Poster Presentation

Virtual Monochromatic Images in Photon-Counting CT: Is there a Tube Voltage Dependence?

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Purpose:

1. **Standardization need:** Variability in CT values due to manufacturer-specific beam spectra requires standard protocols for consistent diagnostic and clinical outcomes, especially in clinical trials.
2. **Role of VMIs:** Virtual monochromatic images (VMIs), enabled by multi-energy CT systems like photon-counting CT (PCCT), offer high contrast at low energy and reduced artifacts at high energy, but their potential for standardizing CT values is underexplored.
3. **Objective:** This study evaluates tube voltage dependence on CT values in VMIs to ensure reproducibility, stability, and accuracy, addressing a critical research gap and proposing potential for new standardization protocols.

Background:

- Virtual Monochromatic Imaging is a technique that reconstructs monoenergetic-like images by combining low- and high-energy images derived from a polychromatic spectrum at a single energy level. Introduced by Alvarez and Macovski in 1976, VMI extends material-specific imaging capabilities beyond conventional CT [11]. PCCT, with advanced photon-counting detectors, allows for precise energy resolution, offering benefits such as improved contrast resolution, reduced noise, and material decomposition in a single scan [2].
- Dual-source dual-energy CT (DSDECT) complements PCCT by generating VMIs that mitigate imaging artifacts, such as beam hardening and metal artifacts, while optimizing tissue contrast [4]. These advancements have made VMIs valuable in both non-contrast and contrast-enhanced imaging, with applications ranging from iodine quantification to improved artifact reduction [3].
- Despite the advancements in VMI technology, the lack of standardization of CT values across different scanners and acquisition protocols remains a significant challenge. Variability in CT values arises due to differences in tube voltages, energy levels, and scanner types, leading to inconsistencies in quantitative imaging.
- This variability affects clinical workflows and limits the adoption of VMIs for broader applications, such as disease characterization, artificial intelligence in diagnostics, and advanced radiomic studies. Standardizing CT values is essential to ensure reproducibility, stability, and diagnostic reliability across systems and protocols.

