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Determination of Optimal Image Type and Lowest Detectable Concentration for Iodine Detection on a Photon Counting Detector-Based Multi-Energy CT System

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Abstract

Photon counting detector (PCD) based multi-energy CT is able to generate different types of images such as virtual monoenergetic images (VMIs) and material specific images (e.g., iodine maps) in addition to the conventional single energy images. The purpose of this study is to determine the image type that has optimal iodine detection and to determine the lowest detectable iodine concentration using a PCD-CT system. A 35 cm body phantom with iodine inserts of 4 concentrations and 2 sizes was scanned on a research PCD-CT system. For each iodine concentration, 80 repeated scans were performed and images were reconstructed for each energy threshold. In addition, VMIs at different keVs and iodine maps were also generated. CNR was measured for each type of images. A channelized Hotelling observer was used to assess iodine detectability after being validated with human observer studies, with area under the ROC curve (AUC) as a figure of merit. The agreement between model and human observer performance indicated that model observer could serve as an effective approach to determine optimal image type for the clinical practice and to determine the lowest detectable iodine concentration. Results demonstrated that for all size and concentration combinations, VMI at 70 keV had similar performance as that of threshold low images, both of which outperformed the iodine map images. At the AUC value of 0.8, iodine concentration as low as 0.2 mgI/cc could be detected for an 8 mm object and 0.5 mgI/cc for a 4 mm object with a 5 mm slice thickness.

Keywords

Photon-counting detectors; computed tomography; multi-energy; iodine quantification; model observer

1. BACKGROUND AND PURPOSE

Photon counting detectors (PCD) count individual photons and measure their energies, thus enabling multi-energy CT using two or more energy bins in a single acquisition. In addition to the conventional single-energy-like images, various types of derived images can be generated from multi-energy CT, such as material specific images (e.g., iodine map) [1] and virtual monoenergetic images (VMIs) [2–4]. Various image types have enabled a wide range of clinical applications using multi-energy CT, such as detection of renal or adrenal lesions [3, 5]. VMI at lower keV has higher iodine contrast due to the increased attenuation of

iodine at energies closer to its k-edge [6]. However, image noise may also increase for VMI at lower keV. Therefore, contrast noise ratio (CNR) in VMI highly depends on the specific keV and an optimal keV may exist with the highest CNR. Material-specific images generated from multi-energy acquisitions allow differentiation and quantification of various types of materials [3]. The benefit of material specific images is its capability to enhance the visibility of the material of interest (e.g., iodine) while suppressing other materials (e.g., soft tissue), which enhances detectability [1]. However, the material decomposition process usually increases image noise which negatively impacts the detectability. In addition, the detectability of iodine signal could also be affected by other image properties such as spatial resolution and noise texture. This leads to two natural questions: which of the image types provides the best performance in terms of iodine detection, and what is the lowest detectable iodine concentration using PCD CT? Answers to these questions could help minimize either iodine contrast dose or radiation dose to the patients without degrading diagnostic performance. Therefore, the purpose of this study is to determine the image type that has the optimal iodine detection in PCD-based multi-energy CT, and to determine the lowest iodine concentration that can be reliably detected.

2. METHODS AND MATERIALS

Experimental Setup and Data Acquisition

A customized cylindrical phantom was made of water equivalent materials with three holes drilled to mimic vessels with sizes of 4 and 8 mm diameter. The vessels were filled with iodine contrast at one of the 4 concentrations (0.2, 0.5, 1.0 and 2.0 mgI/cc) each time. The customized phantom was then placed into a 35 cm cylindrical solid water phantom (Quality Assurance in Radiology and Medicine, Moehrendorf, Germany) representing torso attenuation of a medium size adult (Figure 1). The whole phantom was scanned on a whole-body research PCD-CT scanner built on the platform of a 2nd generation dual source CT scanner (Definition CounT, Siemens Healthcare, Forchheim, Germany). Detailed descriptions of this PCD-CT system could be found elsewhere [7–9]. For each iodine concentration, the phantom was scanned 80 times with the following scanning techniques: 140 kV, 25 and 75 keV energy thresholds, 100 effective mAs, 0.6 helical pitch, and 5.8 mGy volume CT dose index (CTDI_{vol}). Images were reconstructed with a quantitative, medium smooth kernel (D30) and 5 mm slice thickness. VMIs at 50, 60 and 70 keV were generated using a vendor-provided software (eXamine, Siemens Healthcare, Forchheim, Germany). Iodine maps were generated using commercial dual energy post-processing software (Syngo Via, Siemens Healthcare, Forchheim, Germany). Mean and standard deviation of CNR values were calculated and compared between full-spectrum, threshold-low (TL) images, VMI, and iodine map images.

