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Automatic spectral imaging protocol selection and iterative reconstruction in abdominal CT with reduced contrast agent dose: initial experience

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Abstract

Objective To evaluate the feasibility, image quality, and radiation dose of automatic spectral imaging protocol selection (ASIS) and adaptive statistical iterative reconstruction (ASIR) with reduced contrast agent dose in abdominal multiphase CT.

Methods One hundred and sixty patients were randomly divided into two scan protocols ($n = 80$ each; protocol A, 120 kVp/450 mgI/kg, filtered back projection algorithm (FBP); protocol B, spectral CT imaging with ASIS and 40 to 70 keV monochromatic images generated per 300 mgI/kg, ASIR algorithm. Quantitative parameters (image noise and contrast-to-noise ratios [CNRs]) and qualitative visual parameters (image noise, small structures, organ enhancement, and overall image quality) were compared.

Results Monochromatic images at 50 keV and 60 keV provided similar or lower image noise, but higher contrast and overall image quality as compared with 120-kVp images. Despite the higher image noise, 40-keV images showed similar overall image quality compared to 120-kVp images. Radiation dose did not differ between the two protocols, while contrast agent dose in protocol B was reduced by 33 %.

Conclusion Application of ASIR and ASIS to monochromatic imaging from 40 to 60 keV allowed contrast agent dose reduction with adequate image quality and without increasing radiation dose compared to 120 kVp with FBP.

Key Points
• *Automatic spectral imaging protocol selection provides appropriate scan protocols.*
• *Abdominal CT is feasible using spectral imaging and 300 mgI/kg contrast agent.*
• *50-keV monochromatic images with 50 % ASIR provide optimal image quality.*

Keywords Dual-energy CT · Spectral CT · Monochromatic image · Iterative reconstruction · Contrast agent

Abbreviations

AP	Arterial phase
PVP	Portal venous phase
CNR	Contrast-to-noise ratio
kVp	Peak kilovoltage
keV	Kiloelectron volts
CTDIvol	Volume computed tomography dose index
ASIS	Automatic spectral imaging protocol selection
ASIR	Adaptive statistical iterative reconstruction
FBP	Filtered back projection
GSI	Gemstone spectral imaging

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Introduction

With the dramatically increased clinical use of diagnostic CT imaging, attention has been focused on the potential risks of radiation exposure-induced carcinogenesis [1] and contrast agent-induced nephropathy [2]. Although the effect of contrast agent dose on nephropathy is not conclusive, reduced amounts of iodine can be beneficial in terms of patient safety [3, 4] and health care costs [4–7]. Scanning with low tube voltage has been the accepted method to reduce radiation dose

and contrast medium volume [8–13] with iterative reconstruction algorithm used to reduce its quantum noise [14, 15]. However, the real-time variation in the tube voltage level in a single-energy CT examination for each patient is not time efficient and cannot provide more information than dual-energy CT [16].

Spectral CT, a dual-energy CT system with fast kilovoltage switching, allows the reconstruction of monochromatic images with selectable X-ray energy (40 to 140 keV) to optimize contrast and clinical applications [17]. The low-energy range has shown promise to reduce the amount of agent used because of the high contrast [18–20] and is expected to increase the image noise due to the reduced number of photons in the lower X-ray energy spectrum [17]. Adaptive iterative reconstruction algorithm (ASIR) thus has been incorporated into the monochromatic image sets to reduce image noise effectively and take full advantage of the increased contrast over the low-energy range [18, 21]. However, previous research about monochromatic energy level combined with ASIR was limited to fixed energy levels such as 60 keV [18] or 70 keV [21] without evaluating the effect on the lower-energy levels (40 to 60 keV), which show relatively higher iodine contrast [17] similar to the lower polychromatic X-ray energy in conventional CT [19]. Moreover, previously published spectral imaging scanning protocol settings were not based on the principle of individualization, displaying similar or even higher radiation dose as compared with conventional CT [16, 17, 22, 23]. The recently developed automatic spectral imaging protocol selection (ASIS) technique, a commercially available technique (GSI Assist, GE Healthcare), can individualize patient dose by providing assistance in the selection of the optimal preset based on the patient's size and preferred scan parameters.

To the best of our knowledge, no study has been performed on liver spectral CT combining ASIS and low contrast agent volume. The present investigation was designed to investigate the image quality and radiation dose of contrast-enhanced abdominal spectral CT imaging using ASIS and ASIR with reduced contrast agent dose by using the conventional 120-kVp CT with filtered back projection algorithm(FBP)and standard contrast agent dose as a reference standard.

Methods

This prospective single-institution study was approved by the Human Research Committee of our institutional review board, and all patients provided written informed consent.

