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RESEARCH

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Reduced-dose deep learning iterative reconstruction for abdominal computed tomography with low tube voltage and tube current

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Abstract

Background The low tube-voltage technique (e.g., 80 kV) can efficiently reduce the radiation dose and increase the contrast enhancement of vascular and parenchymal structures in abdominal CT. However, a high tube current is always required in this setting and limits the dose reduction potential. This study investigated the feasibility of a deep learning iterative reconstruction algorithm (Deep IR) in reducing the radiation dose while improving the image quality for abdominal computed tomography (CT) with low tube voltage and current.

Methods Sixty patients (male/female, 36/24; Age, 57.72 ± 10.19 years) undergoing the abdominal portal venous phase CT were randomly divided into groups A (100 kV, automatic exposure control [AEC] with reference tube-current of 213 mAs) and B (80 kV, AEC with reference of 130 mAs). Images were reconstructed via hybrid iterative reconstruction (HIR) and Deep IR (levels 1–5). The mean CT and standard deviation (SD) values of four regions of interest (ROI), i.e. liver, spleen, main portal vein and erector spinae at the porta hepatis level in each image serial were measured, and the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated. The image quality was subjectively scored by two radiologists using a 5-point criterion.

Results A significant reduction in the radiation dose of 69.94% (5.09 ± 0.91 mSv vs. 1.53 ± 0.37 mSv) was detected in Group B compared with Group A. After application of the Deep IR, there was no significant change in the CT value, but the SD gradually increased. Group B had higher CT values than group A, and the portal vein CT values significantly differed between the groups ($P < 0.003$). The SNR and CNR in Group B with Deep IR at levels 1–5 were greater than those in Group A and significantly differed when HIR and Deep IR were applied at levels 1–3 of HIR and Deep IR ($P < 0.003$). The subjective scores (distortion, clarity of the portal vein, visibility of small structures and overall image quality) with Deep IR at levels 4–5 in Group B were significantly higher than those in group A with HIR ($P < 0.003$).

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Conclusion Deep IR algorithm can meet the clinical requirements and reduce the radiation dose by 69.94% in portal venous phase abdominal CT with a low tube voltage of 80 kV and a low tube current. Deep IR at levels 4–5 can significantly improve the image quality of the abdominal parenchymal organs and the clarity of the portal vein.

Keywords Low tube voltage, Deep learning iterative reconstruction algorithm, Radiation dose, Image quality, Abdomen, Portal vein

Background

Multiple-phase contrast-enhanced abdominal CT is an indispensable diagnostic tool for evaluating various abdominal diseases [1, 2]. However, concerns remain about the potential risks of ionizing radiation, particularly for populations that may require serial CT examinations [3–5]. Previous studies have reported that the low tube-voltage technique (e.g., 80 kV) can efficiently reduce the radiation dose and increase the contrast enhancement of vascular and parenchymal structures in abdominal contrast-enhanced CT [6]. However, in this setting, a high tube current is always required to reduce the image noise and increase the susceptibility to beam hardening artifacts that occur by reducing the photon flux and energy [7–9]. This limits the further dose reduction at low tube voltages concurrently with low tube currents during abdominal CT with internally low contrast in soft tissues.

In recent years, model-based iterative reconstruction (MBIR) and deep learning reconstruction algorithms have been demonstrated to play vital roles in denoising the low-dose CT images [10, 11]. In principle, manual and empirical value determined regularization functions are required for MBIR to reduce the image noise and artifacts. It is these facts that may change the image texture, and result in “blurred”, “plastic”, or “cartoonish” artifacts [12]. Notably, most deep learning reconstruction algorithms use high-dose FBP or MBIR images as the target data to replicate their noise textures and visual impressions [13, 14], however, low-contrast or high-density anatomical structures such as the abdomen and pelvis are easily overwhelmed by noise in ultra-low-dose images, which affects the clinical diagnosis. To overcome the above limitations, a deep learning iterative reconstruction (Deep IR) that incorporates both MBIR and deep neural convolutional networks was developed to suppress the noise and preserve texture, and has shown remarkable performance in improving the image quality of low-dose CT images [15–17]. In particular, chest and abdomen CT has drawn a great deal of clinical interests, with numerous studies confirming that the Deep IR algorithm can reduce the image noise and improve the image quality of the reduced-dose chest CT and CT angiography [18, 19].

Therefore, we hypothesize that the radiation dose can be efficiently reduced without degrading the image quality by using a low tube voltage and Deep IR algorithm for enhanced CT of the abdomen. The purpose of this study is to explore the feasibility of 80 kV combined with the Deep IR algorithm to reduce the radiation dose and improve the image quality of low-dose abdomen enhanced CT, compared with the commonly used HIR algorithm.