Model Observer Analysis

Channelized Hotelling observer (CHO) was used to predict and compare the performance of iodine detection in each of the image types: TL, VMI, and iodine map images [10–12]. For each image type, the test variable λ is given by:

$$\lambda = \omega_{CHO}^t g_C$$

where g_c is the channel output of the test image and ω_{CHO} is the CHO template defined as:

$$\omega_{CHO} = S_C^{-1} [\overline{g_{sc}} - \overline{g_{bc}}]$$

S_C is the intraclass channel scatter matrix calculated as the average of the channel output covariance matrix of images with signal and background only. $\overline{g_{sc}}$ and $\overline{g_{bc}}$ denote the average channel values of signal present and background only within regional of interests (ROIs).

Gabor filters were used in the CHO, which have been shown to represent the response of human visual system [13]:

$$G(f) = \exp \left[-4(\ln 2) \left((x - x_0)^2 + \frac{(y - y_0)^2}{\omega_s^2} \right) \right] \cos [2\pi f_c ((x - x_0) \cos \theta + (y - y_0) \sin \theta) + \beta]$$

where ω_s is the channel width, f_c is the central frequency (both in cycles per pixels), θ is the orientation angle and β is a phase offset. A total of 20 channels were used in this study with 5 frequency passbands ($f_c = 3/256, 3/128, 3/64, 3/32, 3/16$), 4 orientations ($\theta = 0, \pi/4, \pi/2, 3\pi/4$) and 1 phase ($\beta = 0$) [14]. Internal noise was added to the test variables and area under the ROC curve (AUC) was calculated using a nonparametric method and served as the figure of merit for the detection task.

Human Observer Study

A 2-alternative force choice (2AFC) test was generated with the TL and VMI of the 4 mm inserts and human observer study was conducted to validate the model observer results. Three medical physicists served as the human observers and each reader evaluated 6 data datasets (2 concentration: 0.5 mgI/cc and 1.0 mgI/cc; 3 image types: TL, VMI at 50 and 70 keV), with each dataset contains 80 trials corresponding to 80 repeated scans. All reader studies were performed on a calibrated reading workstation with a customized GUI built with MATLAB (MathWorks, Massachusetts, United States). Percent correct (PC) of the 2AFC task was calculated. Spearman correlation was performed to compare the correlation between PC of human observer and AUC of model observer.

3. RESULTS

Figure 2 shows the example full spectrum (TL) images, VMI at 70 keV and iodine map images from the PCD-CT scans, with iodine concentrations of 0.2 mgI/cc, 0.5 mgI/cc, 1.0 mgI/cc, and 2.0 mgI/cc. In general, the iodine inserts are more visible for higher concentrations and larger sizes, as expected. However, substantial difference is observed for contrast and noise among different types of images.

Figure 3 shows that CNR of the 4mm iodine inserts at different concentrations and image types. As observed, both VMI and iodine map images had higher CNR than that of TL images. For VMI, 50 keV images had higher CNR than that of 70 keV. At the concentration of 1.0 mgI/cc, iodine CNR was 1.47, 1.05, 1.27 and 0.85 for VMI at 50 and 70 keV, iodine map, and TL images.