Patient selection

The inclusion criteria included patients with known or suspected liver lesions, chronic hepatitis, or liver cirrhosis based on a treatment history, prior imaging examination, or abnormally increased tumour marker (a-fetoprotein >11 ng/mL or carcinoembryonic antigen > 5 ng/mL) level and was scheduled for clinically indicated multiphase liver CT. Clinical exclusion criteria were patients younger than 18 years of age, pregnant or lactating, had history of an allergic reaction to iodinated contrast media, or compromised renal function (estimated glomerular filtration rate <30 mL/min/1.73 m^2). Thirty-four (17.5 %) of the 194 patients were excluded for the following: 10 patients had advanced liver cirrhosis defined as Child-Pugh class C; there was a technical failure during contrast injection for six patients; 18 patients declined after reviewing the informed consent.

Finally, 160 patients were recruited between February and May 2015. Morphologic data (weight, height, and body mass index [BMI, calculated as the weight in kilograms divided by height in meters squared]) were recorded. Body weights in all patients prior to CT examination were measured to tailor the amount of contrast media of their individual needs.

Principle of automatic spectral imaging protocol selection

The ASIS technique (GSI Assist) is designed to recommend automatically the optimal spectral imaging preset that has the closest volume CT dose index (CTDIvol, mGy) to the target non-spectral imaging CTDIvol based on the target non-spectral imaging noise index at the same slice thickness, pitch and patient size (absorption path length) determined during the anteroposterior and lateral scout views. In the conventional, non-spectral CT imaging, the selection of noise index determines the required radiation dose (CTDIvol) using an automatic tube current modulation (x-y-z axis) mode such as AutomA/SmartmA techniques. In spectral CT imaging, a number of presets exist, each with fixed tube current during rotation. During spectral imaging, the same noise index as in the conventional non-spectral imaging is used and ASIS technique recommends a preset that has the closest CTDIvol to the conventional imaging mode.

CT examinations and image reconstruction

All patients underwent nonenhanced and two-phase contrast-enhanced CT examinations of the entire liver with a CT scanner (Discovery CT; GE Healthcare, Waukesha, WI, USA). Of the 160 enrolled patients, 80 were randomly assigned to the conventional 120-kVp protocol (protocol A) with automatic tube current selection and standard dose of contrast material (450 mg of iodine per kilogram of body weight[mgI/kg], routinely used in our hospital to obtain adequate liver enhancement of more than 50 HU to perform high diagnostic quality

hepatic CT [24–26]. The other 80 patients were scanned in the spectral imaging protocol (protocol B) with ASIS technique (GSI Assist) for selecting spectral imaging preset and 33 % less contrast agent dose: 300 mgI/kg, based on the previous report [18] and our clinical experience that the contrast agent dose down to 300mgI/kg just can maintain the similar enhancement in the liver to that of 450mgI/kg through the use of optimal low-energy levels in spectral CT. The detailed scanning parameters of each protocol are shown in Table 1.

Iohexol (Omnipaque, 350 mgI/mL, GE Healthcare, Milwaukee, WI, USA) was injected with a power injector (Envision CT Injector, Medrad, GA, USA) through a 20-G catheter inserted into an antecubital vein, followed by 20 mL of saline. The total iodine dose and the injection rate were adjusted by the imaging technicians based on patient body weight [24, 27]. The arterial-phase (AP) and portal venous-phase (PVP) images were acquired 30 s and 60 s after the beginning of contrast agent administration based on the recommendation of Awai et al. [27] to achieve nearly constant degree of arterial enhancement using a fixed delay regardless of patient weight or injection rate.

Images in protocol A was reconstructed with the traditional filtered back projection algorithm to serve as the reference standard. In protocol B, monochromatic images with energy values ranging from 40 to 70 keV in 10-keV increments were reconstructed with 50 % ASIR blending based on the recommendations of the manufacturer, previous study [18], and our practical experience.

Image analysis

Quantitative analysis. A radiologist (P.J.L., with 5 years of experience in abdominal CT) who was blinded to the image review results performed quantitative measurements at a commercially available workstation (Advantage Workstation 4.6; GE Healthcare, Milwaukee, WI, USA). Hounsfield units (HU) of attenuation of the liver, abdominal aorta, portal vein, and paraspinal muscle at the level of portal vein were measured in a circular region of interest (ROI), as described in previous reports [11, 28, 29]. Image noise was defined as the standard deviation of the HU in a homogeneous region of the subcutaneous fat on the anterior abdominal wall away from artefact or vessels [29]. For all measurements, the size, shape, and position of the ROI were kept consistent between the two phases and were performed three times at different image levels to calculate the average values.

