Abdominal Radiology

Published online: 19 September 2018

Abdom Radiol (2019) 44:783–789
https://doi.org/10.1007/s00261-018-1774-y

Dual-energy CT in the obese: a preliminary retrospective review to evaluate quality and feasibility of the single-source dual-detector implementation

Noah E. Atwi,[1] David L. Smith,[1] Carson D. Flores,[2] Ekta Dharaiya,[3] Raman Danrad,[1] Avinash Kambadakone,[4] and Aran M. Toshav[1]

[1]Department of Radiology, LSU Health Sciences Center New Orleans, 1542 Tulane Avenue, New Orleans, LA 70112, USA
[2]School of Medicine, LSU Health Sciences Center New Orleans, 1542 Tulane Avenue, New Orleans, LA 70112, USA
[3]Philips Healthcare, 595 Miner Road, Highland Heights, OH 44143, USA
[4]Division of Abdominal Imaging and Intervention, Massachusetts General Hospital, 55 Fruit Street, Boston, MA 02114, USA

Abstract

Purpose: To determine the feasibility of performing dual-energy CT with a single-source spectral detector system in obese patients.
Materials and methods: Retrospective, IRB-approved review of 28 patients weighing ≥ 270 lbs (122 kg) who underwent CT of the abdomen on a single-source spectral detector system was performed. Two blinded, independent radiologists rated relative preference between conventional CT images taken at 120 kVp (CCT120) and monoenergetic 70 keV equivalent (MonoE70) as well as iodine map image quality in the spleen, pancreas, kidneys, and liver. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were compared between conventional CT and MonoE70 images and correlated with body habitus markers of weight, height, and abdominal diameter.
Results: MonoE70 images were preferred by radiologists 100% of the time (1-sample t test, $p < 0.0001$) over conventional CCT120 images. Noise was significantly lower; SNR and CNR were significantly higher in MonoE70 images than in CCT120 images (paired t tests, $p < 0.0001$). Mean iodine map rating (scale 1–5) was 4.54 ± 0.58, denoting near homogenous and complete iodine mapping through the spleen, pancreas, kidneys, and liver for the majority of patients. Body habitus markers were not significantly correlated with image preference score; noise; MonoE70 SNR; MonoE70 CNR; change in noise, SNR, or CNR from CCT120 to MonoE70, or iodine map quality; ordinal and linear regression, $p = 0.2547$, $p = 0.6837$, $p = 0.1888$, $p = 0.5489$, $p = 0.9830$, $p = 0.8849$, $p = 0.8741$, $p = 0.1522$, respectively.
Conclusion: The single-source spectral detector implementation of dual-energy CT provides viable, high-quality imaging for obese patients.

Key words: DECT—Virtual monoenergetic imaging—Obesity—Dual-layer detector DECT—Iodine map

Abbreviations

CCT120	Conventional CT images taken at 120 kVp
CNR	Contrast-to-noise ratio
DECT	Dual-energy CT
MonoE70	Virtual monoenergetic 70 keV equivalent dual-energy images
SNR	Signal-to-noise ratio

Dual-energy computed tomography (DECT) has many of the same limitations as conventional CT, particularly in the imaging of obese and overweight patients [1]. The tradeoff between higher radiation dose and lower image quality remains an issue [2]. In addition, rapid voltage switching and dual-source DECT implementations fundamentally rely on acquiring images at both high and low tube voltages, and so increasing tube voltage is not an option in dose reduction strategies for DECT [3].

Correspondence to: Aran M. Toshav; *email:* atosha@lsuhsc.edu

Dual-source DECT implementations are further limited in imaging of obese patients. To accommodate two detectors in the gantry, the second detector (usually the low-energy detector) must be smaller. The smaller detector results in a decreased field of view; a limitation which affects the obese almost exclusively [4].

Rapid voltage switching implementations also have several additional limitations which hinder imaging of the obese. While high and low voltages can be rapidly alternated, current cannot be correspondingly alternated to provide adequate numbers of photons at low energy. Higher current—and thus higher radiation exposure—becomes necessary. The second limitation is that automated current modulation algorithms cannot be employed. Again, the resulting radiation exposure increases are magnified further in the imaging of obese patients [4].

Due to these limitations, rapid switching and dual-source DECT implementations have been restricted to patients with BMI less than 30 kg/m^2 and weight less than 260 lbs (118 kg). In patients between 200 and 260 lbs, the low-energy acquisition is often performed at 100 kVp, rather than routine settings of 70 or 80 kVp, leading to inferior energetic separation, and thus lower quality DECT image series [5].

