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Low kV versus dual-energy virtual monoenergetic CT imaging for proven liver lesions: what are the advantages and trade-offs in conspicuity and image quality? A pilot study

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Abstract

Purpose—Single-energy low tube potential (SE-LTP) and dual-energy virtual monoenergetic (DE-VM) CT images both increase the conspicuity of hepatic lesions by increasing iodine signal. Our purpose was to compare the conspicuity of proven liver lesions, artifacts, and radiologist preferences in dose-matched SE-LTP and DE-VM images.

Methods—Thirty-one patients with 72 proven liver lesions (21 benign, 51 malignant) underwent full-dose contrast-enhanced dual-energy CT (DECT). Half-dose images were obtained using single tube reconstruction of the dual-source SE-LTP projection data (80 or 100 kV), and by inserting noise into dual-energy projection data, with DE-VM images reconstructed from 40 to 70 keV. Three blinded gastrointestinal radiologists evaluated half-dose SE-LTP and DE-VM images, ranking and grading liver lesion conspicuity and diagnostic confidence (4-point scale) on a per-lesion basis. Image quality (noise, artifacts, sharpness) was evaluated, and overall image preference was ranked on per-patient basis. Lesion-to-liver contrast-to-noise ratio (CNR) was compared between techniques.

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Compliance with ethical standards

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Conflict of interest

Dr. McCollough receives Grant support from Siemens Healthcare. Dr. Halaweish is an employee of Siemens Healthcare. No other authors declare a 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 was obtained from all individual participants involved in the study. This article does not contain any animal studies.

Results—Mean lesion size was 1.5 ± 1.2 cm. Across the readers, the mean conspicuity ratings for 40, 45, and 50 keV half-dose DE-VM images were superior compared to other half-dose image sets ($p < 0.0001$). Perlesion diagnostic confidence was similar between half-dose SE-LTP compared to half-dose DE-VM images ($p = 0.05$; 1.19 vs. 1.24–1.32). However, SE-LTP images had less noise and artifacts and were sharper compared to DE-VM images less than 70 keV ($p < 0.05$). On a per-patient basis, radiologists preferred SE-LTP images the most and preferred 40–50 keV the least ($p < 0.0001$). Lesion CNR was also higher in SE-LTP images than DE-VM images ($p < 0.01$).

Conclusion—For the same applied dose level, liver lesions were more conspicuous using DE-VM compared to SE-LTP; however, SE-LTP images were preferred more than any single DE-VM energy level, likely due to lower noise and artifacts.

Keywords

Dual-energy CT; Virtual monoenergetic imaging; Liver; Artifacts; Image quality; Radiation dosage

Recent studies have highlighted the potential benefits of dual-energy virtual monoenergetic (DE-VM) images [1–3]. These advantages include improved image quality, increased contrast-to-noise ratio (CNR), and reduced beam hardening. There is also significant clinical appeal for dual-energy techniques, which are capable of generating multiple sets of monoenergetic (40–140 keV) images, which can be used to highlight pathology or minimize artifacts.

Maximizing iodine signal is an important potential advantage of DE-VM images compared to the conventional method of viewing dual-energy CT data, which involved blending the low- and high-energy images together to form a single image set. However, previous studies using early DE-VM algorithms have shown that high-contrast, low-monoenergetic-energy images that contain increased iodine signal also contain higher levels of image noise [4, 5]. This significant noise burden at lower energies has been a limiting factor in the clinical application of virtual monoenergetic imaging. An improved monoenergetic algorithm has been described to address this concern [6].

For DE-VM imaging to become a viable clinical tool, measures of lesion conspicuity, image quality, and overall preference must be equal to or better than conventional single-energy CT acquired at the same radiation dose. Several studies have investigated the use of DE VM imaging on both anthropomorphic phantoms with simulated abdominal lesions, as well as in patient cohorts [7–11].