Figure 4 shows the performance comparison between model observer and human observer. The performance of model observer in general agreed well with that of human observer, with a Spearman correlation coefficient $\rho = 0.941$ with $P < 0.01$. This validated the use of model observer to characterize iodine detection.

Figure 5 shows the AUC values calculated based on the full spectrum and VMI (50, 60 and 70 keV) of the 4 mm inserts at different iodine concentrations. Unlike the CNR results which showed that 50 keV VMI was superior to the 70 keV, AUC values demonstrated 70 keV VMI had the highest detectability among different keVs. Therefore, 70 keV was selected as the representative keV of VMI in the following analysis.

Figure 6 shows the AUC values for iodine detection at different sizes (4 mm and 8 mm) and concentrations (0.2, 0.5, 1 and 2 mgI/cc) using VMI, iodine map and TL images. For all sizes and concentrations, similar performance of iodine detection was observed between VMI and TL images, both of which were better than that of iodine map. For the 4 mm insert with 1.0 mgI/cc concentration, AUC values were 0.959, 0.951, and 0.775 for VMI, TL images, and iodine map. Based on these data, the lowest detectable iodine concentration can be readily derived once a target AUC value is provided. For example, if 0.8 is considered the lowest acceptable AUC in clinical practice, the lowest detectable iodine concentration would be 0.2 mgI/cc for the 8 mm insert, and 0.5 mgI/cc for the 4 mm insert.

4. DISCUSSION

In this study, we investigated the performance of iodine detection in different types of multi-energy CT images obtained from a PCD-CT scanner. To the best of our knowledge, this is the first study to systematically compare iodine detectability in multiple image types including full spectrum threshold low, VMI and iodine map images from PCD-based multi-energy CT acquisition.

A CHO with Gabor channels was used for model observer study and AUC under ROC curve was selected as the figure of merit after validation with the performance of human observers. The agreement between model and human observer performance indicated that model observer could serve as an effective approach to determine optimal image type for clinical practice. For VMI at different keVs, 70 keV had the highest AUC value, although its CNR was lower than those of 50 and 60 keV. This discrepancy could be due to the difference of spatial resolution and noise texture at different keV [15], which were effectively incorporated in the CHO while excluded in CNR calculation. Comparing different types of images, the optimal VMI at 70 keV had similar iodine detectability as that of threshold low images, both of which outperformed the iodine map images, although the iodine map had the highest CNR.

Chandarana et al demonstrated iodine quantification maps generated from dual-source, dual-energy acquisitions could determine 0.5mgI/cc iodine enhancement in renal lesions with size larger than 2.0 cm [16]. Our data suggested that the lowest detectable iodine concentration was 0.2 mgI/cc for an 8 mm object, and 0.5 mgI/cc for a 4 mm object, if 0.8 is considered to be the lowest acceptable AUC in clinical practice.

5. CONCLUSIONS

In this study, we demonstrated that the most sensitive image type for iodine detection in multi-energy CT can be determined and the lowest detectable iodine concentration can be estimated using channelized Hotelling observer. Results demonstrated the virtual monoenergetic images at 70 keV had similar detectability compared to the threshold low images, both of which outperform the iodine map images. The lowest detectable iodine concentration depends on the object size, with as low as 0.2 mgI/cc detectable for an 8 mm object.

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Figure 1.
Experimental setup: a water equivalent cylinder with vessels of different diameters was inserted into a 35 cm QRM phantom.

Figure 2.

Representative images from 140 kV full spectrum (TL), virtual monoenergetic image at 70 keV and iodine map at different iodine concentrations.

Figure 3.
CNR of threshold-low (TL, full spectrum), VMI at 50 and 70 keV, and iodine map images.

Figure 4.
Performance (AUC) comparison between model observer (MO) and human observer (HO)

Figure 5. Area under curve (AUC) values from CHO for iodine detection using VMI at 50, 60 and 70 keV.

Figure 6.

Area under curve (AUC) comparison between full spectrum (TL), 70 keV VMI and iodine map for 4 and 8 mm size inserts with different iodine concentrations.