Single-source spectral detector implementations of DECT are promising to overcome this difficulty in imaging overweight patients. Because the separation of signal from high- and low-energy photons is done at the detector rather than at the X-ray source, imaging is performed at a normal peak tube voltage, typically 120 or 140 kVp [6]. Thus, radiation dose is theoretically equivalent to conventional CT [7]. However, it is unknown if enough low-energy photons reach the detector in this implementation to provide acceptable image quality in obese patients.

Previous studies have shown that dual-energy CT series—such as virtual monoenergetic imaging (VMI)—improve contrast-to-noise ratios (CNR), particularly at a reference energy of 70 keV. Again though, none of these studies included patients heavier than 109 kg [8–10]. Additional studies have shown that quality and accuracy of iodine quantification are maintained in phantom models simulating different sized patients; however, no in vivo studies have been performed to date [11].

The aim of this retrospective study is to qualitatively and quantitatively determine whether single-source, spectral detector DECT is feasible in the population of patients weighing > 270 lbs (122 kg) through comparison of conventional CT images taken at 120 kVp (CCT120) to virtual monoenergetic 70 keV DECT images (MonoE70), and by assessment of iodine maps generated by DECT.

Materials and methods

A retrospective imaging review with waiver of informed consent was approved by the institutional review board. The study was compliant with the Health Insurance Portability and Accountability Act.

Patients

Twenty-eight consecutive patients were identified for review at a single medical center between December 2016 and August 2017 with the following inclusion criteria: weight > 270 lbs (122 kg), CT images of the abdomen and pelvis taken between 65 and 100 s after IV contrast administration, and available raw DECT data. No studies were excluded. The study population characteristics were as follows: 12 men and 16 women, mean age of 51, mean weight of 139.9 ± 13.0 kg (range 122.9–166.1 kg), and mean BMI of 48.8 ± 7.8 kg/m^2 (range 33.9–71.5 kg/m^2).

Imaging

CT imaging was performed on a 128-slice single-source spectral detector system (IQon Spectral CT; Philips Healthcare, Cleveland, USA). Helical data were acquired at 120 kVp and a tube rotation time of 0.5 s. Images were acquired 65–100 s after 100 mL of Omnipaque 300 (GE Healthcare, Chicago, Illinois, USA) was injected.

Measurements were performed on Philips Intellispace Portal version 9.2.15033.0 (Philips Healthcare, Haifa, Israel). Pitch was 0.953, collimation was 64 × 0.625 mm, and three-dimensional automated tube current modulation was used (DoseRight, Philips Healthcare) set at an index of 14. Conventional CT images were reconstructed in the axial plane using an iterative algorithm (iDose^4; Philips Healthcare). Virtual monoenergetic images at a reference energy of 70 keV and iodine density maps were reconstructed from spectral base image (SBI) data using a projection-based 2-material decomposition algorithm. Images were reconstructed in the axial plane with a slice thickness of 2.5 mm, resolution of 512 × 512 pixels, and pixel spacing of 0.9766 mm/pixel.

Subjective measurements

CCT120 versus MonoE70 image preference

CCT120 and MonoE70 images were prepared at the level of the porta hepatis. Pairs of images from the same patient, one CCT120 and one MonoE70, were rated by two blinded, board-certified abdominal radiologists (AT and DS), each with 8 years of experience. The raters indicated neutrality, weak preference for one of the images, or strong preference for one of the images. Scores were then tabulated to a 5-point Likert scale from − 2 to 2, where − 2 indicated strong preference for conventional CT images, and 2 indicated strong preference for DECT images.

Iodine map quality rating

Iodine concentration map images of the of the liver, spleen, pancreas, and kidneys were prepared and presented to radiologists AT and DS, who scored the images on a Likert scale from 1 to 5. The scale ranged from 1, denoting homogenous and complete iodine map in none or 1 of the above organs, to 5, denoting homogenous and complete iodine map of all of the presented organs (Table 1).

Objective measurements

Patient transverse diameter was measured at the level of the porta hepatis.

