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Assessment of 70-keV virtual monoenergetic spectral images in abdominal CT imaging: A comparison study to conventional polychromatic 120-kVp images

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Abstract

Purpose: To evaluate the image quality of 70-keV virtual monoenergetic (monoE) abdominal CT images compared to 120-kVp polychromatic images generated from a spectral detector CT (SDCT) scanner.

Methods: This prospective study included generation of a 120-kVp polychromatic dataset and a 70-keV virtual monoE dataset after a single contrast-enhanced CT acquisition on a SDCT scanner (Philips Healthcare) during portal venous phase. The attenuation values (HU), noise, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were measured in the liver, spleen, pancreas, kidney, aorta, portal vein, and muscle. The subjective image quality including noise, soft tissue contrast, sharpness, and overall image quality were graded on a 5-point Likert scale by two radiologists independently (1-worst image quality, 5-best image quality). Statistical analysis was performed using paired sample t test and Fleiss's Kappa.

Results: Fifty-five patients (54.3 ± 16.8 y/o; 28 M, 27 F) were recruited. The noise of target organs was significantly lower in virtual monoE images in comparison to polychromatic images ($p < 0.001$). The SNR and CNR were significantly higher in virtual monoE images ($p < 0.001$ for both). Subjective image quality of 70-keV virtual monoE images was significantly better ($p < 0.001$) for all evaluated parameters. Median scores

for all subjective parameters were 3.0 versus 4.0 for polychromatic vs virtual monoE images, respectively. The inter-reader agreement for overall image quality was good (Kappa were 0.767 and 0.762 for polychromatic and virtual monoE images, respectively). **Conclusion:** In abdominal imaging, 70-keV virtual monoE CT images demonstrated significantly better noise, SNR, CNR, and subjective score compared to conventional 120-kVp polychromatic images.

Key words: Spectral detector CT—SDCT—Dual-layer CT—Monoenergetic image

Computed tomography (CT) has become an established technology in the clinical care because of its wide availability, low cost compared to MRI, and consistent image quality [1]. In traditional CT, X-ray generated by the X-ray tube has a continuous energy distribution called polychromatic X-ray. Since the introduction of CT, polychromatic 120-kVp X-rays have been widely used in clinical diagnosis as the standard acquisition in abdominal CT imaging [2–6].

In recent years, the emergence of spectral imaging has improved the detection rate of diseases and has offset some issues of the traditional CT imaging including beam hardening artifact and tissue characterization [3]. Currently, three spectral CT scanners

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are available, including (1) CT scanner with 2 X-ray tubes spaced approximately 90° apart and 2 detector sets manufactured by Siemens Medical Solutions (dual source dual detector), (2) CT Scanner with one rapid kVp-switching source and new detector based on gemstone scintillator materials manufactured by GE Healthcare (single source dual energy), and (3) CT scanner with a single source and two layers of detectors manufactured by Philips Healthcare (single source dual detector) which enables acquisition of conventional 120-kVp CT images and retrospective generation of different spectrums of virtual monoenergetic CT images (spectral detector CT, SDCT). Although there is only a single X-ray source, there are two layers of detector. The top layer selectively absorbs low energy photons and the bottom layer absorbs high energy photons, thus providing two distinct energy datasets. In addition to the conventional 120-kVp images that are obtained by utilizing combined data from both detector layers, additional spectral analysis can be obtained by decomposition of the low and high energy data into photoelectric and Compton data components of attenuation.

The advantages of spectral CT imaging include the ability to generate virtual non-contrast images, which has the potential to decrease radiation and cost, iodine map, effective atomic number (Z), and virtual monoenergetic images at different keV levels throughout the X-ray spectrum. These on-demand virtual monoE images can give us extra information and can improve the evaluation and characterization of lesions. Virtual monoE images can also reduce different artifact (metal, beam hardening, and blooming) [7–11]. No need for prospective patient selection, no rotation time limitations, full FOV, and no cross scatter are among the unique advantages of SDCT in comparison to the other spectral technologies. However, SDCT has some limitations including short Z axis (4 cm) and requirement of at least 120-kVp tube potential.