An alternative approach for enhancing iodine signal is the use of single-energy low-tube-potential (SE-LTP) imaging. For example, SE-LTP can be used with iterative reconstruction to improve lesion conspicuity and reduce radiation dose without increasing image noise [12–14]. However, an evaluation comparing DE VM imaging and SE-LTP CT in dose-matched studies in patients with proven liver lesions has not been performed. Therefore, the purpose of this study was to compare the conspicuity of proven liver lesions, artifacts and radiologist preferences in dose-matched SE-LTP and DE-VM images.

Materials and methods

Patient selection

This retrospective, single institution study was approved by our Institutional Review Board. Consent to use clinical and imaging data was obtained from each patient included in the study. Selection criteria included a previously performed, clinically indicated, contrast-enhanced multiphase hepatic CT acquired with a dual-source dual-energy protocol (tube potential pair of 80/140Sn or 100/140Sn), and the presence of at least one proven liver lesion.

Retrospective image datasets were reviewed by a single gastrointestinal radiologist with expertise in hepatic imaging, along with all prior and subsequent clinical imaging, including the clinical and surgical record. The role of this non-reader radiologist was to select proven benign and malignant liver lesions within the CT exams that would be visually compared by radiologist readers examining DE-VM and SE-LTP images. Proven malignant lesions occurred in patients with documented primary malignancies that demonstrated progression (enlargement over time) or regression (diminishing size with treatment), or which were diagnosed as malignant based on histopathologic analysis of the resected specimen or biopsy. Criteria for proven benign lesions included stability on CT or MR imaging for at least 6 months, in addition to demonstration of typical imaging features for a cyst (cystic lesion without enhancement or wall) or hemangioma (nodular, peripheral and progressive enhancement isointense with the blood pool) [15]. For each patient, up to three liver proven lesions were used in this study, and the phase of enhancement on which the lesion was the most subtle was chosen for inclusion. From the clinical full-dose dual-energy blended images, an image file showing each selected proven liver lesion was created for subsequent use by radiology readers for lesion identification.

Image reconstruction and processing

Conventional low- and high-energy CT images were reconstructed from projection data with a 3 mm image thickness and 2 mm image increment using an iterative reconstruction technique (SAFIRE strength 3) and I30f kernel. These images were then combined using a linear blending technique which entailed a weighted summation of the low and high kV images. For this study, the blending ratio was set to 0.6 (i.e., the low kV images were weighted by 0.6 and the high kV images by 0.4). These were the *full-dose blended images*. We then created seven types of half-dose images: one linear blend image, one SE-LTP image and five DE-VM images, each using half of the full dose applied to the patient (Fig. 1).

SE-LTP images

Because the dose was divided approximately equally between the low- and high-energy (tube potential) acquisitions of a dual-source scan, the reconstructed images from the low tube potential setting used half of the dose as the complete dual-source, DECT scan [16]. Reconstructed as described above, these were the *halfdose SE-LTP images*.

DE-VM and blended images

To obtain the DE-VM and blended images at half of the total dose applied to the patient, both the low- and high-energy datasets were required. To obtain these data at “half-dose”, we used a validated technique [17] to insert noise into the CT projection data from both tubes such that each image set (low- or high-energy images) corresponded to one-half the radiation dose *initially applied to the patient at each energy*. Since half of the total dose is given to each of the low- and high-energy data, these “half-dose low-energy” and “half-dose high-energy” images each used approximately one quarter of the total dose applied to the patient. From these CT projection data, half-dose dual-energy images were reconstructed. From these, five sets of DE-VM images corresponding to 40, 45, 50, 60, and 70 keV were created from an image-based virtual monoenergetic algorithm using an offline computer workstation (Mono-energetic Plus, syngo CT 2010A; Siemens Healthcare, Forchheim, Germany). The DE-VM energy levels were chosen because it has been previously demonstrated that lesion CNR reaches an optimal level in this region over a range of patient sizes [10]. A *half-dose blended image* was also created by linearly blending the quarter-dose low- and high-energy images.