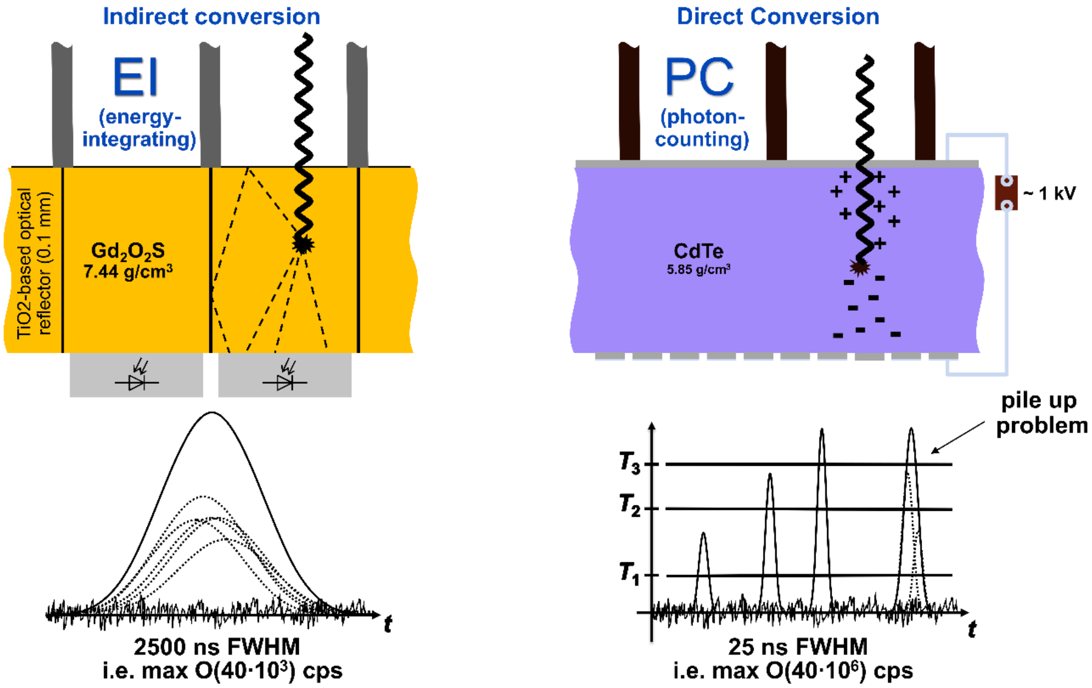
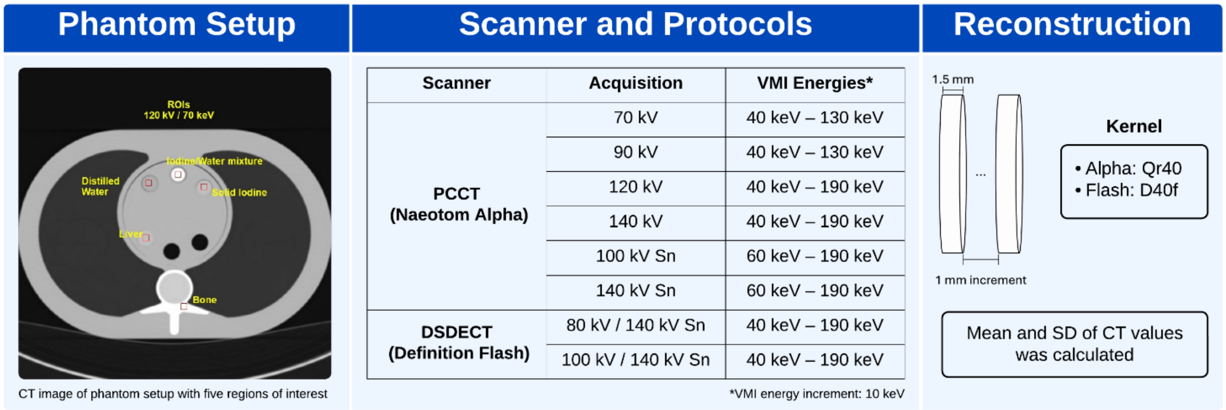


Figure 1: Schematic illustration of EI detector and PC detector. Comparison of x-ray photon interactions are seen for each detector. In EI detectors, an incoming x-ray is converted into a visible photon which is then read-out in a photodiode. These are summed over the measurement time (t) as seen in the plot below. PC detector is made of semiconductor material which directly converts the x-ray photon into an electron-hole pair charge cloud which are detected and weighted individually. Image is adapted from [1].

Current Literature:

Extensive research has focused on optimizing low-keV VMIs for iodine contrast enhancement and high-keV VMIs for reducing imaging artifacts [7]. While these studies have demonstrated improved image quality, contrast-to-noise ratio, and artifact mitigation, they largely overlook intermediate energy levels, which could offer a balance between contrast and noise. Stability studies on VMIs are limited to specific PCCT models or single energy levels, with little exploration of tube voltage effects and cross-system reproducibility. Moreover, comparative analyses between PCCT and DSDECT for standardizing CT values are sparse. Recent studies, such as those by McCollough et al. (2023) and Wolf et al. (2023), have examined VMI stability but within narrow parameters, such as single energy levels or limited radiomic features [4,5]. These gaps in the literature underscore the need for comprehensive studies evaluating VMI reproducibility and standardization across diverse imaging technologies and protocols.