We compared 70-keV virtual monoE images to 120-kVp polychromatic images generated from a SDCT scanner in this study. The choice of 70-keV was based on previously published reports which showed the lowest image noise and the highest contrast-to-noise ratio at 70-keV among more than hundred sets of virtual monoenergetic images in the range of 40–140 keV (2). Although there are few published articles comparing the spectral CT imaging with the conventional 120-kVp CT imaging, to the best of our knowledge, no clinical study has compared SDCT to conventional 120-kVp CT images.

The purpose of this study was to evaluate the objective and subjective image quality of 70-keV virtual monoE images compared to 120-kVp polychromatic images generated from a SDCT scanner.

Materials and methods

Study population

This prospective HIPPA compliant study was approved by the institutional review board of our institution. Written informed consent was obtained from all of the patients. From October 2013 to December 2015, patients older than 18 years who scheduled for contrast-enhanced CT imaging of the abdomen or abdomen and pelvis as part of their clinical standard-of-care study were included. CT scans with suboptimal portal phase (mean attenuation <70 HU in portal vein), metal artifact, or lack of the upper abdomen were excluded. Fifty-five patients were finally recruited to our study. The scan time (the time patient was in the CT machine) and radiation dose were not affected by using SDCT scanner.

Imaging protocol and reconstruction

Abdominal examinations were performed for various clinical indications, including pancreas, liver or renal mass evaluation, pre-renal and liver transplant assessment, or abdominal pain evaluation using an SDCT scanner (product name IQon, Philips, Cleveland, OH). Post-contrast imaging was performed in the portal venous/nephrographic (65–120 s delay) phase only or multiphasic including the arterial, portal venous/nephrographic, and excretory (5–10 min delay) phases as indicated clinically. However, for the purpose of this study, image analysis was done on portal venous phase images. Isovue 370 (Bracco Diagnostics Inc, Princeton, NJ) or Ultravist 350 (Bayer HealthCare, Wayne, NJ) was used as contrast and the dose varied depending on the protocol and weight. All examinations were performed at a tube potential of 120-kVp and a detector configuration of 64×0.625 mm with automatic tube current modulation. Scans were performed at pitch range of 0.5–1.17 and gantry rotation time of 0.3–0.75 s depending on the clinical protocol. All examinations were performed in the supine position. Slice thickness was 2 mm at 1 mm increments. On the SDCT, images were obtained directly from the scanner which combined the data from the top and bottom detector layers and utilized iterative reconstruction algorithm (iDose⁴ Level 3). 70-keV virtual monoE images were reconstructed retrospectively using the spectral diagnostic suite (SPDS, Philips, Haifa, Israel).

Image analysis

Image analysis was performed retrospectively. Conventional 120-kVp and 70-keV virtual monoE images were sent to a separate viewing station (SPDS, Philips, Haifa, Israel). Conventional 120-kVp and 70-keV virtual monoE post-contrast images were evaluated side by side

Fig. 1. Polychromatic 120-kVp vs. 70-keV virtual monoE images. Significantly better overall image quality, noise, sharpness, and tissue contrast was observed in our study for virtual monoE images as compared to the conventional 120-kVp polychromatic images.

Table 1. Subjective scoring of image quality using 5-point Likert scale

	Image noise	Soft tissue contrast	Sharpness	Overall image quality
5	Minimum/no noise	Excellent	Sharpest	Best
4	Less than average	Above average	Above average	Above average
3	Average	Average	Average	Average
2	Above average	Below average	Below average	Below average
1	Unacceptable	Poor	Blurry	Unacceptable

for objective analysis (Fig. 1). Multiple regions of interest (ROI) were drawn by one of the two readers in liver (segment 1), spleen, pancreas, portal vein, renal cortex, abdominal aorta, paraspinal muscle, and abdominal fat in the posterior abdominal wall (as background) on conventional 120-kVp images. The ROI was then copied to the 70-keV virtual monoE images to ensure constant size and location of the ROI. The size of each ROI was approximately 20 mm. Smaller size was used when 20 mm ROI placement was not possible.