Noise, signal-to-noise ratio, and contrast-to-noise ratio

Objective assessment of the CT image data sets was performed by radiologist in-training, NA. A 1000 mm^2 region of interest (ROI) was placed in the posterior right lobe of the liver at the level of the porta hepatis, away from large vessels or ducts; mean pixel intensity (S_M) and standard deviation (S_σ) were recorded. Additional identical ROIs measuring 1000 mm^2 were selected in subcutaneous fat in the adjacent right posterior abdominal wall, and mean pixel intensity (C_M) was again recorded.

Noise was defined as the standard deviation of attenuation (noise = S_σ). Signal-to-noise ratio (SNR) was calculated with the following formula: SNR = S_M/S_σ. CNR was calculated as CNR = $(S_M - C_M)/S_\sigma$. Measurements and parameters were calculated with identical locations and ROIs for CCT120 and MonoE70 images of the same patient. Relative SNR and CNR changes from CCT120 to MonoE (ΔSNR and ΔCNR) were calculated as $\Delta SNR = SNR_{MonoE70}/SNR_{CCT120}$ and $\Delta CNR = CNR_{MonoE70}/CNR_{CCT120}$.

Statistical analysis

Statistical analysis was performed in SAS version 6p.2.688de4662a09-1-1 (SAS Institute Inc., Cary, North Carolina, USA).

Radiologist image preference was analyzed using a 1-sample *t* test.

Weight, height, and transverse diameter were used as patient habitus markers. BMI was not used due to dependence on weight and height.

Logistic regression was performed to evaluate the relationship between radiologist average image preference (AIP) and body habitus markers (weight, height, and diameter). The following model was used: AIP = c_1 weight + c_2 height + c_3 diameter. Wald Chi-squared test was performed to determine model significance.

Noise, SNR, and CNR were compared between CCT120 and MonoE70 with paired *t* tests.

Multiple regression was performed to evaluate the relationship between each of $SNR_{MonoE70}$, $CNR_{MonoE70}$, ΔSNR, ΔCNR, and body habitus markers of weight, height, and diameter. The following models were used: $SNR_{MonoE70}$ = c_1 weight + c_2 height + c_3 diameter and $CNR_{MonoE70}$ CNR = c_1 weight + c_2 height + c_3 diameter, ΔSNR = c_1 weight + c_2 height + c_3 diameter, and ΔCNR = c_1 weight + c_2 height + c_3 diameter. Wald Chi-squared test was performed to determine model significance.

The relationship between iodine map quality (IMQ) and the body habitus markers of weight, height, and diameter was evaluated with logistic regression. The following model was used: IMQ = c_1 weight + c_2 height + c_3 diameter. Wald Chi-squared test was performed to determine model significance.

Results

Subjective image analysis

Radiologist image preference

Both readers preferred MonoE70 images in all 28 patients. The average preference score of R1 was 1.68 ± 0.48. The average preference score of R2 was 1.61 ± 0.50. Scores for both radiologists ranged from 1 to 2. Interrater agreement was 78.6%, and all disagreements were by 1 point on the Likert scale. Results for average image preference are shown on Table 2, and representative images are shown in Figs. 1 and 2.

The overall average image preference score was 1.64 ± 0.43, which falls between moderate and strong preference for MonoE70 images. Average image prefer-

Table 1. 5-point Likert scale for evaluating the quality of dual-energy CT (DECT) iodine maps of the abdomen

Score	Criteria
1	Homogenous and complete iodine map of none or 1 of the following organs: liver, spleen, pancreas, kidneys
2	Homogenous and complete iodine map of 2 of the following organs: liver, spleen, pancreas, kidneys
3	Homogenous and complete iodine map of 3 of the following organs: liver, spleen, pancreas, kidneys
4	Homogenous and complete iodine map of the spleen, pancreas, and kidneys with incomplete iodine mapping of the liver
5	Homogenous and complete iodine map of the liver, spleen, pancreas, and kidneys

Table 2. Average image preference and characteristics of the patients

Average image preference score	Number of patients (%)	Weight (kg)	Height (cm)	Diameter (cm)
2.0–0 (preference for CCT120 or no preference)	0			
1.0 (weak preference for MonoE70)	7 (25%)	139.2 ± 13.4	173 ± 12	48.9 ± 8.9
1.5 (intermediate preference for MonoE70)	6 (21.43%)	143.6 ± 18.6	167 ± 10	50.2 ± 7.9
2.0 (strong preference for MonoE70)	15 (53.57%)	138.7 ± 10.9	170 ± 10	44.2 ± 3.3