Multi-reader image evaluation

A detailed flowchart of the reader evaluation schema can be seen in Fig. 2. Four board-certified radiologists served as radiologist readers for this study (three subspecialty gastrointestinal faculty members with 7, 21, and 23 years of experience as a consultant radiologist; and one abdominal imaging fellow). Each patient’s images were evaluated by three of these four radiologists, who were blinded to the image type (either half-dose SE-LTP, half-dose DE-VM, or half-dose blended). Images were reviewed on a clinical workstation (Advantage Windows, GE Healthcare, Milwaukee, WI). During image evaluation, full-dose images of the proven liver lesion(s) were shown to the readers in the upper left hand window (Fig. 3). The half-dose SE-LTP, half-dose DE-VM and half-dose blended images were then loaded into random locations on the workstation to prevent the reader from identifying specific image types. Readers scrolled through image volumes and adjusted window/level settings to evaluate the relative advantages/disadvantages of each series for each patient as described below.

The first comparison task was to rank the visual conspicuity of the proven liver lesions amongst the half-dose datasets. The reader was shown the reference lesion and was asked to rank the visual conspicuity of that lesion across all half-dose image series from best to worst, allowing for ties. This process was repeated for every proven lesion selected for comparison for each patient.

The second comparison task was performed comparing (in random order) each half-dose image series to the full-dose blended images. For each reference liver lesion, the reader compared each of the half-dose series to the full-dose clinical blended series, grading the relative conspicuity of the liver lesion compared to the reference image and providing a level of diagnostic confidence. Relative conspicuity was graded on a 5 point scale [18]. No difference in lesion conspicuity between the half-dose series and the full-dose blended image series was given a rating of “zero”. Mild, unimportant differences in lesion conspicuity

were rated +1 or -1, with positive values indicating the half-dose images were superior to the full-dose blended kV images. Substantial, important differences were rated as +2 or -2. Per-lesion evaluation of diagnostic confidence was then assessed for each half-dose series on scale of 1 (“full confidence”) to 4 (“unacceptable”), with a rating of 2 indicating the reader was “probably confident,” and a rating of 3 indicating the reader was “confident under limited conditions for visualization”. Scores less than or equal to 2 were considered to be diagnostically acceptable.

Once lesions had been evaluated for each patient, the radiologist reader assigned image quality scores for artifacts, noise and sharpness. Image artifacts were scored from 1 to 4 with a score of 1 corresponding to no artifacts and a score of 4 corresponding to severe artifacts. Image noise and sharpness were graded on scales from 1 to 4 and 1 to 3 respectively, as previously reported using a modified European CT Image quality score [19].

The qualitative evaluation for each patient ended with the radiologist reader providing an overall preference ranking of the half-dose SE-LTP (i.e., low kV) and DE VM images, not allowing for ties. This preference ranking was meant to gauge to the overall quality of each image series in terms of increasing the conspicuity of liver lesions without having compromising artifacts or noise.

Quantitative analysis

Utilizing the viewing workstation, region of interest (ROI) measurements were drawn within each lesion using a freehand tool, attempting to include as much of each lesion as possible. A second ROI was then placed, in the same image, in surrounding normal liver parenchyma while avoiding vessels, edges and artifacts. Lesion-to-liver CNR was then calculated as follows:

$$\text{Lesion-to-liver CNR} = (\text{ROI}_{\text{lesion}} - \text{ROI}_{\text{liver}}) / \text{SD}_{\text{noise}}$$

with $\text{ROI}_{\text{lesion}}$ being the mean CT number of the lesion, $\text{ROI}_{\text{liver}}$ being the mean CT number of the normal liver parenchyma, and SD_{noise} the standard deviation of CT number within the normal liver ROI.