Objective image quality

CT attenuation values (Hounsfield units [HU]) and image noise [standard deviation (SD)] were recorded for all image sets at different locations. The signal-to-noise ratio (SNR) was then calculated by dividing the CT attenuation values by the corresponding image noise. The contrast-to-noise ratio (CNR) of the liver, kidney, pancreas, spleen, portal vein, and aorta were calculated using the following formulae [2, 12–14]:

$$\text{CNR}_{\text{Liver, Kidney, Pancreas, Spleen}} = (\text{ROI}_{\text{Liver, Kidney, Pancreas, Spleen}} - \text{ROI}_{\text{Background}}) / \text{SD}_{\text{Background}}$$

$$\text{CNR}_{\text{Portalvein}} = (\text{ROI}_{\text{Portalvein}} - \text{ROI}_{\text{Liver}}) / \text{SD}_{\text{Background}}$$

$$\text{CNR}_{\text{Aorta}} = (\text{ROI}_{\text{Aorta}} - \text{ROI}_{\text{Muscle}}) / \text{SD}_{\text{Background}}$$

ROI in multiple organs denote the attenuation values (HU) of these organs. SD and ROI background denotes the image noise and attenuation of fat, respectively [2, 12–14].

Subjective image quality

Subjective image quality of each conventional 120-kVp and 70-keV virtual monoE image was assessed by two blinded radiologists with 6 and 12 years of experience in abdominal imaging independently. The image quality, including noise, soft tissue contrast, sharpness (with re-

Fig. 2. Mean attenuation (HU) in conventional 120-kVp polychromatic images in comparison to 70-keV virtual monoE images. Kidney, aorta, and portal vein demonstrated significantly higher CT attenuation in virtual monoE images as compared to conventional 120-kVp images ($p < 0.05$).

CT attenuation of the liver, spleen, and pancreas was comparable between virtual monoE images and conventional 120-kVp images ($p > 0.05$). Box shows 25th and 75th percentiles. Error bars demonstrated 2 standard deviations from mean.

Table 2. Comparison of CT attenuation and noise between 70-keV virtual monoE images and conventional 120-kVp polychromatic images

Organ	Attenuation value (HU)			Noise (SD)		
	Poly	monoE	<i>p</i> value	Poly	monoE	<i>p</i> value
Liver	95.14 ± 21.42	96.30 ± 24.18	0.173	18.23 ± 4.89	14.64 ± 3.68	<0.001
Spleen	104.68 ± 19.63	104.72 ± 21.94	0.954	15.68 ± 5.09	12.55 ± 4.18	<0.001
Pancreas	88.69 ± 20.67	88.61 ± 21.22	0.840	16.86 ± 4.04	13.88 ± 3.42	<0.001
Kidney	153.06 ± 36.78	157.10 ± 40.39	0.001	17.49 ± 5.42	14.77 ± 5.30	<0.001
Aorta	144.50 ± 41.34	148.75 ± 46.35	0.028	19.10 ± 5.04	15.38 ± 4.17	<0.001
Portal vein	138.51 ± 31.77	144.84 ± 34.25	<0.001	18.34 ± 5.00	15.42 ± 4.70	<0.001

spect to the borders of organs and intrahepatic vascular wall), and overall image quality were graded on a 5-point Likert scale (1—worst image quality, 5—best image quality, ≤ 3 defined as fair, and > 3 defined as good) (Table 1).

Statistical analysis

Statistical analysis was performed using SPSS version 21.0 (IBM Corp, 2012). Quantitative variables were expressed as mean ± standard deviation (SD). Paired *t* test was used to compare the attenuation value (HU), objective image noise, SNRs, and CNRs among the polychromatic and 70-keV virtual monoE images. A *p* value of < 0.05 was considered statistically significant. Fleiss's Kappa and McNemar's test were used to evaluate the agreement between the two readers for the subjective image quality scoring. Poor reliability was defined

as a kappa of < 0.4 , fair reliability as 0.4 – 0.6 , good reliability as > 0.6 – 0.8 , and excellent reliability as > 0.8 .

