow- and rapid-kV data compared to fully registered reconstructions.

Keywords: Dual and multi-energy imaging, Image reconstruction, Photon counting CT.

1. INTRODUCTION

The constrained one-step spectral CT Image Reconstruction method (cOSSCIR) has been developed to estimate basis material maps directly from spectral CT data.[1,8] cOSSCIR includes modeling of polyenergetic x-ray transmission, which can prevent beam hardening artifacts. Also, constraints can be placed on the basis material maps to stabilize the material decomposition inversion. The cOSSCIR framework has been investigated for spectral data from photon counting detectors. Recently, preliminary work has applied cOSSCIR to dual energy CT using an integrating detector model, where the dual energy problem is modeled in the cOSSCIR framework as a two-window spectral CT problem with significant overlap between the acquisition spectra. Previous work assumed the spectral data are fully registered (i.e., all spectral measurements are collected for each ray), as is generally the case with current photon-counting detector technologies. However, clinical dual energy diagnostic CT or cone-beam CT data may be acquired using Rapid- or Slow-kV acquisitions, resulting in unregistered spectral CT data. Typically, unregistered dual kV acquisitions are reconstructed by a two-step approach that first reconstructs CT images from each spectra and then performs image-domain material decomposition. However, such approaches cannot take advantage of polyenergetic modeling and are susceptible to beam hardening artifacts. One advantage of one-step direct inversion material decomposition methods such as cOSSCIR is that polyenergetic transmission can be modeled while the spectral data need not be registered. This study investigates the application of cOSSCIR to unregistered, dual energy acquisitions. First, an inverse crime simulation using a pelvic phantom was performed to determine whether the cOSSCIR optimization algorithm converges for the case of unregistered data. Our results demonstrate that convergence is possible for the Slow- and Rapid-kV, dual energy, problem using cOSSCIR. We further demonstrate the approach on a preliminary experimental dataset.

Further author information: (Send correspondence to B. M. Rizzo)

B. M. Rizzo .: E-mail: benjamin.rizzo@marquette.edu

E. Y. Sidky: E-mail: sidky@uchicago.edu

T. G. Schmidt: E-mail: tal.gilat-schmidt@marquette.edu

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2. PURPOSE

The goal of this study is to investigate the use of cOSSCIR on unregistered dual kV data, such as that acquired by Rapid- or Slow-kV switching acquisition. Specifically, this investigation will focus on inverse-crime studies and experimental reconstructions to establish the feasibility of using cOSSCIR on unregistered dual-kV data.

3. METHODS

The cOSSCIR algorithm is designed to solve the concave-convex optimization problem,[1–3]

$$x^*_{km} = \text{argmin}\Big\{D(c_{w\ell}, \hat{c}_{w\ell})\Big\} : \textstyle\sum_m \|x_m\|_{TV} \le \gamma,$$

where the objective is to find the optimal basis material images x^*_{km} that minimizes

$$D_{TPL}(c_{w\ell}, \hat{c}_{w\ell}) = \textstyle\sum_{w\ell}[\hat{c}_{w\ell}(y) - c_{w\ell}\,\log(\hat{c}_{w\ell}(y))],$$

where D_{TPL} is the Transmission data discrepancy derived from a Poisson likelihood (TPL). An anisotropic penalty was applied for the proceeding studies. The data model utilized by the method is

$$\hat{c}_{w\ell} = N_{w\ell} \textstyle\sum_i S_{w\ell i} \exp(-\sum_{mk} \mu_{mi} P_{\ell k} x_{km}),$$

where $\hat{c}_{w\ell}$ represents the mean photon counts along a ray ℓ in energy window w. The variable $N_{w\ell}$ represents the number of counts along ray ℓ in energy window w in the absence of an object, and $S_{w\ell i}$ is the normalized x-ray energy spectrum. $P_{\ell k}$ is the x-ray projection operator. Finally, μ_{mi} represents the attenuation of material m at energy E_i. This one-step direct inversion[2,5,6] method for CT has been investigated for the photon counting problem. The method was found to be more stable than traditional two-step approaches as it utilizes all rays in the reconstruction, and places constraints on the basis images x_{km} directly. In the one-step approach, the spectral measurements need not be registered, and cOSSCIR may potentially be applied to dual energy CT.[7] Dual energy CT, therefore, presents a unique opportunity to test cOSSCIR on the unregistered reconstruction problem. In the case of dual energy CT, the spectral model requires minimal modification to account for an energy integrating detector. The spectra $S_{w\ell i}$ may be replaced by

$$\hat{S}_{w\ell i} = \beta_{w\ell i}\, S_{w\ell i}\, E_i,$$

where $\beta_{w\ell}$ represents the detector gain along the transmission path ℓ in energy window w. The effect of unregistered data was investigated by simulating data from a pelvis phantom, consisting of a bone and water basis material maps, as shown in Fig. 1. Using a polyenergetic x-ray transmission model,[8] projections at 80 and 140