Statistical analysis

ANOVA and Duncan’s Multiple Range test were used to evaluate hypotheses of qualitative data across half-dose image sets, evaluating for differences between the seven half-dose series (SE-LTP, DE-blended, and DE-VM images corresponding to 40, 45, 50, 60 and 70 keV), with a p value less than 0.05 considered statistically significant. The quantitative iodine CNR data was evaluated by comparing lesion-to-liver CNR measured in each half-dose DE-VM image series to the corresponding half-dose SE-LTP series, with a p -value of less than 0.01 using a two-tailed paired t -test considered significant. ANOVA was performed to examine for the relationship of mean lesion CT noise, noise, liver-to-lesion CNR, and absolute CT number difference between liver lesion and background liver and overall radiologist reader preference.

Results

Patients and lesions

A total of 31 patients were included in this retrospective study. There were 12 men and 19 women with a mean patient age of 60 ± 11 years (range 37–84 years), and a height, weight, and BMI of 167 ± 9 cm, 77 ± 17 kg, and 28 ± 5 , respectively. Nineteen were female (61%; 19/31). Twenty-six patients were scanned using 100/140Sn kV and five were scanned using 80/140Sn kV. The mean CTDIvol was 12.7 ± 4.0 mGy for the phase of enhancement included in the study for each patient, so the mean CTDIvol for the DE-VM and SE-LTP images in the study corresponded to a mean CTDIvol of 6.4 mGy. A total of 72 lesions were identified and evaluated (51 malignant; 21 benign). The mean lesion size was 1.5 ± 1.2 cm (0.27–6.3). Malignant disease was found in 21/31 patients, while only benign lesions were found in 10/31 patients. Of the patients with malignant disease, three had one benign lesion in addition to at least one malignant lesion. Malignancy of a lesion was proven using prior or subsequent imaging in 17/21 of the patients, surgery or biopsy of a lesion in 9/21 patients, and both techniques in 5/21 patients.

Metastatic liver disease was present in 14 patients with 38 metastases. The metastases were most commonly from the colon (22/38) or pancreas (8/38), with another eight metastases of different types. Primary hepatic neoplasms were present in seven patients with 13 tumors (12 hepatocellular carcinomas, one cholangiocarcinoma). Of the 21 lesions that were classified as benign, the most common types were cysts (11/21) and hemangiomas (3/21), with the rest classified as other types of benign lesions (7/21).

Examples of DE-full-dose and dose-matched half-dose SE-LTP and half-dose DE-VM images can be found in Figs. 3 and 4.

Per-lesion analysis

For the initial assessment of per liver lesion conspicuity rank amongst the half-dose images, Table 1 shows the frequency with which each half-dose series was ranked first (as the reconstructed series with greatest lesion conspicuity, allowing for ties). The frequency data were calculated by finding the ratio of the total number one rankings assigned to each reconstruction type across all lesions to the total amount of number one rankings assigned throughout the study.

The half-dose conspicuity rank was highest for 40, 45, and 50 keV DE-VM images, which were ranked first in conspicuity 18%–20% of the time, and had significantly improved conspicuity ranks compared to SE-LTP and 60 keV DE-VM images, which performed the next highest ($p < 0.05$). Taking 40, 45, and 50 keV DE-VM images into account, these three energies had the highest conspicuity rank 57% of the time, compared to SE-LTP, which was selected only 12% of the time.

When the half-dose image series were compared to the full-dose images, the mean conspicuity score compared to full-dose DE-blended images was near zero for all half-dose reconstructions (Table 1). In contrast, perlesion diagnostic confidence was slightly higher for

SE-LTP images than DE-VM images (1.10 vs. 1.24–1.32), but this difference was not statistically significant ($p = 0.05$).

Table 1 also summarizes measured quantitative variables for individual lesions on the half-dose CT images. For each of the 72 lesions, lesion-to-liver CNR was calculated for the full-dose DE-blended series and each of the half-dose series. The full-dose blended series had the highest lesion-to-liver CNR (5.0). While the CT number differences were larger for lower DE-VM energies, noise was substantially higher, so lesion-to-liver CNR was significantly greater for SE-LTP images compared to DE-VM images ($p < 0.01$, 4.3 vs. 3.3–3.7).