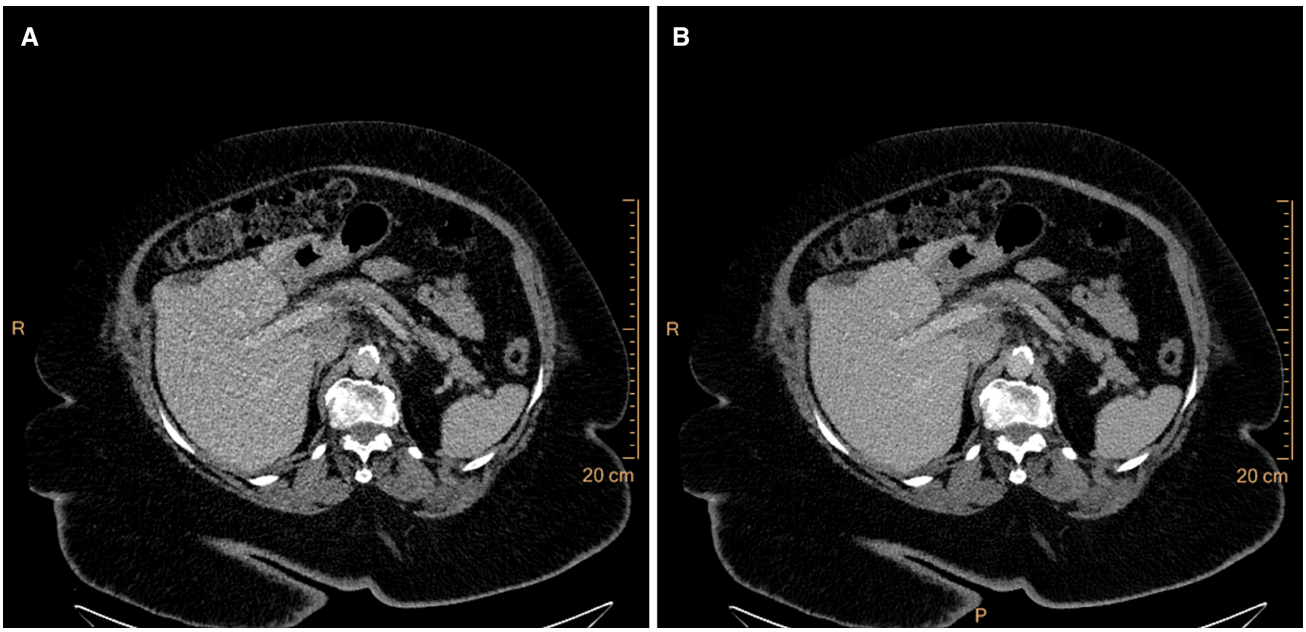

Fig. 1. Representative conventional 120 kVp CT (CCT120) (**A**) and dual-energy CT Monoenergetic 70 keV equivalent (MonoE70) (**B**) images showing substantially higher quality of the MonoE70 image. Signal-to-noise ratio and contrast-to-noise ratio were 1.37 and 3.93, respectively, for CCT120 and 1.70 and 4.75, respectively, for MonoE70. Both radiologists strongly preferred the MonoE70 image in this case.

ence score was significantly different from 0 (no preference) ($p < 0.0001$, 1-sample t test).

No correlation between the body habitus markers (weight, height, and diameter) and average image preference score was found ($p = 0.2655$, Wald Chi-squared test of logistic regression model).

Noise, signal-to-noise ratio, and contrast-to-noise ratio

Noise was uniformly lower in MonoE70 images than in conventional CT images (lower is better). SNR and CNR were uniformly higher in MonoE70 images than in conventional CT images (higher is better). For conventional CT noise was 26.81 ± 2.77, SNR was 3.11 ± 0.65, and CNR was 7.21 ± 1.28 (Fig. 3). For MonoE70 noise was 21.93 ± 2.34, SNR was 3.83 ± 0.77, and CNR was 8.60 ± 1.42 (Fig. 3). Noise, SNR, and CNR were significantly different between CCT120 and MonoE70 images ($p < 0.0001$ for all pairs, paired t tests).

No correlation between body habitus markers (weight, height, and transverse diameter) and noise$_{MonoE70}$, $SNR_{MonoE70}$, or $CNR_{MonoE70}$ was found ($p = 0.6837$, $p = 0.1888$, and $p = 0.5489$, respectively, Wald Chi-squared test).

