Spectral Inconsistency Analysis On a CdTe Photon-Counting Detector

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INTRODUCTION

Photon-counting detector (PCD) based computed tomography (CT) is an emerging spectral imaging technology with great potentials in medical applications[1], by advantages of higher signal-to-noise ratio, better material identification ability and lower dose requirements. In practice, the spectral recording among detector pixels is inconsistent, directly leading to ring artifacts in reconstructed CT images and to inaccuracies in material discrimination[2].

The recorded spectral inconsistency is of great concern. Some related work developed theoretical and numerical models and proposed calibration methods[3][4]. In this work, we analyze the spectral inconsistency of a CdTe photon-counting detector with experimental practice by using flat filters, X-ray tube voltages and current and energy threshold settings, and characterize the factors that affect the inconsistency.

METHOD

As shown in Fig.1, the photon counting CT detector makes use of direct conversion of the energy deposited by each x-ray photon to charge and on counting each photon in pixel. To facilitate the analysis, an air scan model is used as follows.

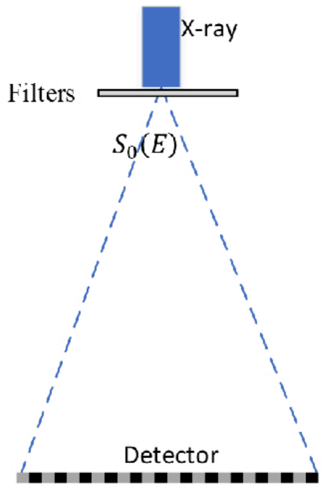

Fig. 1. Photon-counting detector based CT

Air scan:

$$\lambda_i = I_0 \int_{E_{Ti}}^{E_{\max}} dE' \int_0^{+\infty} S_0(E)\, \boldsymbol{R_i}(\boldsymbol{E'};\boldsymbol{E}) dE$$

Where

$\boldsymbol{\lambda_i}$: *photon counts detected in i pixel*

$\boldsymbol{I_0}$: *X-ray incident intensity*

$\boldsymbol{S_0}(E)$: *incident spectrum for the detector*

$\boldsymbol{E_{Ti}}$: *the energy threshold of i pixel*

$\boldsymbol{R_i}(E';E)$: *detector response of i pixel*

$$\frac{\lambda_{ki}}{\lambda_{0i}} = \frac{\int_{E_{Ti}}^{E_{max}} dE' \int_0^{+\infty} S_{k0}(E)\, \boldsymbol{R_i}(\boldsymbol{E'};\boldsymbol{E}) dE}{\int_{E_{Ti}}^{E_{max}} dE' \int_0^{+\infty} S_0(E)\, \boldsymbol{R_i}(\boldsymbol{E'};\boldsymbol{E}) dE}$$

Specifically, a row-by-row self-normalized transmission ratios $\frac{\lambda_{ki}}{\lambda_{0i}}$ are calculated during the data processing, where air scan without any filter in the beam is divided by the flat filter ones, which can reflect the spectral inconsistency of the PCD. It can be observed that energy threshold and spectrum are the important factors affecting the inconsistency. Through physics experiments, we could investigate the details by changing the effective spectra using flat filters, X-ray tube voltages and energy threshold settings.

RESULTS

Experimental setup: A tabletop experiment based XCounter FliteX1 CdTe PCD detector is shown in Fig. 2.