Per patient analysis

The visual comparison of reader image quality scores for artifact, noise, and sharpness is given in Table 2, along with the overall radiologist reader preference ranking. When image artifacts were assessed, the lowest (best) mean scores were assigned to half-dose SE-LTP, blended, and 70 keV DE-VM, which ranged from 1 to 1.05, with 40–50 keV DE VM having the worst (1.79–1.94, $p < 0.05$). Following a similar pattern, 40–50 keV DE VM images had significantly more noise and less sharpness than SE-LTP images and blended images ($p < 0.05$).

Radiologists concluded visual analysis of each case by ranking their overall preference for interpretation of the half-dose image series. SE-LTP images were preferred most often [being ranked as first preference in 45/93 (48%) cases], and 40 keV DE-VM was least preferred [being ranked seventh in 48/93 (52%) cases]. SE-LTP had a mean overall preference rank of 2.3, which was significantly better than any of the blended or DE-VM alternatives ($p < 0.05$).

We subsequently sought to determine if quantitative parameters could account for perceived differences in conspicuity rank or overall image preference using ANOVA. Liver-to-lesion CNR and absolute CT number difference between lesion and background CT number did have a significant influence on the variance in conspicuity ranking ($p < 0.0001$ for both comparisons), but only accounted for 3.6% and 3% of the variability in the dataset, respectively. None of the measured quantitative variables accounted for variability in overall image preference.

Discussion

We performed a dose-matched comparison of SE-LTP images versus DE-VM images in patients with proven liver lesions at contrast-enhanced abdominal CT. We found that while DE-VM images at low keV settings resulted in significantly increased liver lesion conspicuity, radiologists preferred SE-LTP imaging, potentially due to improved noise and a reduced number of artifacts.

Regardless of the fact that lesion conspicuity was significantly increased using DE-VM imaging, SE-LTP images were preferred far more frequently than any of the DE-VM or blended images. This finding was supported by the image quality scores for overall artifacts,

noise, and sharpness, which tended to worsen for the DE-VM images as keV was decreased. Although artifacts were deemed to be mild in DE-VM images at all energies, mean scores for noise and sharpness indicated that in some cases there was enough image noise to affect interpretation, and that noticeable blurring and slice thickening was present.

Multiple phantom studies have examined the potential of DE-VM images to improve image metrics such as contrast-to-noise ratio and image noise. While some have concluded that improved contrast-to-noise ratio can be obtained with DE-VM images [2, 5, 20], others have shown that this may come at a cost of increased radiation dose, may not be true compared to SE-LTP CT approaches, and may not be true for patients of all sizes [5, 21, 22].

Patient studies have examined the advantages and disadvantages of DE-VM imaging at various photon energies. De Cecco et al. [7] determined that parenchymal and vascular attenuation could be significantly increased using the Mono + algorithm at 50 keV when compared to 70 keV using a standard mono-energetic algorithm and blended images. This study also showed that lesion detectability was optimized using this low 50 keV setting. Husarik et al. [8] examined a more extensive spectrum of photon energies in both phantoms and a small patient cohort ($n = 4$). Similarly to De Cecco, they concluded that conspicuity and CNR in hyperattenuating lesions could be improved using low DE-VM energies, as long as patients were not too large.