Table 1 Scanning Parameters for Each Protocol

CT Parameter	Protocol A	Protocol B												
Detector Configuration (no. of sections × mm)	64 × 0.625	64 × 0.625												
Voltage (kVp)	120	80 and 140												
*GSI preset number	—	48†† n=4	54 n=2	36 n=5	44 n=4	40 n=5	31 n=2	22 n=22	1 n=2	15 n=6	27 n=2	10 n=9	4 n=4	5††† n=13
Gantry rotation time (s)	0.7	0.7	0.6	0.8	0.7	0.6	0.6	0.7	0.5	0.6	0.8	0.8	0.9	1
Tube current (mA)	101-480	260	275	260	275	360	375	375	630	640	550	600	600	600
CTDIvol (mGy)	7.56-24.51	6.48	6.52	7.37	7.64	8.79	9.25	10.76	12.72	15.64	16.87	18.28	20.71	23.28
Detector coverage (mm)	40	40												
Pitch	1.375:1	1.375:1												
Scan field of view (cm)	50	50												
Noise index (HU) †	10	10												
Section/interval thickness (mm)	5.0/5.0	5.0/5.0												
Reconstructed section thickness/interval (mm)	1.25 /1.25	1.25/ 1.25												
Reconstruction algorithm	FBP	50%ASIR blended with 50 % FBP												
Iodine concentration (milligrams of iodine per millilitre)	450	300												

*GSI= gemstone spectral imaging

† With 5-mm section thickness.

†† Minimum CTDIvol in the spectral imaging with ASIS under the specific scanning parameters

†††Maximum CTDIvol in the spectral imaging with ASIS under the specific scanning parameters

ASIS = automatic spectral imaging selection, FBP = filtered back projection, ASIR = adaptive statistical iterative reconstruction

Contrast-to-noise ratios (CNRs) relative to muscle for the organ of interest (liver, aorta, and portal vein) were calculated by using the following formulas: $CNRo = (ROIo - ROIm)/SDn$, where ROIo is the mean attenuation of the organ of interest, ROIm is the mean attenuation of the paraspinal muscle, and SDn is the mean image noise.

Qualitative analysis. Two radiologists (J.L. [observer 1] and J.B.G. [observer 2] with 15 and 33 years of clinical experience, respectively) and one radiology chief resident (X.P.Y. [observer 3]) independently performed a blinded qualitative analysis of CT images at the same workstation. A total of 800 images ($80 \times 5 \times 2$), at the level of hepatic portal vein, comprising both 120 kVp images in protocol A and monochromatic images in the range of 40–70 keV in protocol B, were presented in a random order to each of the readers at each session. Patient demographics or CT parameters were removed from the images to ensure blinded evaluation. Although the images were initially presented on a preset soft-tissue window with width of 400 HU and level of 40 HU, the readers were allowed to change the window settings as necessary.

The three readers were asked to rank the image quality based on a previously reported three-point or five-point scoring scheme [11]. The assessment of image noise and overall image quality were according to a five-point scale (1, severe image noise and artefacts, unacceptable; 2, high image noise and artefacts, confidence in details and anatomical structure decreased, just acceptable; 3, moderate image noise and artefacts, decreased confidence in details, but anatomical structure still relatively clear; 4, mild image noise and artefacts, less clear anatomical structure and details; and 5, no obvious image noise and artefacts, sharp anatomical structure and satisfactory details) on both AP and PVP images, while evaluation of visibility of small vascular structures was based on a five-point scale (1, unacceptable visualization; 2, suboptimal visibility; 3, acceptable visibility; 4, above average visibility; and 5, excellent visualization) on AP images and abdominal organ contrast enhancement was done by using a three-point scale (1, unacceptable; 2, acceptable; and 3, excellent) on PVP images.

Lesion analysis

Twenty-five of the 160 patients (protocol A, $n = 10$; protocol B, $n = 15$) had solitary or multiple hypervascular hepatocellular carcinoma nodules. In total, 15 hypervascular hepatocellular carcinomas were identified in protocol A while 18 were identified in protocol B. Clinical diagnosis of hepatocellular carcinoma was confirmed by means of histological findings ($n = 12$) or typical imaging findings ($n = 21$) includes hypervascular lesions in the hepatic arterial phase with

wash-out in the portal venous phase [23]. Only the three largest tumours were included if cases had more than three tumours.

An abdominal radiologist (Y.R.C.) with 3 years of experience measured the attenuations of the high-enhancing portions of the hypervascular liver lesions and adjacent non-tumorous liver parenchyma. The tumour-to-liver contrast ratio was calculated as the attenuation ratio between hypervascular liver lesions and adjacent hepatic parenchyma [18]. For the qualitative lesion analysis, three abdominal radiologists assessed the conspicuity of 33 hypervascular liver tumours on AP images, according to a five-point scale (score of 1, definitely an artefact mimicking a lesion; 2, probably an artefact mimicking a lesion; 3, subtle lesion; 4, well-seen lesion with poorly visualized margins; 5, well-seen lesion with visualized margins) [30].