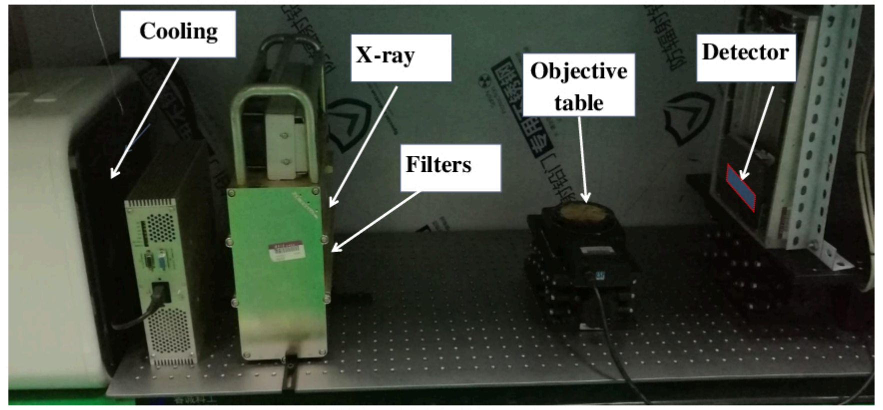

Fig. 2. A tabletop PCD CT system

The testing PCD CT scans are roughly considered as fan-beam CT using one-dimensional line array detector with 1,536 pixels (0.1 mm x 0.1 mm). A set of flat filters made of aluminum and PMMA are sequentially placed in the beam on our tabletop CT. Detector signals are collected at X-ray tube voltages ranging from 80 to 140 kVp, tube current is set as 0.2 mA, and under four energy threshold settings at 24 keV, 30.2 keV, 37.4 keV, 46 keV, respectively.

To determine the inconsistency among the pixels, we calculated the transmission ratios $\frac{\lambda_{ki}}{\lambda_{0i}}$ by using the above flat filters, X-ray tube voltages and current and energy threshold settings, where setting different tube voltages or placing different thickness filters in the beam results in producing different system spectra.

For a better comparative analysis, we also normalized the transmission ratios $\frac{\lambda_{ki}}{\lambda_{0i}}$ to $\mathrm{Nor}(\frac{\lambda_{ki}}{\lambda_{0i}}) = \frac{\frac{\lambda_{ki}}{\lambda_{0i}}}{mean(\frac{\lambda_{ki}}{\lambda_{0i}})}$, and computed its standard deviation to quantify the change of inconsistency under different setting.

Results: The detailed results are shown in Fig.3. Under different incident intensities (tube currents) in Fig.3(a) and Fig.3(b), the self-normalized transmission ratios are almost the same, which indicate the pulse pileup has little impact in the tube current setting ranging from 0.2 mA to 0.35 mA. Under different system spectra (tube voltages) in Fig.1(c) and Fig.1(d), the inconsistency is in a similar trend. Fig.1(e) and Fig.1(f) indicate that the system spectrum (different filter) has some effect on the inconsistency. Due to the incident angle difference, the signals on both sides are filtered down, which may also includes the effects of scattering by the filter. The energy threshold has a greater effect on the inconsistency, in Fig.1(g) and Fig.1(h), the inconsistency trend is varies, and the difference at the same pixel is obvious.

Table I also validates that the inconsistency is related to energy threshold and system spectrum. The inconsistency varies with the energy threshold and has a maximum between 37.4 keV and 46 keV, increases as the spectral energy gets higher.