Several studies utilizing DE-VM have determined that the optimal energy for virtual monochromatic imaging depends on patient size. These studies were designed to examine the optimal energy settings using dual energy, so did not compare patient results between SE-LTP CT and DE-VM images. Mileto et al. showed that tumor-to-liver CNR was highest at 50 keV, and decreased with increasing patient size [10]. Large patients achieved higher tumor-to-liver CNR's at higher monoenergetic energies. While a preliminary arm of this experiment compared DE-VM results with SE-LTP and found higher tumor-to-liver CNR at 80 kV, the authors suggested that lesion detection and overall conspicuity could be optimized by viewing DE-VM images at multiple photon energies. Marin et al. examined DE-VM images with a Mono + algorithm to decrease noise, and found the maximum DE-VM CNR was at 40 keV, but that when a noise constraint limiting the acceptable energies to a 50% increase over baseline 70 keV was employed, the virtual energy selected was 55 keV [9]. The newer Mono + algorithm evaluated by Marin et al. further resulted in patient size having less effect on the selection of the optimal energy selected. Schuman et al. evaluated single-source DE-VM images in 72 patients with 128 lesions and compared visual evaluation of 77 keV images with DE-VM images from 40 to 77 keV. They found that CNR and subjective conspicuity were greater at 50 keV [11]. Our data confirm the previous findings, but add to this knowledge base by including patients with a dose-matched SE-LTP acquisition to the analysis. In addition, our analysis of subjective image quality suggests that there may be a significant trade-off when lowering the photon energy below 60 keV, and that the loss of image quality may out-weigh the gain of CNR and conspicuity.

Because DE-VM images can increase the conspicuity of liver lesions, but were less preferred for overall interpretation, we examined our clinical practice to determine diagnostic tasks where small differences in attenuation may be diagnostically important, and

how we can minimize the impact of noise in DE-VM images. Certainly, there are many diagnostic areas of abdomen and pelvis imaging where small differences in conspicuity are not important (e.g., diverticulitis, appendicitis). However, for multiphase liver imaging to detect HCC, we have adopted dual-energy imaging technique for the late arterial and delayed phases, where evaluation of CT number in comparison to the background liver is of paramount importance. We reconstruct both blended images in these phases to minimize noise, and 50 keV images to maximize lesion conspicuity and improve detection. Portal phase images are acquired using single energy. This approach is similar to that recently recommended in a Multi-Institutional consensus document for abdominopelvic CT exams, which recommended dual-energy acquisition for the arterial phase of liver exams (in addition to pancreas, renal cell carcinoma and GI bleeding studies), with virtual monoenergetic images reconstructed using 50 and 70 keV [23].

Principal limitations of our study include its retrospective design from a single institution, and radiologist unfamiliarity with DE-VM images at the time of our study. Additionally, using our methodology, we compared lesion conspicuity but did not measure lesion detection and characterization to measure observer performance, as lesions were identified prior to the reader study to facilitate comparison across image reconstruction alternatives. This study was performed prior to the release of the commercially available version of Monoenergetic Plus; therefore, the half-dose monoenergetic images were generated using an offline workstation, rather than the commercially available workstation that we now use for clinical work.

We have demonstrated that DE VM imaging can play an important role in improving liver lesion conspicuity, but with a significant reduction in image quality, noise and overall reader preference compared to single-energy or blended dual-energy images. For routine contrast-enhanced CT, single-energy low tube potential scanning was preferred more often than any single keV dual-energy monoenergetic reconstruction. When subtle differences in contrast enhancement are diagnostically important and may impact lesion detection, dual-energy acquisition and reconstruction of low keV dual-energy monoenergetic images in addition to blended images and higher keV reconstructions may be used to balance lesion conspicuity and image quality, but this approach will require further validation with observer performance studies.

Abbreviations

SE-LTP	Single-energy, low tube potential
DE-VM	Dual-energy, virtual monoenergetic

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Fig. 1.

Full-dose dual-source, dual-energy CT projection raw data was used to create half-dose images (SE-LTP, DE-VM, and linear blended). Half-dose SE-LTP images were reconstructed at the time of interpretation, and were used in the creation of full-dose blended images. Noise insertion is used to generate a simulated half-dose raw data file that is used to produce the half-dose DE-VM and half-dose linear blended images.

Fig. 2.