Radiation dose

For each patient, the CTDIvol (mGy) and dose-length product (DLP, mGy·cm) values were recorded in protocols A and B on the AP images. Radiation dose for the PVP scan acquired during a single breath-hold by helical scan of the liver using the same scanning parameters as that for the AP scan, was not included in the analyses. The estimated effective radiation dose (mSv) was obtained by multiplying the DLP by a conversion factor of 0.015 for abdominal examination, as recommended by the International Commission on Radiological Protection (ICRP) publication 103[31]. To analyze effective radiation dose distribution according to patient sizes, four groups were categorized according to their body mass indices (BMI) (less than 18.5 kg/m^2, underweight; between 18.5 and 23.9 kg/m^2, normal BMI; between 24 and 28.9 kg/m^2, overweight; and 29 kg/m^2 or greater, obese)[32]. The correlations between BMI and recommended CTDIvol with ASIS technique were calculated.

Statistical analysis

All statistical calculations were performed using SPSS software (SPSS, version 16, SPSS Inc., Chicago, IL, USA) with $P < 0.05$ indicating a statistically significant difference. All numeric values were reported as means ± standard deviation of the mean, and categorical variables were summarized by using counts and proportions. An independent sample t-test was used to investigate differences for CT attenuation, tumour-to-liver ratio, CNR for liver and vessels, CTDIvol, DLP and effective radiation dose between protocol A and protocol B. Mann–Whitney U test was used to analyze differences in categorical variables, qualitative parameters and effective radiation dose in BMI subgroup with non-normal

Table 2 Baseline Patient Characteristics

Characteristics	Protocol A	Protocol B	*P* value
Age (years)*	54.24 ± 13.22	54.90 ± 14.00	0.759
Sex (M/F)	43/37	47/33	0.525
Weight (kg) *	63.48 ± 11.20 (range, 40–99)	62.93 ± 11.80 (range, 41–95)	0.768
BMI (kg/m^2)			0.785
<18.5	5 (6)	6 (8)	
Between 18.5 and 23.9	41 (51)	41 (51)	
Between 24 and 28.9	26 (33)	28 (35)	
≥29	8 (10)	5 (6)	
Liver disease			0.798
Absent	23 (14.8)	19 (13.0)	
Viral††	15 (9.7)	8 (5.5)	
Liver cirrhosis	24 (15.5)	26 (17.8)	
Cyst	35 (22.6)	43 (29.5)	
Hemangioma	19 (12.3)	15 (10.3)	
Hepatocellular Carcinoma	18 (11.6)	20 (13.7)	
Metastasis	18 (11.6)	10 (6.8)	
Other	3 (1.9)	5 (3.4)	

Except where indicated, data are frequencies of scores, with percentages in parentheses.

*Data are means ± standard deviation.

††Hepatitis B virus or hepatitis C virus

distribution and heterogeneity of variance. Pearson correlation coefficient was calculated for the correlations between BMI and recommended CTDIvol with ASIS technique. Kappa analysis was used to evaluate the inter-reader agreement for qualitative parameters with κ statistics [17].

Results

Details of the baseline characteristics for all patients are shown in Table 2. No significant differences in age (*P* = 0.759), sex (*P* = 0.525), weight (*P* = 0.768), BMI distribution (*P* = 0.785) and the presence of underlying disease (*P* = 0.798) were observed between the two protocols.

Quantitative image analysis

Compared with protocol A, the mean CT numbers from 40 to 70 keV for the liver, abdominal aorta and portal vein in protocol B were significantly higher (*P* < 0.001 for each comparison) for the energy levels at 40 keV and 50 keV except for the liver during the AP at 50 keV (*P* = 0.215), similar for the energy level at 60 keV (*P* = 0.060 for AP and 0.184 for PVP) and lower at 70 keV (*P* < 0.001 for each comparison) (Table 3).