Methods:



Scanner	Acquisition	VMI Energies*
PCCT (Naeotom Alpha)	70 kV	40 keV – 130 keV
	90 kV	40 keV – 130 keV
	120 kV	40 keV – 190 keV
	140 kV	40 keV – 190 keV
	100 kV Sn	60 keV – 190 keV
	140 kV Sn	60 keV – 190 keV
DSDECT (Definition Flash)	80 kV / 140 kV Sn	40 keV – 190 keV
	100 kV / 140 kV Sn	40 keV – 190 keV

*VMI energy increment: 10 keV

- Alpha: Qr40
- Flash: D40f

Mean and SD of CT values was calculated

Figure 2: Figure illustrates methodology explaining semianthropomorphic thorax phantom setup on left, with two scanners and their respective tube voltages and available VMI energy levels with reconstruction steps on the right.

The VMIs in this study were reconstructed using the default standard mode of VMI acquisitions on the PCCT system. The Naeotom Alpha system offers different tube voltages, namely at 70 kV, 90 kV, 120 kV, 140 kV, 100 kV Sn and 140 kV Sn, with the first two being limited for child and small patient scans and last two with tin filtration. For lower tube voltages (70 kV and 90 kV), the VMI energy levels range from 40 keV to 130 keV and the higher tube voltages (120 kV and 140 kV) allow for a broader energy range from 40 keV to 190 keV. For tube voltages with tin filtration, the VMI energy levels range from 60 keV to 190 keV. The automatic dose reduction tool, CARE keV was turned off for manual reconstructions at 10 keV increments for entire range of energy levels. The Relative error analysis was performed with scaled CT values to avoid any inherent behavior of CT values. An additional set of experiments was conducted to assess the stability of VMI values in PCCT at a given tube voltage, repeated five times for reliability. The standard tube voltages 70 kV, 90 kV, 120 kV, and 140 kV were used and VMIs were reconstructed with the same phantom setup. Energy levels from 40 keV to 130 keV were included to enable direct comparison across all tube voltages.

Results: As expected the contrast decreased with increase in the energy levels. For all VMI energy levels (40-190 keV) and all regions of interest, the measured VMI CT values were consistent with theoretical expectations at 70 kV on the Alpha system. The mean CT values at 70 keV for all tube voltages are tabulated in

Table 1: CT values for all tube voltages at 70 keV energy level for all regions of interest.

Tube voltages	Solid Iodine	Water	Bone	Liver	Iodine/water
70 kV	118 HU	8 HU	546 HU	96 HU	777 HU
90 kV	113 HU	8 HU	553 HU	102 HU	760 HU
120 kV	109 HU	4 HU	550 HU	102 HU	754 HU
140 kV	107 HU	2 HU	546 HU	102 HU	750 HU
100 kV Sn	106 HU	-2 HU	541 HU	95 HU	768 HU
140 kV Sn	97 HU	-9 HU	521 HU	90 HU	778 HU

80 kV/140 kV Sn	108 HU	-1 HU	557 HU	101 HU	806 HU
100 kV/140 kV Sn	108 HU	-2 HU	552 HU	100 HU	809 HU

The elevated CT values seen at 70 kV compared to other tube voltages is linked to issues observed in VMIs at higher tube voltages on the Naeotom Alpha PCCT. The relative error analysis performed with 120 kV Alpha values as baseline showed larger deviations at low energy levels (below 70 keV) across all tube voltages, particularly for high-contrast materials like iodine and bone. Tin filtration protocols introduced slightly larger deviations due to spectrum separation. Water, solid iodine, bone and liver demonstrated stable relative errors within ±2%, while iodine/water mixture exhibited the largest deviations, up to ±4.4%, at lower energy levels. Deviations decreased at higher energy levels (above 100 keV), where VMIs stabilized, offering more consistent CT values. The repeated experiments on Alpha system supports the reproducibility of VMI values and potential to be used for standardization.