The average relative decrease in noise from CCT120 to MonoE70 (Δnoise) was 17 ± 7%. The average relative increase in SNR from CCT120 to MonoE70 (ΔSNR) was 24 ± 10%. The average relative increase in CNR (ΔCNR) from CCT120 to MonoE70 was 20 ± 9%.

No correlation between body habitus markers (weight, height, and diameter) and Δnoise, ΔSNR, or ΔCNR was found ($p = 0.9830$, $p = 0.8849$, and $p = 0.8741$, respectively, Wald Chi-squared test).

Iodine map quality

The average iodine map score of R1 was 4.64 ± 0.62. The average iodine map score of R2 was 4.54 ± 0.58. Scores for both raters ranged from 3 to 5. Interrater agreement was 75.0%, and all disagreements were by 1 point on the Likert scale. The overall average iodine map score was 4.59 ± 0.54. The results of average iodine map

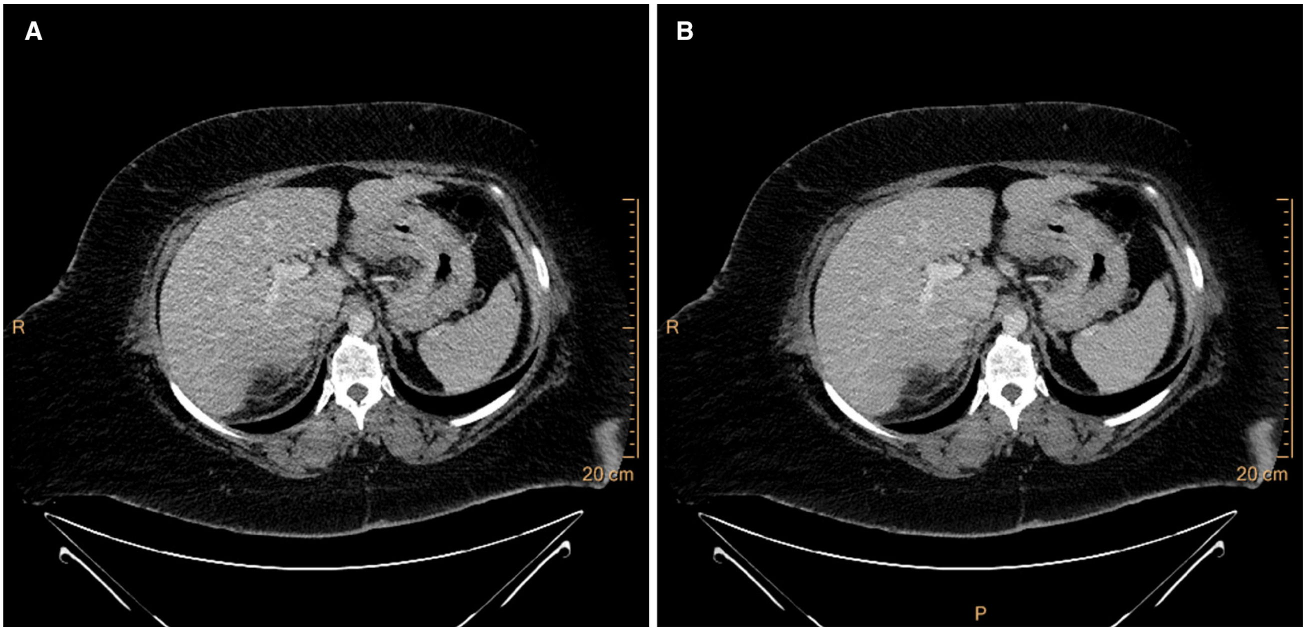

Fig. 2. Representative conventional 120 kVp CT (CCT120) (**A**) and dual-energy CT Monoenergetic 70 keV equivalent (MonoE70) (**B**) images showing slight improvement of quality of the MonoE70 image. Signal-to-noise ratio and contrast-to-noise ratio were 4.01 and 9.25, respectively, for CCT120 and 4.53 and 9.74, respectively, for MonoE70. Both radiologists weakly preferred the MonoE70 image in this case.