In protocol B, the mean image noise decreased as the monochromatic energy level increased from 40 to 70 keV. Mean image noise for protocol A was 17.00 HU ± 4.38 in AP and 17.29 HU ± 4.26 in PVP, respectively, significantly lower than those for the energy levels at 40 keV (23.37 HU ± 5.21 and 22.51HU ± 4.23), similar to those at 50 keV (16.98

Table 3 Quantitative analysis results in protocol A (120 kVp) and protocol B (40–70 keV)

Parameter	A	B			
		40 keV	50 keV	60 keV	70 keV
CT numbers (HU)					
Liver during AP	73.7 ± 15.0	90.0 ± 26.6**	77.0 ± 17.4	69.9 ± 12.1	64.2 ± 9.5**
Liver during PVP	105.5 ± 14.6	179.4 ± 53.2**	136.3 ± 33.7**	109.7 ± 22.7	90.9 ± 10.0 **
Aorta during AP	260.9 ± 38.6	541.8 ± 112.0**	368.8 ± 69.5**	260.6 ± 47.3	191.0 ± 35.9 **
Portal vein during PVP	144.2 ± 18.7	305.7 ± 52.7**	210.9 ± 32.2**	152.5 ± 21.4*	115.2 ± 17.0**
Muscle during AP	61.1 ± 8.9	66.4 ± 17.0*	59.8 ± 12.3	55.7 ± 9.8*	54.0 ± 8.3**
Muscle during PVP	66.3 ± 9.7	80.9 ± 19.2**	70.3 ± 14.0*	61.8 ± 10.7*	57.6 ± 9.8**
CNR					
Liver during AP	1.0 ± 0.8	1.3 ± 1.2	1.2 ± 1.1	1.3 ± 1.4	1.1 ± 1.3
Liver during PVP	2.7 ± 1.9	4.5 ± 2.3**	4.2 ± 2.1**	4.2 ± 2.1**	3.1 ± 1.4*
Aorta during AP	12.7 ± 4.4	21.2 ± 6.5**	19.2 ± 5.9**	18.2 ± 5.9**	12.9 ± 4.6
Portal vein during PVP	5.23 ± 3.4	10.2 ± 2.9**	9.0 ± 2.7**	7.9 ± 2.9**	5.3 ± 2.0

Data are means ± standard deviation. *P* < 0.05 indicates a statistically significant difference between protocol A and each energy level (keV) of protocol B. * *P* < 0.05; ** *P* < 0.001
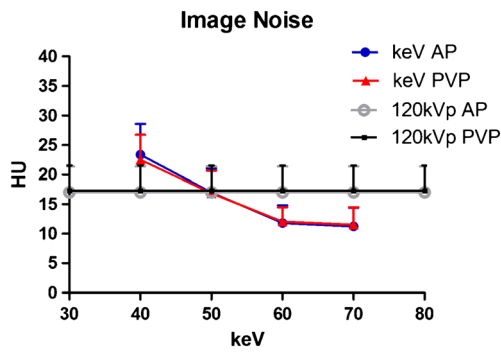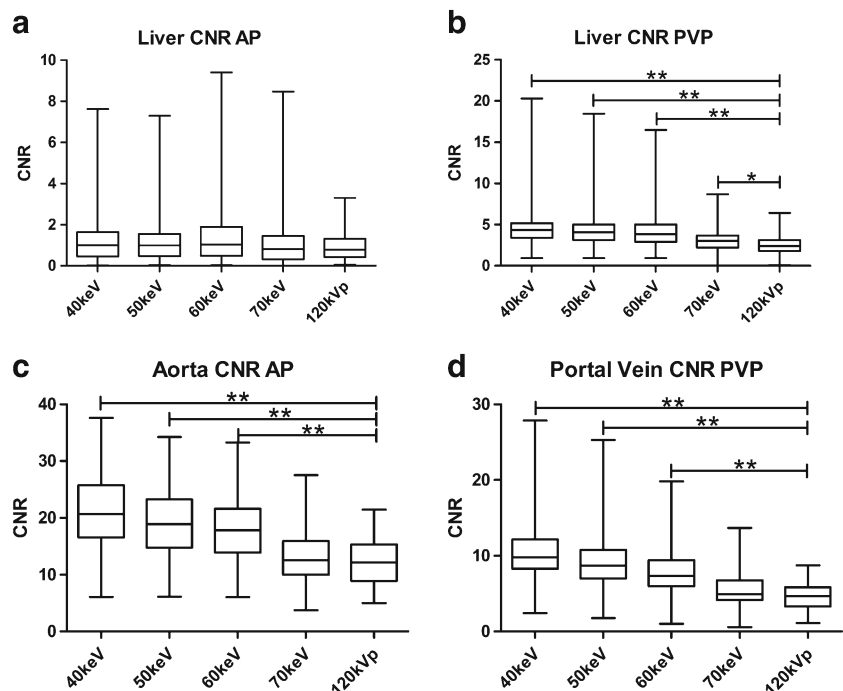
Fig. 1 Graph shows mean image noise on monochromatic images (40 to 70 keV) and 120-kVp CT images. Compared with 120-kVp CT images, image noise levels on monochromatic images were significantly higher at 40 keV, similar at 50 keV, and significantly lower at 60 keV and 70 keV

HU $\pm$ 4.07, P = 0.985 and 16.85 HU $\pm$ 3.84, P = 0.078), higher than those at 60 keV (11.83 HU $\pm$ 2.98 and 12.06 HU $\pm$ 2.43) and 70 keV (11.25 HU $\pm$ 3.16 and 11.50 HU $\pm$ 2.97), an average increase of 44 % and 43 % for 60 keV, 51 % and 50 % for 70 keV, respectively (P < 0.001 for each comparison with statistical difference) (Fig. 1).