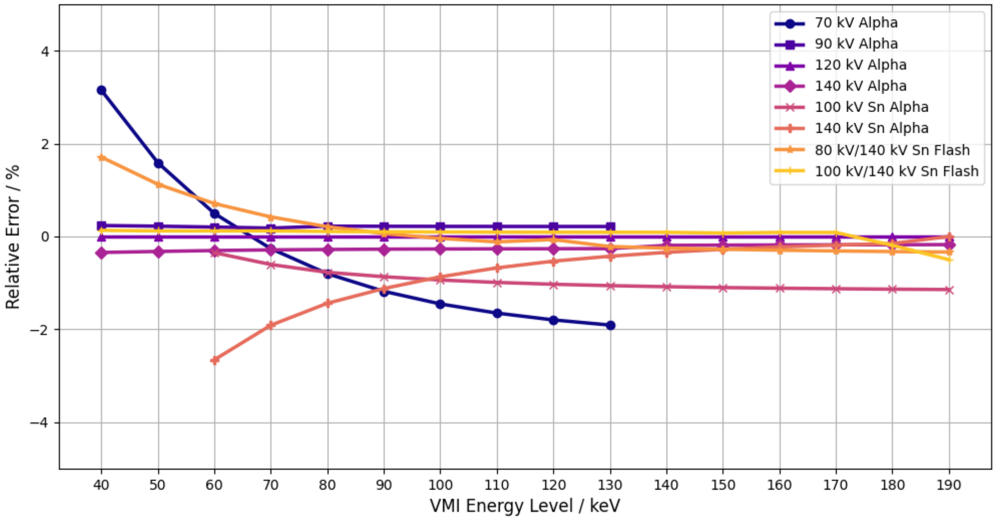


Figure 3: Relative errors for Bone with respect to 120 kV Naeotom Alpha VMI values

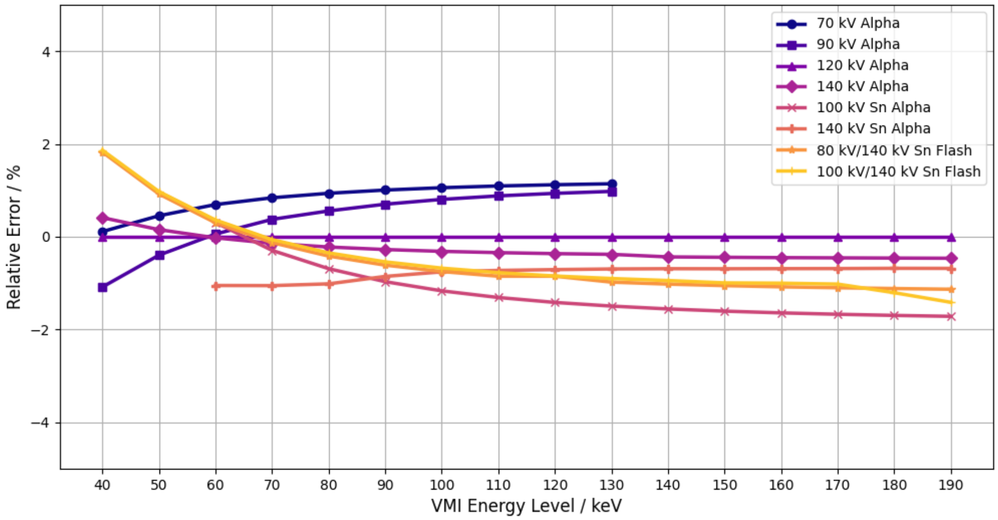


Figure 4: Relative errors for Solid iodine with respect to 120 kV Naeotom Alpha VMI values