A flowchart of the reader study shows per-lesion conspicuity ranking step for all half-dose datasets, followed by per-lesion conspicuity and diagnostic confidence scoring relative to full-dose images. Per-patient image quality and overall image preference was then performed.

Fig. 3. Full-dose and half-dose linear blend and SE-LTP images (top row) along with DE-VM images (bottom row) show a liver with a subtle hypo-enhancing hepatocellular carcinoma with pseudocapsule enhancement, with images obtained in the delayed phase. Window and level are kept constant at 475/40 to show increase in iodine signal.

Fig. 4.

Full-dose and half-dose linear blend and SE-LTP images (top row) along with DE-VM images (bottom row) show a liver with a hyper-enhancing benign hemangioma. Window and level were individually manipulated in each series to provide similar levels of visual contrast, to mimic how they may look at interpretation. A 6 month follow up CT and 10 month follow up MRI (upper right) confirm lesion stability.

Table 1

Per-lesion reader analysis of conspicuity (amongst the half-dose images, and then relative to the full-dose images), relative diagnostic confidence compared to full dose, and per-lesion CT number assessment compared to background liver

Series	Lesion-specific mean score				ROI measurements			
	#1 ranking for lesion conspicuity (%)	Half-dose conspicuity rank	Group	Relative conspicuity c/w full dose	Relative diagnostic confidence c/w full dose	Group	Mean CT# lesion/bkg	Mean absolute difference CT#
40	20	1.3	A	0.35	A	A/B	199/221	132
45	19	1.4	A	0.30	A	A/B	170/190	108
50	18	1.4	A	0.04	B	A/B	147/166	91
60	12	1.7	B	0.12	B	A/B	115/132	66
70	9	2.2	C	-0.16	C	A/B	95/111	50
LB	9	2.4	D	-0.36	D	B	87/103	43
SE-LTP	12	1.8	B	-0.10	C	A	99/115	53
								14
								3.68
								3.62
								3.60
								3.51
								3.33
								3.09
								4.27

For groups assigned different letters, the difference between them is statistically significant with $p < 0.05$. For groups assigned the same letter, the difference between them is not statistically significant ($p \geq 0.05$). The results of the Duncan's Multiple Range tests for half-dose conspicuity rank, relative conspicuity compared to routine dose, and diagnostic confidence show that there were overall significant differences between the mean scores for various groups of configurations, with an overall p -value of < 0.0001 . ROI measurements of liver lesion and background CT number, background noise, and CNR across all lesions and reconstruction types show that low keV images have greater lesion-to-background contrast, while L-KV images have lower noise and higher CNR. For full-dose blended images, the lesion-to-liver CNR was 5.0 (not shown). (bkg background liver)

Table 2

Per-patient scores for image quality assessment and overall image preference rank

Series	Patient-level mean scores									
	Artifacts	Group	Noise	Group	Sharpness	Group	#1 overall preference	(%)	Overall preference rank	Group
40	1.92	C	3.22	F	2.31	D	4	6.28		E
45	1.94	C	3.18	F	2.22	C/D	2	5.81		D/E
50	1.79	C	3.11	E/F	2.05	C	1	5.22		D
60	1.37	B	2.77	C/D	1.62	B	9	4.04		C
70	1.05	A	2.62	B/C	1.27	A	17	3.32		B
LB	1.05	A	2.31	A	1.18	A	18	3.47		B/C
SE-LTP	1	A	2.48	A/B	1.11	A	48	2.3		A

The results of the Duncan's Multiple Range tests for artifacts, noise, sharpness, and overall preference rank show that there were significant differences between the mean scores for various groups of configurations, with an overall p -value of < 0.0001 . For groups assigned different letters, the difference between them is statistically significant with $p < 0.05$. For groups assigned the same letter, the difference between them is not significant. Additionally, the percent of number one overall preference scores for each reconstruction type show that SE-LTP images are most preferred, and low keV images are least preferred