The CNR values for the liver, abdominal aorta and portal vein on monochromatic images in the range of 40–60 keV in protocol B were all significantly higher than those in protocol A (P < 0.001 for each comparison) except for the liver in AP (P = 0.127, 0.307, 0.121 for 40–60 keV, respectively) (Figs. 2 and 3), an average increase of 44–67 % in AP and 50–94 % in PVP, respectively. However, there were no significant differences in CNR of any ROI between protocol B at 70 keV and protocol A, except for the liver in PVP (P = 0.017) (Fig 2, Table 3).
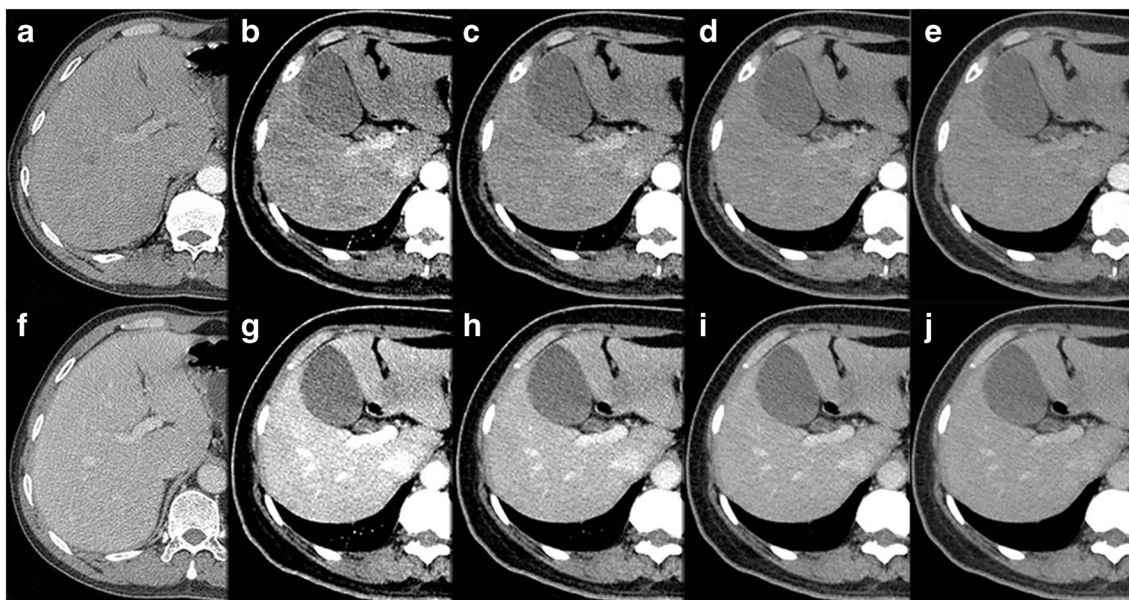
Qualitative image analysis

The image quality scores of the two protocols and the level of inter-observer agreement are shown in Table 4. All image quality scores, irrespective of the protocol, were equal to or greater than 2 which indicate an acceptable overall image quality. Compared with protocol A , the analyses of the subjective readers' rankings were significantly higher in protocol B at 50 keV and 60 keV with regard to overall image quality (P < 0.001 for each comparison), similar at 50 keV, but lower at 60 keV with respect to image noise (P < 0.001), higher at 50 keV (P < 0.001), but similar at 60 keV with respect to small vascular structure visibility and abdominal organ enhancement. The energy level at 40 keV in protocol B showed higher small vascular structure visibility (P < 0.001), abdominal organ enhancement (P < 0.001), and image noise (P = 0.004 for AP; P < 0.001 for PVP), but similar overall image quality as compared with protocol A. Lower overall image qualities were observed for the energy level at 70 keV in protocol B than that in protocol A.

Lesion analysis

The tumour-to-liver contrast ratio and lesion conspicuity are shown in Table 5. Among the energy levels from 40 to 70 keV in protocol B, only 40-keV and 50-keV images manifested both higher tumour-to-liver ratio and lesion conspicuity as compared to protocol A (P values ranging from < 0.003 to 0.033).