Results

Fifty-five patients (28 males, 27 females) with the mean age of 54.3 ± 16.9 years old were recruited in our study.

The objective image quality measurements including the CT attenuation (HU), noise (SD), SNR, and CNR in standard 120-kVp polychromatic images versus 70-keV virtual monoE images are summarized in Tables 2 and 3.

At 70-keV virtual monoE level, there was no significant difference in CT attenuation of the liver, spleen, and pancreas but attenuation of the kidney, aorta, and portal vein was significantly higher ($p < 0.05$) in virtual monoE images in comparison to polychromatic images (Fig. 2). The noise of target organs was significantly lower ($p < 0.001$) in virtual monoE images as compared to polychromatic images (Table 2; Fig. 3).

Fig. 3. Transverse abdominal CT images obtained in a 28-year-old woman. The noise is higher in polychromatic images (*left*) in comparison to virtual monoE images (*right*). The Noise in the liver was 12.3 in conventional 120-kVp polychromatic images and 9.8 in virtual monoE images. The SNR and CNR are higher in virtual monoE images (*right*) in

comparison to polychromatic images (*left*). The SNR in the spleen was 9.61 in conventional 120-kVp polychromatic images and 12.34 in virtual monoE images. The CNR in the spleen was 18.70 in conventional 120-kVp polychromatic images and 24.52 in virtual monoE images.

The SNR of target organs was significantly higher ($p < 0.001$) in virtual monoE images (Fig. 3). The CNR of the target organs was also significantly higher ($p < 0.001$) in virtual monoE images (Table 3; Fig. 3).

Subjective image quality of 70-keV virtual monoE images was significantly better ($p < 0.001$) for all evaluated parameters, including noise, soft tissue contrast,

sharpness, and overall image quality (Fig. 4). Median scores (poly vs. virtual monoE) were 3.0 and 4.0 for all subjective parameters (Table 4).

The inter-observer agreement for all evaluated parameters was good and Kappa values for polychromatic and virtual monoE images are summarized in Table 5.

Fig. 4. Axial CT images of the abdomen obtained in an 87-year-old man. 70-keV virtual monoE images (*right*) had better subjective scores in comparison to polychromatic 120-kVp images (*left*).

Table 3. Comparison of SNR and CNR between 70-keV virtual monoE images and conventional 120-kVp polychromatic images

Organ	SNR			CNR		
	Poly	monoE	<i>p</i> value	Poly	monoE	<i>p</i> value
Liver	5.84 ± 2.01	6.99 ± 2.63	<0.001	19.33 ± 5.89	24.29 ± 7.17	<0.001
Spleen	7.31 ± 2.50	9.17 ± 3.46	<0.001	20.05 ± 5.78	25.10 ± 7.16	<0.001
Pancreas	5.66 ± 2.23	6.91 ± 2.79	<0.001	18.71 ± 5.72	23.34 ± 6.87	<0.001
Kidney	9.55 ± 3.91	11.72 ± 4.62	<0.001	24.84 ± 7.77	31.62 ± 9.76	<0.001
Aorta	8.08 ± 3.10	10.31 ± 4.13	<0.001	8.70 ± 3.97	11.60 ± 5.53	<0.001
Portal vein	8.00 ± 2.62	10.09 ± 3.64	<0.001	4.17 ± 2.84	5.91 ± 3.81	<0.001

Table 4. Subjective image quality of 70-keV virtual monoE images as compared to conventional 120-kVp polychromatic images

	Poly (median)	monoE (median)	<i>p</i> value
Noise	3	4	<0.001
Soft tissue contrast	3	4	<0.001
Sharpness	3	4	<0.001
Overall image quality	3	4	<0.001

Table 5. Inter-observer agreement (kappa scores) for subjective evaluation of 70-keV virtual monoE images and conventional 120-kVp polychromatic images

	Poly	monoE
Noise	0.847	0.806
Soft tissue contrast	0.735	0.764
Sharpness	0.803	0.703
Overall image quality	0.767	0.762

Discussion

In our prospective study, we compared the subjective and objective image quality of 70-keV virtual monoE images to 120-kVp standard polychromatic images obtained from the SDCT scanner. Virtual monoE images at 70-keV images provided significantly reduced objective image noise, increased SNR, and CNR. The qualitative scores for noise, soft tissue contrast, sharpness, and overall image quality were higher in 70-keV images in comparison to conventional 120-kVp polychromatic images.