(a) (b)

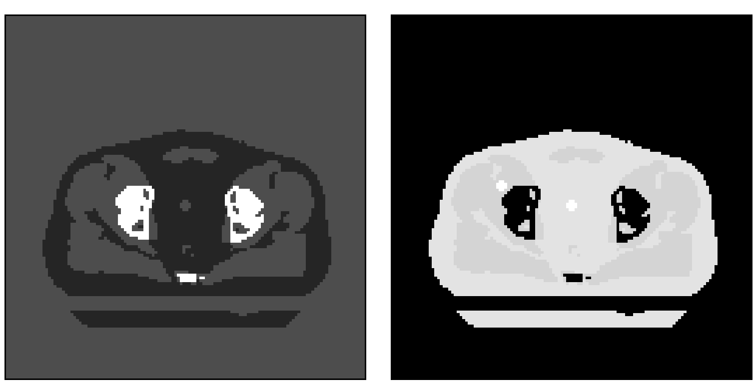

Figure 1: Pelvis phantom; (a) The bone basis material map, and (b) the water basis material map.

kV data were simulated using realistic x-ray spectra. One simulation generated fully registered noiseless data using 256 equally spaced views for each energy. A Rapid-kV protocol was simulated by subsampling the fully sampled dataset so that the 80 kV data used the even view angles and the 140 kV data used the odd view angles. Likewise, a Slow-kV protocol was simulated by dividing the fully sampled data into blocks of 10 consecutive views, where each block of 10 views alternated between the 80 and 140 kV data. For comparison, 128-view, registered data, was also simulated by subsampling the fully sampled data, using the even view angles for each kV.

For all simulations, data were reconstructed using the cOSSCIR framework using the same x-ray transmission model that was used to simulate the data. During the reconstructions, two error metrics were monitored with iteration; the Root-Mean Squared-Error (RMSE) between the phantom basis images and the basis map estimates, and the TPL between the measured data and the modeled data.

Additionally, Dual-kV data was obtained from an experimental micro-CT system using a high resolution flat panel detector (Varian PaxScan 2520 DX) and a micro-focal x-ray source (Hamamatsu 9181-02). A cylindrical phantom with PMMA, Polystyrene, and Teflon inserts was imaged, as pictured in Fig. 2. For each phantom, fully registered projections were acquired from 500 equally spaced view angles using 80 and 130 kV.

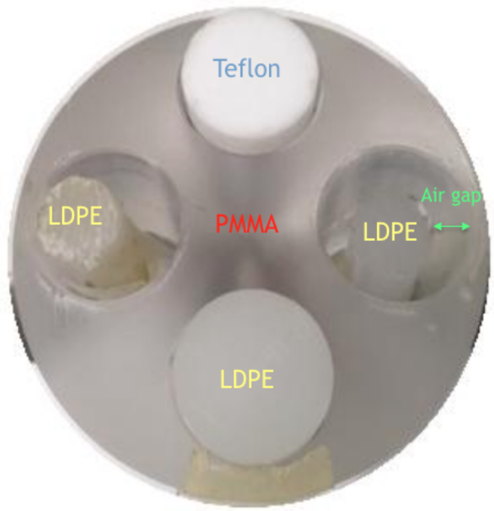

Figure 2: Rod phantom consisting of PMMA, LDPE, and Teflon

As in the inverse-crime studies, a Rapid-kV-switching acquisition was simulated by reconstructing from only 250 views for each spectra, with the spectra alternating across angle. For each subsampled dataset, the 80 and 130 kV sinograms were offset by a single view angle. Likewise, to further test the method, Slow-kV-switching data was subsampled from the registered data by alternating between the 80 and 130 kV sinograms every 10 consecutive views. Reconstructions were then performed using the cOSSCIR algorithm using Aluminum and PMMA as the basis materials. Reconstructions of the fully sampled data and registered data using 128 views/kV were performed for comparison. For each basis material image, the mean value in the LDPE, PMMA, and Teflon regions were measured. The percent error was taken between the mean measurements and the predicted ground truth material decomposition values obtained from the XCOM NIST database.[4]

4. RESULTS

cOSSCIR was performed on the noiseless data to investigate the effect of unregistered data on the reconstructions, and the resulting difference images for each material map are shown in Fig. 3 for 10^5 iterations. The top row shows the bone difference images and the bottom row shows the water basis images. Columns (c) and (d) show the results for the Rapid- and Slow-kV reconstructions, respectively. The difference images for the fully sampled data and the 128-view registered data are shown in columns (a) and (b) for comparison.