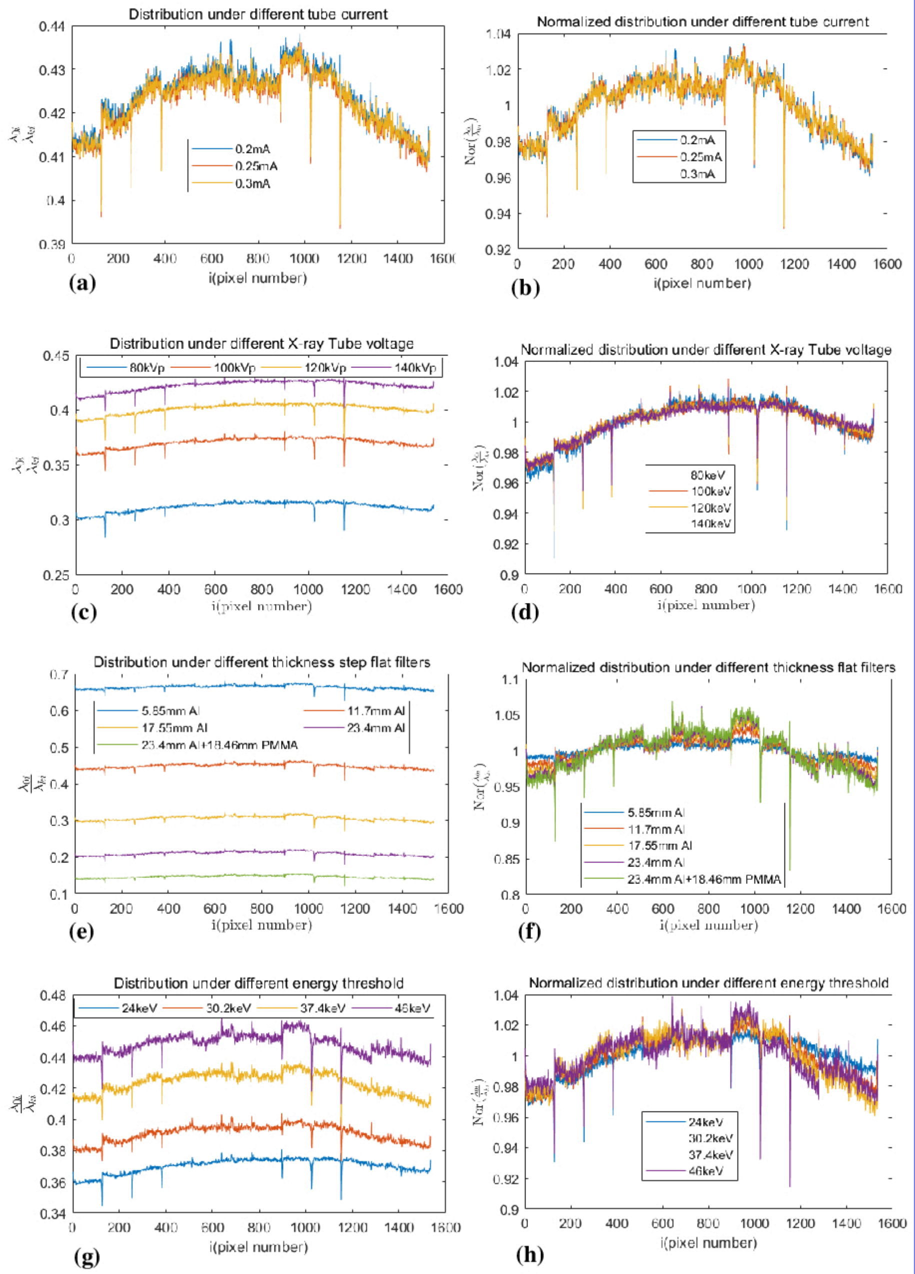

Fig.3 experimental results

TABLE I. Standard deviation of inconsistency under different setting

Std($\mathrm{Nor}(\frac{\lambda_{ki}}{\lambda_{0i}})$)	Threshold 24 keV	Threshold 30.2 keV	Threshold 37.4 keV	Threshold 46 keV
Filter: 5.85 mm Al	7.0e-3	8.0e-3	9.0e-3	8.1e-3
Filter: 11.7 mm Al	12.6e-3	13.8e-3	16.0e-3	14.8e-3
Filter: 17.55 mm Al	17.6e-3	18.4e-3	21.7e-3	20.8e-3
Filter: 23.4 mm Al	21.4e-3	22.1e-3	26.3e-3	25.8e-3

CONCLUSIONS

We present a practical analysis on CdTe photon-counting detector. Our analysis indicates that variation of energy threshold and the effective system spectrum across detector pixels are critical factors that can induce significant recorded spectral inconsistency in photon-counting detector when photon flux is away from the pulse pileup effect. Comparatively speaking, the energy threshold has greater effect on the inconsistency.

Our analysis is meaningful in practical applications, which can provide important physics insights to better understanding of the photon-counting detectors spectral inconsistency. With the findings, one can model the energy threshold variation and the effective system spectrum changes, and then apply calibration and correction to reduce the spectral inconsistency and related CT image artifacts, which can therefore improve the image quality and promote the practical application of photon-counting spectral CT. For further details, please refer to our report in [5].

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