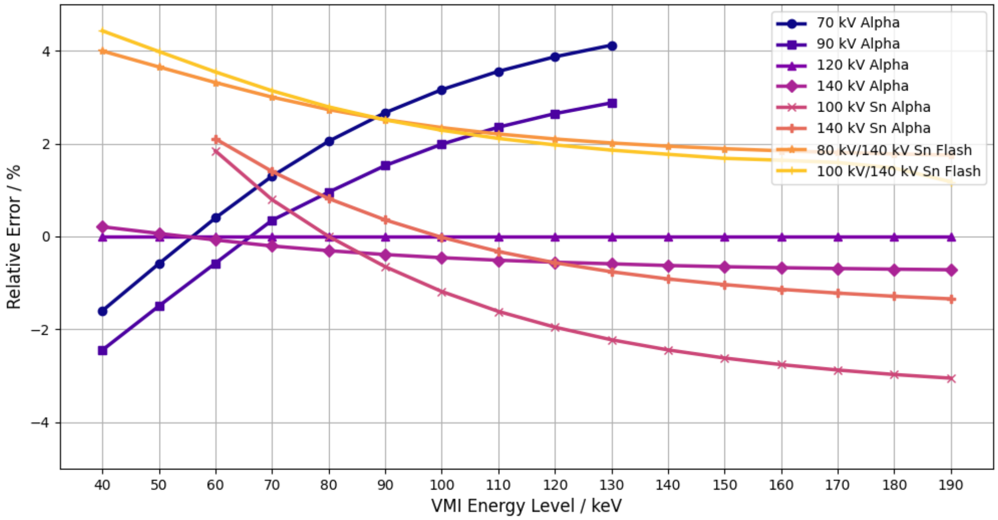


Figure 5: Relative errors for iodine/water mixture with respect to 120 kV Naeotom Alpha VMI values

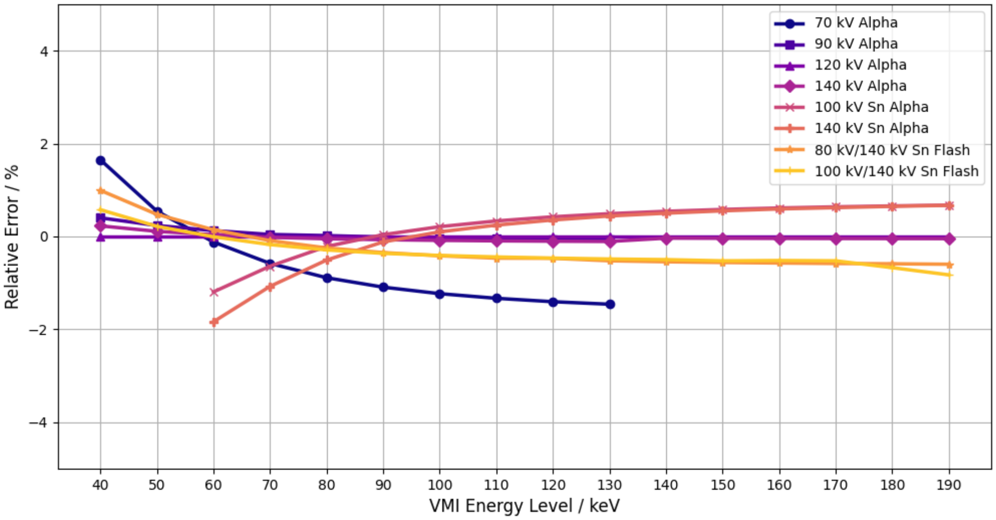


Figure 6: Relative errors for Liver with respect to 120 kV Naeotom Alpha VMI values