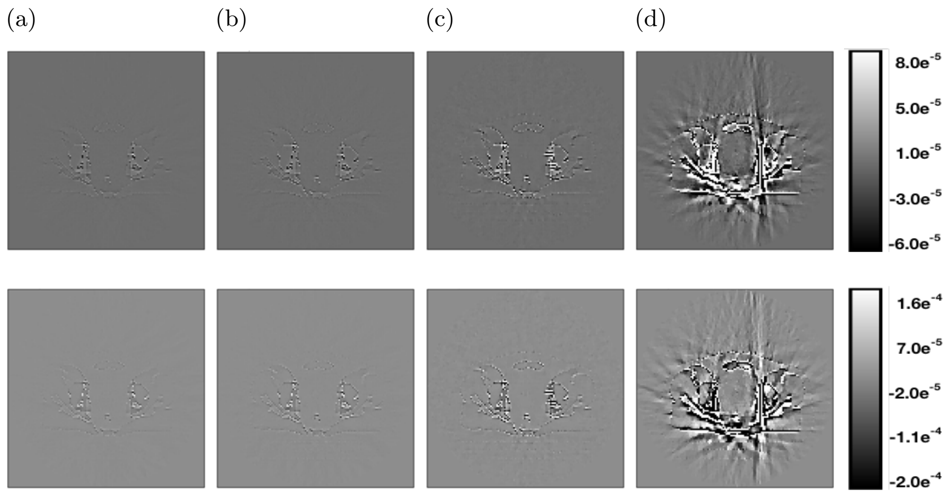

Figure 3: Difference images for the pelvis phantom reconstructions for (a) Fully Sampled (registered) data using 256 views/kV, (b) Registered data using 128 views/kV, (c) Rapid-kV, (d) Slow-kV. The top row shows the difference images in the bone basis, and the bottom row shows the difference images in the water basis.

As indicated by the small errors, the basis images are recovered well for the unregistered 128 views/kV in Fig. 3(c-d), although the errors were larger than the registered data in Fig. 3(a-b) after 10^5 iterations. The algorithm performance was further evaluated by monitoring the data error and basis image error with iteration, and are plotted in Fig. 4.

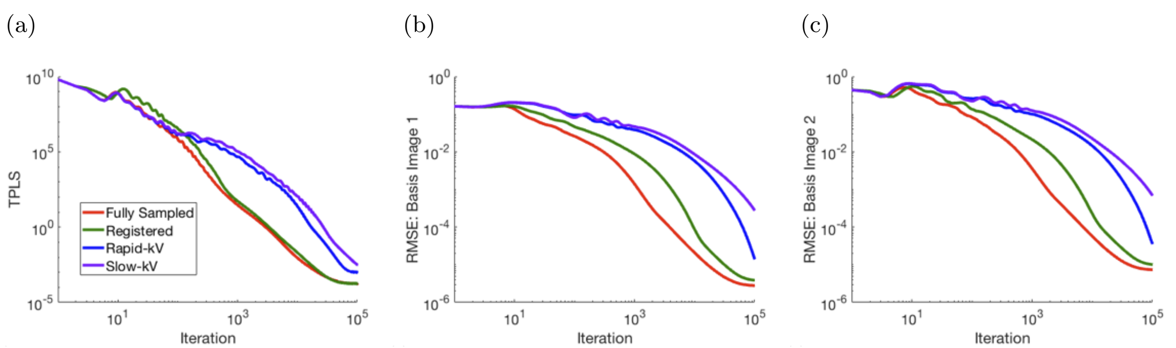

Figure 4: (a) Data error, (b) RMSE for the bone basis image, (c) RMSE for the water basis image.

As in the case of the reconstructions, the basis image error indicate good recovery after 10^5 iterations. The RMSE between the phantom and basis images suggest the registered and unregistered reconstructions are approaching the same solution. More iterations are required, in the case of the unregistered data, before the image RMSE approaches the same values as the registered reconstructions. Although the data error is decreasing with iteration in Fig. 4(a), in general, the TPL also indicates more iterations were required for Rapid- and Slow-kV switching, suggesting there is a penalty to using fewer projections per spectra compared to the fully registered case. An interesting aspect of these unregistered inverse-crime studies was convergence to a solution was only observed using μ-preconditioning,[1] where the material attenuation energy functions $\mu(E)$ were orthogonalized. μ-preconditioning was not required for convergence on the registered data, but was used in the results presented above.