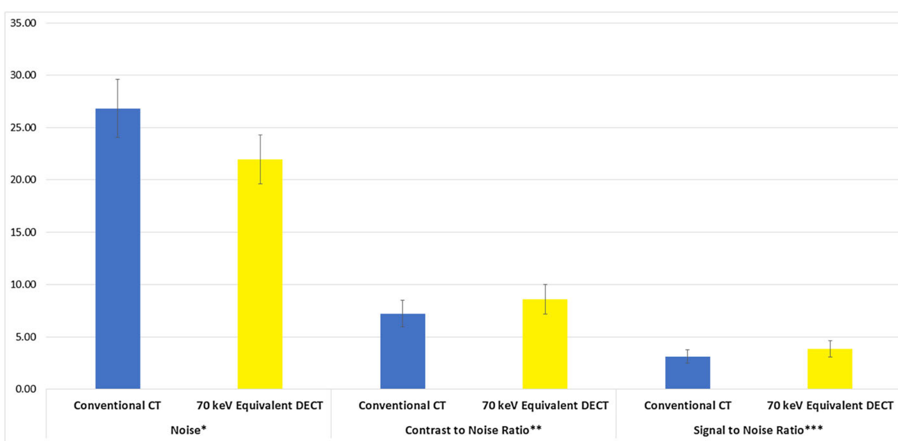

Fig. 3. Noise (lower is better), contrast-to-noise ratio (CNR, higher is better), and signal-to-noise ratio (SNR, higher is better) measurements of conventional 120 kVp CT (CCT120, in blue) and Monoenergetic 70 keV equivalent DECT (MonoE70, in yellow) images. *Significant difference in noise between CCT120 and MonoE70 images (paired *t* test, $p < 0.0001$). **Significant difference in CNR between CCT120 and MonoE70 images (paired *t* test, $p < 0.0001$). **Significant difference in SNR between CCT120 and MonoE70 images (paired *t* test, $p < 0.0001$).

Table 3. Average iodine map ratings and characteristics of the patients

Average iodine map rating	Number of patients (%)	Weight (kg)	Height (cm)	Diameter (cm)
1-2.5	0			
3.0	1 (3.57%)	127.0	178	47.0
3.5	1 (3.57%)	163.3	178	57.0
4.0	5 (17.86%)	142.0 ± 13.9	173 ± 9	50.0 ± 8.5
4.5	6 (21.43%)	140.2 ± 14.8	179 ± 9	41.8 ± 4.2
5.0	15 (53.57%)	138.4 ± 11.7	165 ± 9	46.7 ± 5.7

rating are shown in Table 3, and representative images are shown in Fig. 4.

21 studies (75%) were given average ratings of 4.5 or 5.0 (optimal IMQ). 7 studies (25%) were given average ratings of 4.0 or lower (suboptimal IMQ). No correlation between the predictors (weight, height, and diameter) and IMQ was found ($p = 0.1400$, Wald Chi-squared).

Discussion

Dual-energy CT acquisition in obese patients is often limited due to effects of photon starvation, which has hindered its clinical application; this study provides evidence that single-source spectral detector implementations of DECT are not susceptible to this limitation.

In our patients weighing 270–366 lbs (122–166 kg) and BMI from 33.9 to 71.5 kg/m^2, single-source spectral detector DECT produced lower noise, higher signal-to-noise, and higher contrast-to-noise attenuation images than conventional CT. These quantitative findings were reinforced by universal reader preference for spectral virtual monoenergetic images over conventional CT images. In addition, single-source spectral detector DECT produces diagnostically acceptable iodine maps in the majority of cases. Subjective preference and objective improvement in image noise, SNR, and CNR were independent of patient habitus markers, indicating that imaging performance may not degrade with increasing patient obesity.

This study has several limitations. The primary limitations were small sample size and retrospective nature. Noise, SNR, and CNR analyses were limited to one organ, and radiologist quality preference was based on a single slice. Another confounding factor is that all imaging was performed with automated exposure control (AEC). The purpose of AEC is to maintain a consistent level of noise between images in a series and scans on a machine, no matter the patient habitus. Lack of statistically significant relationship between patient habitus and noise, SNR, or CNR likely in-part reflects a properly functioning AEC, as well as low sample size.

It was not clear why IMQ in some studies was suboptimal. Possible etiologies include poor patient cardiac function resulting in delayed perfusion of abdominal organs with contrast material or low-energy photon starvation at the detector. The proportion of studies with optimal IMQ in patients under 122 kg was not examined, but a comparison is a topic of future study.

Lastly, the only limitations to CT examined were those resulting from X-ray source and detector characteristics. Additional limitations exist, including table weight limit and gantry bore size. At our institution, table weight limit for the IQon Spectral scanner is 450 lbs (204 kg), though the limit can be increased to 650 lbs (295 kg) with a bariatric table. Gantry bore size—and thus maximal patient diameter—is 70 cm. It is unknown how often patients cannot undergo CT examination due to tertiary problems of this nature.