Fig. 2 Box plots show the comparison of CNR for liver (**a**, **b**), aorta (**c**), and portal vein(**d**) during the AP and PVP between monochromatic images (40 to 70 keV) and 120-kVp CT images. * P < 0.05; ** P < 0.001

Fig. 3 Transverse contrast-enhanced conventional CT images (a for AP, f for PVP) with 120 kVp, 90 mL contrast agent and FBP in a 57-year-old man with BMI of 25.71 kg/m² and monochromatic images (b-e for AP and g-j for PVP) with spectral imaging, 43 mL contrast agent and ASIR in a 55-year-old man with BMI of 24.44 kg/m². The overall image qualities for the images at 120 kVp were similar to that at 40 keV, lower than those at 50 keV and 60 keV, and higher than that at 70 keV

Radiation dose

There were no significant differences between the protocol A and protocol B in CTDIvol (12.52 ± 4.85 vs. 11.95 ± 4.21, $P = 0.517$), DLP (354.53 ± 124.27 vs. 332.70 ± 119.67, $P = 0.363$), and effective radiation dose (5.32 ± 1.86 vs. 4.99 ± 1.80, $P = 0.363$), irrespective of BMI (Fig. 4). The correlation between BMI and recommended CTDIvol with ASIS technique was positive (coefficient = 0.632, $P < 0.001$) .

Discussion

Previously published dose reports in rapid kV switching were inconclusive [16, 17, 22, 23] perhaps because of the failure of tube voltage-specific tube current modulation and photon starvation of 80-kVp images [16]. The recently introduced ASIS technique can individualize the spectral CTDIvol based on the target non-spectral imaging noise index to maintain similar dose as the conventional non-spectral imaging. Our results

Table 4 Qualitative analysis results in protocol A (120 kVp) and protocol B (40–70 keV)

Parameter	A	B								κ value	P value
		40 keV	P value	50 keV	P value	60 keV	P value	70 keV	P value		
AP											
Small structures	3.56 ± 0.47	4.50 ± 0.31	<0.001	4.07 ± 0.21	<0.001	3.49 ± 0.44	0.455	3.01 ± 0.24	<0.001	0.715	<.001
Image noise	3.17 ± 0.40	2.99 ± 0.26	0.004	3.27 ± 3.17	0.137	3.79 ± 0.42	<0.001	4.12 ± 0.22	<0.001	0.689	<.001
Overall quality	3.22 ± 0.27	3.14 ± 0.23	0.109	3.59 ± 0.37	<0.001	3.71 ± 0.37	<0.001	3.08 ± 0.32	0.017	0.593	<.001
PVP											
Organ enhancement	2.13 ± 0.21	2.76 ± 0.24	<0.001	2.55 ± 0.23	<0.001	2.22 ± 0.23	0.152	1.80 ± 0.20	<0.001	0.707	<.001
Image noise	3.32 ± 0.51	2.94 ± 0.23	<0.001	3.31 ± 0.31	0.869	3.73 ± 0.48	<0.001	4.04 ± 0.17	<0.001	0.687	<.001
Overall quality	3.20 ± 0.26	3.13 ± 0.22	0.124	3.55 ± 0.35	<0.001	3.68 ± 0.37	<0.001	2.96 ± 0.28	<0.001	0.662	<.001

Data are means ± standard deviation. Mean values were calculated for the categorical data for clarity. $P < 0.05$ indicates a statistically significant difference between protocol A and each energy level (keV) of protocol B. No case was rated as unacceptable in the total case. κ value: the coefficient of inter-reader agreement.

A three-point ordinal scale for organ enhancement was used as follows: 1, unacceptable; 2, acceptable; and 3, excellent.

Small structures, image noise and overall quality were graded on 5-point scale where image quality increases as grade increases (see "Qualitative analysis")

Table 5 Lesion Conspicuity and Tumour-to-Liver Contrast Ratio of 33 Hypervascular Hepatocellular Carcinomas

Parameter	A (n = 15)	B (n = 18)			
		40 keV	50 keV	60 keV	70 keV
Tumour-to–liver contrast ratio	1.58 ± 0.32	2.43 ± 0.74	2.12 ± 0.63	1.63 ± 0.62	1.47 ± 0.45
P value	—	0.005	0.033	0.283	0.952
Lesion conspicuity	3.31 ± 0.46	4.18 ± 0.64	3.86 ± 0.32	3.36 ± 0.71	2.82 ± 0.34
P value	—	0.003	0.006	0.941	0.003

Data are means ± standard deviation. Mean values were calculated for the categorical data for clarity. $P < 0.05$ indicates a statistically significant difference between protocol A (120 kVp) and each energy level (40–70 keV) of protocol B. A five-point ordinal scale where conspicuity increases as grade increases (see "Lesion analysis") was used

confirm that this principle can be applied to abdominal multiphase CT studies: based on the same noise index, the radiation dose in spectral CT with ASIS technique was almost the same as the 120-kVp CT, irrespective of BMI. It should be pointed out that for the patients with too low or too high BMI, the CTDIvol recommended in spectral CT may exceed the CTDIvol range allowed in the ASIS system, resulting in higher (for very small patients) or lower (for very large patients) dose than in 120-kVp CT.