Experimental data was also reconstructed as a preliminary demonstration cOSSCIR applied to dual-kV data. 500 view dual energy data were acquired, then unregistered Rapid- and Slow-kV data were simulated by applying masks to the fully registered data for a total of 256 views/kV. A 256 views/kV registered dataset was

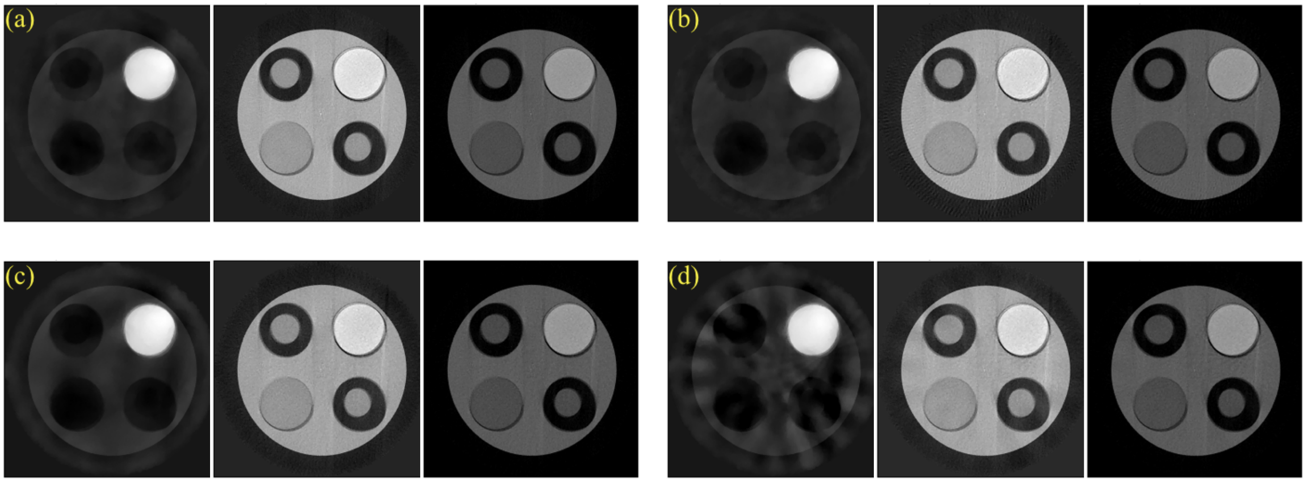

Figure 5: Reconstructions using (a) Fully Sampled (registered) data using 500 views/kV, (b) Registered data using 250 views/kV, (c) Rapid-kV, and (d) Slow-kV data. The columns of each subfigure display the Aluminum, PMMA, and the 50 keV mono-energetic image.

also constructed from the 500 view acquisition. The fully sampled dataset was also reconstructed for comparison. Results for each of the reconstructions are shown in Fig. 5 using Aluminum and PMMA as the basis materials for 1000 iterations. μ -preconditioning was also used to perform all reconstructions. Compared to the registered results in Fig. 5, the recovered Rapid- and Slow-kV PMMA basis images and virtual mono-energetic images are quite similar. There are noticeable ray artifacts in the Rapid- and Slow-kV Aluminum basis images. However, these appear to be largely in areas of the image where Aluminum has limited contribution.

Material quantification was performed on the LDPE, PMMA, and Teflon regions of the phantom. The percent errors between the recovered grayscale values and their ground truth for each basis are shown in Table 1. The recovered material vectors are nearly identical for the registered and Rapid-kV reconstructions, demonstrating that unregistered acquisition does not impact quantitative accuracy.

Table 1

% Error	Image	LDPE	PMMA	Teflon
Fully Sampled	AL	35.28	-	0.453
	PMMA	4.635	4.200	1.341
	50 keV	0.335	0.335	0.791
Registered	AL	39.91	-	0.291
	PMMA	4.863	4.100	1.267
	50 keV	0.314	0.057	0.876
Rapid-kV	AL	53.77	-	2.685
	PMMA	6.364	6.390	1.857
	50 keV	0.006	0.499	0.276
Slow-kV	AL	53.77	-	3.429
	PMMA	6.570	6.400	2.001
	50 keV	0.067	0.496	0.316

5. NEW AND BREAKTHROUGH WORK TO BE PRESENTED

This is the first demonstration and application of cOSSCIR on unregistered dual-kV data.

6. CONCLUSIONS

Our preliminary results demonstrate the application of the one-step cOSSCIR algorithm to unregistered data. The inverse-crime studies demonstrate a challenging reconstruction problem, compared to reconstructing registered data. More iterations and orthogonalized material attenuation energy functions are required for basis image recovery. Our results suggest this may be due to using fewer views per spectra. Finally, the inverse-crime results were extended to experimental unregistered dual-kV data using a physical rod phantom. The results demonstrate that the cOSSCIR may also be applied to experimental, unregistered, dual-kV data. Furthermore, the unregistered data appears to have minimal impact on material basis quantification using 256 views/kV.

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