Future directions for study include evaluating virtual monoenergetic images at lower reference energies (40–50 keV). Due to greater weighing of the lower energy data, low reference energy monoenergetic image quality may degrade disproportionately in higher weight patients. From a clinical perspective, these image sets are promising for their potential to reduce contrast dose requirements, or even for just general radiologic application when higher tissue contrast resolution is needed or desired, such as in the pancreas [12, 13].

Several of the patients included in this study had CT scans on both conventional CT and dual-energy CT scanners. Due to differences in AEC settings, the radiation exposure could not be directly compared. Phantom work comparing radiation exposure adds credence to the theory that spectral detector DECT is dose neutral, but in vivo studies have not been formally conducted [14]. Comparing radiation exposure in vivo between scans

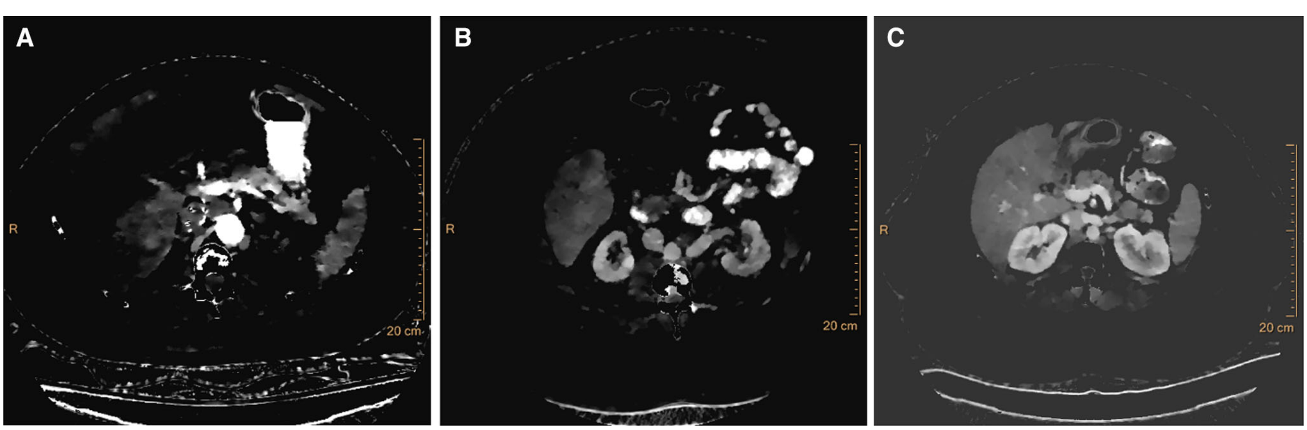

Fig. 4. Representative iodine maps showing various levels of quality. Panels **A**, **B**, and **C** demonstrate average radiologist quality ratings of 3, 4, and 5, respectively. Window length and width were adjusted independently for each image to maximize organ visualization.

performed on a DECT scanner and conventional CT scanner remains of interest, but is limited by the risks of rescanning patients.

A study examining dose-to-quality ratio of conventional CT and virtual monoenergetic DECT would more completely define the relative advantages of the two techniques. Metrics have already been established to evaluate the tradeoff between dose and quality in prior work comparing the quality of iterative model-based reconstruction techniques to iterative statistically based ones; these metrics may easily be applied to comparison of virtual monoenergetic and conventional CT images [15].

In summary, the single-source spectral implementation of dual-energy CT shows potential for imaging in the obese population, with promising results in patients between 270 and 366 lbs (122–166 kg). Generated iodine maps were deemed optimally usable by radiologists in most cases. Monoenergetic 70 keV equivalent images were universally rated as superior to their conventional CT equivalents; noise was lower, SNR and CNR were significantly higher. None of the dual-energy-specific series degraded with patient habitus markers, indicating that no habitus threshold should keep a patient from undergoing imaging of the abdomen on a single-source, spectral detector implementation of DECT if it would provide an advantage to patient care.

Compliance with ethical standards

Funding None.

Conflicts of interest Author ED is an employee of Philips Healthcare, which developed the DECT implementation used in this study. Author AT is a member of the Philips Healthcare speaker's bureau. Data were analyzed and controlled by author NA; no data were analyzed or controlled by the authors ED or AT. LSU Health Sciences Center Department of Radiology has a research agreement with Philips Healthcare; however, no funding was provided for this project.