Yamada et al. compared quantitative and subjective image quality of abdominal CT at 70-keV virtual monoE images to conventional 120-kVp polychromatic images from fast kVp-switching dual-energy CT [2]. Filtered back projection (FBP) and iterative reconstruction (IR) were generated for both virtual monoE 70-keV and polychromatic 120-kVp images. They compared virtual monoE 70-keV and polychromatic 120-kVp images both subjectively and objectively. They concluded that 70-keV virtual monoE images with FBP and IR have a higher image quality than polychromatic 120-kVp images. The quality of 70-keV images with IR was superior to 70-keV images with FBP [2]. In our study, we compared the subjective and objective image quality of abdominal CT

from the SDCT scanner, while in Yamada et al. study patients underwent sequential fast kVp-switching dual-energy (80/140 kVp) and single-energy (120-kVp) abdominal enhanced CT. Furthermore, in our study we evaluated 70-keV virtual monoE images with IR, not FBP. Our results were consistent with this mentioned clinical study.

Image quality of virtual monoE images at different levels of energy to conventional 120-kVp in abdominal CT angiography from single-source dual-energy CT scan was compared in a study by Pinho et al. [14]. They evaluated the image quality in the same patients but images were obtained at different times with a 6-month inter-scan interval [14]. They concluded that 70-keV virtual monoE images improve image quality for aortoiliac CT in comparison to conventional 120-kVp images [14]. Their results were consistent with our results, but we compared just one level of energy (70-keV) to conventional 120-kVp at portal phase in intra-abdominal organs. In our study, both conventional 120-kVp and 70-keV virtual monoE images were created using single dataset obtained from single scan. However, their images were generated from two image sets obtained from two scans with six-month inter-scan interval. This can result in difference in noise or image quality, because of changes in the body weight or hemodynamics of the patients.

Matsumoto et al. compared the image quality of virtual monoE images from fast kilovoltage switching to conventional 120-kVp in phantoms [15]. They concluded that 70-keV virtual monoE images had lower noise and higher CNR in comparison to conventional 120-kVp images [15]. Although they used phantoms and our study is a prospective study on patients, our results are consistent.

Based on our results and previous studies, 70-keV virtual monoE images have lower noise and higher CNR and SNR in comparison to conventional 120-kVp images. Since SDCT generates a dataset that provides conventional polychromatic images as well as retrospective reconstruction of different levels of virtual monoE images with several clinical applications as mentioned in Introduction, this new technology could have the potential to replace conventional CT technology.

Our study had some limitations. Our subjective and objective assessment included different organs. However, same evaluation on different lesions and pathologies would be of great interest. All comparisons were made in the portal phase in our study. We also compared virtual monoE images at only one level of energy (70-keV) to polychromatic 120-kVp images. Further studies with different contrast phases (arterial, portal, and delayed) and multiple levels of virtual monoE images are warranted to confirm our findings.

Conclusion

Seventy-keV virtual monoE CT images for abdominal imaging can significantly improve the noise, SNR, and CNR as compared to conventional 120-kVp polychromatic images. The noise, soft tissue contrast, sharpness, and overall image quality of virtual monoE images were much better than that of polychromatic images subjectively.

Compliance with ethical standards

Funding This study was funded by institutional research grant from Philips Healthcare.

Conflict of interest Prabhakar Rajiah received a speaker honorarium from Philips Healthcare. Amar Dhanantwari is an employee of Philips Healthcare. The other all authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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