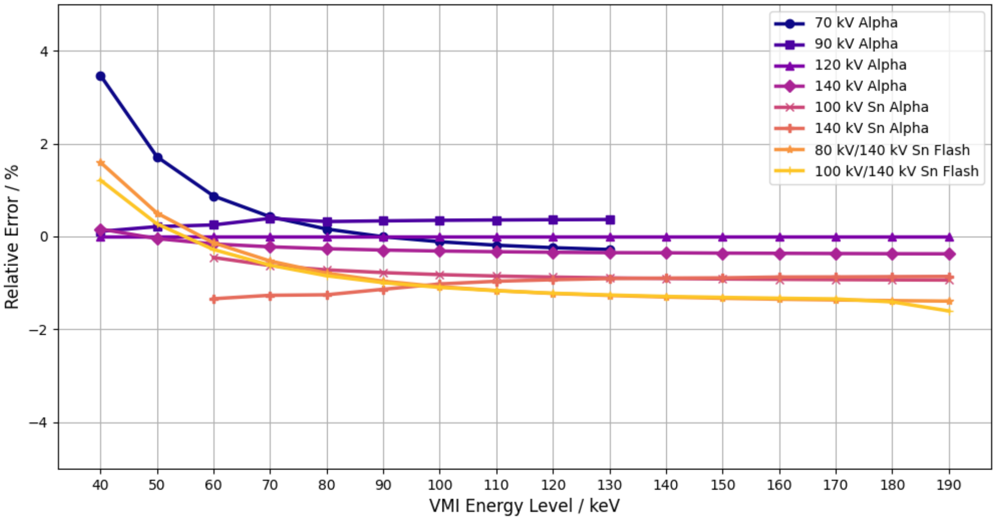


Figure 7: Relative errors for Water with respect to 120 kV Naeotom Alpha VMI values

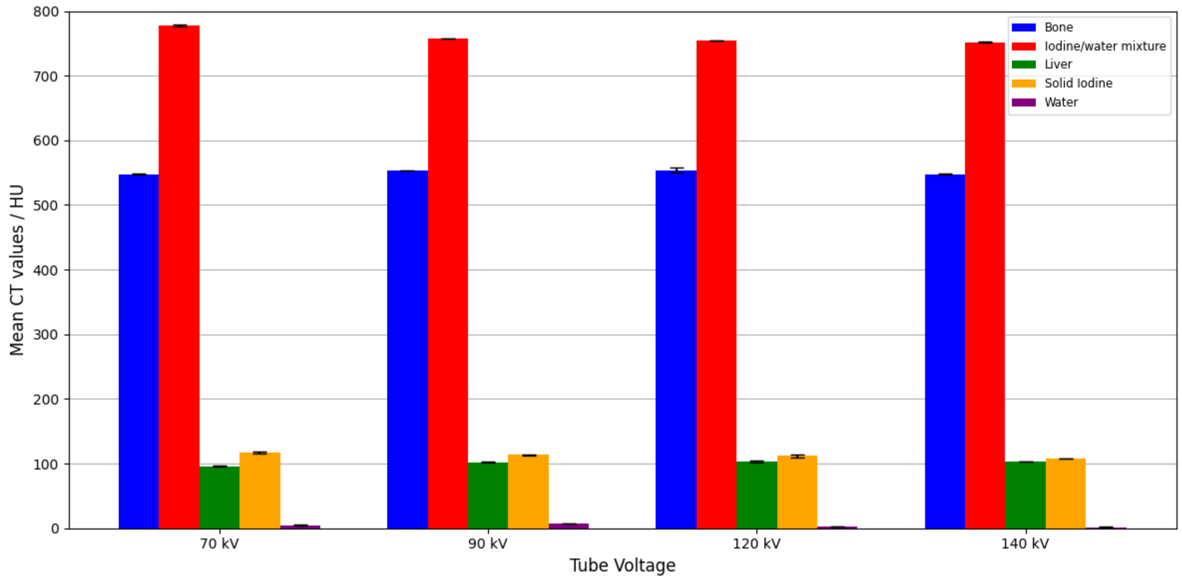


Figure 8: Bar graph representing CT values from repeated experiments at four tube voltages 70 kV, 90 kV, 120 kV and 140 kV Naeotom Alpha for VMI energy level 70 keV. CT values show robustness for all five regions of interest regardless of tube voltage.

Conclusion: VMIs offer potential for standardization, improving diagnostic accuracy and stability in clinical practice. While VMIs demonstrated consistency, the observed ±2% error, though minor for material differentiation, could impact quantitative assessments in tasks like tumor growth monitoring. Additionally, the need for regular maintenance and quality assurance to address spectral distribution and detector response issues is crucial for ensuring reliable diagnostic outcomes.

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