IRB statement A retrospective imaging review with waiver of informed consent was approved by the institutional review board. The study was compliant with the Health Insurance Portability and Accountability Act.

Summary statement Dual-energy CT acquisition in obese patients is often limited due to effects of photon starvation, which has hindered its clinical application; this study provides evidence that single-source spectral detector implementations of DECT are not susceptible to this limitation.

Implications for patient care No habitus threshold should keep a patient from undergoing imaging of the abdomen on a single-source, spectral detector implementation of DECT if it would provide an advantage to patient care.

References

1. Modica MJ, Kanal KM, Gunn ML (2011) The obese emergency patient: imaging challenges and solutions. RadioGraphics 31:811–823. https://doi.org/10.1148/rg.313105138
2. Parry RA, Glaze SA, Archer BR (1999) The AAPM/RSNA physics tutorial for residents. RadioGraphics 19:1289–1302. https://doi.org/10.1148/radiographics.19.5.g99se211289
3. Huda W, Scalzetti EM, Levin G (2000) Technique factors and image quality as functions of patient weight at abdominal CT. Radiology 217:430–435. https://doi.org/10.1148/radiology.217.2.r00nv35430
4. Johnson TR (2012) Dual-energy CT: general principles. Am J Roentgenol 199(5_supplement):S3–S8
5. Megibow AJ, Sahani D (2012) Best practice: implementation and use of abdominal dual-energy CT in routine patient care. Am J Roentgenol 199:S71–S77. https://doi.org/10.2214/AJR.12.9074
6. Rajiah P, Abbara S, Halliburton SS (2017) Spectral detector CT for cardiovascular applications. Diagn Interv Radiol 23:187–193. https://doi.org/10.5152/dir.2016.16255
7. Rassouli N, Chalian H, Rajiah P, Dhanantwari A, Landeras L (2017) Assessment of 70-keV virtual monoenergetic spectral images in abdominal CT imaging: a comparison study to conventional polychromatic 120-kVp images. Abdom Radiol 42:2579–2586. https://doi.org/10.1007/s00261-017-1151-2
8. Apfaltrer P, Sudarski S, Schneider D, et al. (2014) Value of monoenergetic low-kV dual energy CT datasets for improved image quality of CT pulmonary angiography. Eur J Radiol 83:322–328. https://doi.org/10.1016/j.ejrad.2013.11.005
9. Leng S, Yu L, Fletcher JG, McCollough CH (2015) Maximizing iodine contrast-to-noise ratios in abdominal CT imaging through use of energy domain noise reduction and virtual monoenergetic dual-energy CT. Radiology 276:562–570. https://doi.org/10.1148/radiol.2015140857
10. Pinho DF, Kulkarni NM, Krishnaraj A, Kalva SP, Sahani DV (2013) Initial experience with single-source dual-energy CT abdominal angiography and comparison with single-energy CT angiography: image quality, enhancement, diagnosis and radiation dose. Eur Radiol 23:351–359. https://doi.org/10.1007/s00330-012-2624-x
11. Sauter AP, Kopp FK, Münzel D, et al. (2018) Accuracy of iodine quantification in dual-layer spectral CT: influence of iterative reconstruction, patient habitus and tube parameters. Eur J Radiol 102:83–88. https://doi.org/10.1016/J.EJRAD.2018.03.009
12. Yu L, Christner JA, Leng S, et al. (2011) Virtual monochromatic imaging in dual-source dual-energy CT: radiation dose and image quality. Med Phys 38:6371–6379. https://doi.org/10.1118/1.3658568
13. Yuan R, Shuman WP, Earls JP, et al. (2012) Reduced iodine load at CT pulmonary angiography with dual-energy monochromatic imaging: comparison with standard CT pulmonary angiography—a prospective randomized trial. Radiology 262:290–297. https://doi.org/10.1148/radiol.11110648
14. Marin D, Nelson RC, Schindera ST, et al. (2010) Low-tube-voltage, high-tube-current multidetector abdominal CT: improved image quality and decreased radiation dose with adaptive statistical iterative reconstruction algorithm—initial clinical experience. Radiology 254:145–153. https://doi.org/10.1148/radiol.09090094
15. van Ommen F, Bennink E, Vlassenbroek A, et al. (2018) Image quality of conventional images of dual-layer SPECTRAL CT: a phantom study. Med Phys 45(7):3031–3042