Under the similar radiation dose as the conventional 120-kVp CT, reported by Matsumoto et al. [19] in vitro, the CT numbers of monochromatic spectral images at approximately 70 keV was equal to those of the 120-kVp CT images and increased as the X-ray energy decreased. Generally, the monochromatic energy is selectable with low energies yielding more contrast between materials [17]. The photoelectric effect in X-ray attenuation is increased at reduced X-ray energy, particularly in structures with a high effective atomic number, such as iodinated contrast material, providing iodine more attenuating at lower energies. Therefore, hypervascular hepatic lesions with more iodine are also more conspicuous at lower energies [17]. Findings of the our study revealed that low monochromatic energies (40–60 keV) maintain the same and even higher contrast by reducing 33 % contrast agent (300 vs. 450 mgI/kg); the tumour-to-liver contrast ratio that reflected

Fig. 4 Graph shows distribution of effective radiation dose from AP images in protocols A and B according to each BMI subgroup. No significant differences were found between protocol A and protocol B in each BMI subgroup

the lesion detection capability gradually increased as the energy level decreased, significantly higher at 40 keV and 50 keV, similar to previous finding [17].

However, higher contrast in low-energy levels was often accompanied by higher image noise due to the lack of photon flux [16, 17, 19]. To compensate for the increased image noise, an ASIR algorithm can be incorporated [18, 21] to preserve the natural appearance of images [29]. Considering the process of customized ASIR for each energy level was not time efficient and would disrupt clinical workflow, we preset the energy levels with same ASIR percentage to choose the optimal level that can be sent directly to the picture communication systems. On the basis of the recommendations of the manufacturer, previous study [18], and our practical experience, the ASIR percentage was set at 50. Besides ASIR, the beam hardening artefacts are also less at the "virtual" monochromatic images than conventional 120-kVp CT images [17], favouring the reduction of image noise at all low-energy levels, particularly at 50 keV and 60 keV. These two energy levels manifested higher contrast and overall image quality. Previous study [18] of spectral imaging in vessels had also demonstrated that similar enhancement and image quality at 60 keV and 50 % ASIR with reduced contrast dose were obtained compared with conventional CT scan of 120 kVp.

Similar findings about the methods for reducing contrast agent and radiation dose were also reported by using low-kVp setting and iterative reconstruction algorithm, especially at 80 kVp [11, 33, 34]. Although the low-kVp CT scan may have the advantage of dose reduction over spectral CT, as a single-energy CT examination, its fixed energy level cannot optimize contrast and image noise for different patient sizes and clinical applications, and most importantly, cannot provide more information than dual-energy CT.

Several potential limitations of our study merit consideration. Firstly, this study reflects our preliminary experience with a relatively small patient population. Secondly, the target spectral imaging noise index setting in the ASIS technique was not individualized in the current study, and was based on the fixed target non-spectral imaging noise index.
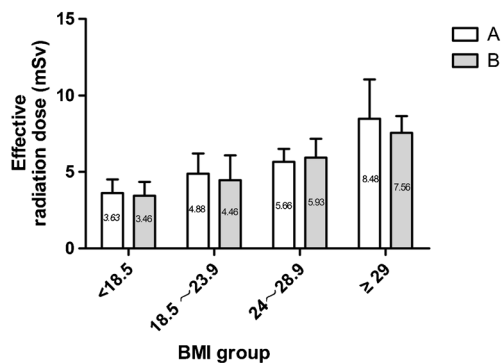
Thirdly, considering the convenience of clinical operations, the ASIR percentage was only set at 50 instead of being adjusted according to the energy level. This may influence the study results. Fourthly, reconstructed data of 120 kVp with ASIR were not included for comparison and further study will be performed. Fifthly, the same contrast media dose given to all patients regardless of patient size might result in unnecessary higher doses in smaller size patients and too low doses in larger patients. Lastly, no comparison between GSI-IR technique and a low kVp-IR technique were performed. Further work along these lines will be the next step.

In conclusion, spectral CT using ASIS technique and ASIR algorithm in the range of 40–60 keV monochromatic energy levels can dramatically decrease contrast agent dose with adequate image quality for the hepatic dynamic CT without increasing radiation dose in most patients, compared to 120 kVp with FBP algorithm. The use of spectral images at the energy level of 50 keV in combination with 50 % ASIR algorithm provides optimal balance between image contrast and image noise in both AP and PVP images.

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