Methods

Patient population

Patients who underwent contrast-enhanced abdominal CT at our institution from March 2023 to June 2023 were prospective enrolled in the study. The inclusion criteria were as follows: (1) patients with clinical need for upper abdominal enhanced CT examination and (2) patients without a history of severe contrast media allergy or renal insufficiency. The exclusion criteria were as follows: (1) patients whose image quality was affected by poor respiratory coordination; (2) patients with metal implants in the abdomen; and (3) patients age < 18 years. Two patients’ images affected by poor respiratory coordination and a patient’s images with substantial metal artifacts at the fundus of stomach were excluded. Ultimately, 60 patients were included in the study and were randomly divided into two groups, labeled A and B. This study was approved by the Hospital Ethics Committee, and all patients were informed of the examination precautions and signed informed consent forms.

Imaging technique and postprocessing

All patients underwent contrast-enhanced abdominal CT on a 320-detector row CT scanner (uCT 960+, United Imaging Healthcare, Shanghai, China). Patients underwent breath-hold training prior to the scan to reduce respiratory motion artifacts. Patients were also informed of the examination precautions. Group A adopted the routine scanning protocol of our institution, and the protocol was as follows: tube voltage 100 kV, AEC, and tube current setting level 3 (reference tube current: 213 mAs). The low-dose scanning scheme for Group B during the portal venous phase was as follows: tube voltage 80 kV, automatic exposure control (AEC), and tube current setting level 2 (reference tube current: 130 mAs); the arterial and delayed phase scanning schemes were the same as those Group A. The pitch and rotation speeds for the two groups were the same, at 0.9937 and 0.5 s/r, respectively. The scope of the scan was from the upper extent of the diaphragm to the upper edge of the pelvis. Contrast agent of 370 mgI/ml of (Ultravist, Bayer, Healthcare Ltd, Guangzhou, China) was used. The volume was selected according to the participants' body weight at 1.2 ml/kg, with an allowable dose range of 50–95 ml and an injection speed of 2.7 ml/s. The abdominal aorta was monitored via the bolus tracking technique with a threshold of 150 HU and artery, portal and delayed phase scanning was commenced at 16 s, 50 s and 120 s, respectively, after threshold triggering. After scanning, the raw data from the portal phase were transferred to the Explorer Platform (uInnovation-CT, R001, United Imaging Healthcare, Shanghai, China) for reconstruction and analysis. In group A, the hybrid iterative reconstruction (HIR) algorithm [20] was used at a strength level 5 (with the maximum being 10) for reconstruction, and in group B, the Deep IR algorithm was applied at levels 1 to 5 for reconstruction. In both groups, the slice thickness was 1 mm, and the slice interval was 1 mm.

Deep learning iterative reconstruction

Deep IR is the latest-generation deep-learning based algorithm utilizing the newly designed backbone for CT image reconstruction. Technically, Deep IR combines the advantages of deep-learning methods and MBIR, where the regularization term in MBIR is replaced by a convolutional neural network. Therefore, this algorithm not only allows for a substantial noise suppression without inducing plastic image appearance that is easily caused by the regularization term, but also retains the ability of characterizing image detail provided by MBIR. In addition, Deep IR provides five reconstruction strength levels to control the amount of noise reduction, which could be adjusted by radiologists according to their preference and the scanning body parts.

Radiation dose

The volume CT dose index (CTDIvol) and dose–length product (DLP) were recorded, and the effective dose (ED) was calculated for the two groups using the formula ED = DLP × k, where k represents the radiation dose conversion factor, which equals 0.015 mSv/(mGy.cm) for the abdomen.

Image quality evaluation

Objective image quality assessment

The CT values and standard deviations (SDs) of the liver parenchyma, spleen, main portal vein, and left paravertebral muscle were measured by a radiologist (with 5 years of experience in CT imaging). The region of interest (ROI) avoided interfering factors that might affect the measurement results, such as vessels, lesions, and obvious local fat deposition, to ensure that the shape, size, and location of each ROI were basically consistent in each part and under the reconstruction method. The ROI size was 30–50 mm^2. All of the data were measured three times, and the average value was taken. The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of the liver parenchyma, spleen and portal vein were calculated. As the muscle SD value was relatively constant and not strongly affected by contrast enhancement, the muscle SD was selected to represent the image noise.

$$\mathrm{SNR}=\frac{\mathrm{CTvalue}_{\mathrm{target}}}{\mathrm{SD}_{\mathrm{target}}}$$

$$\mathrm{CNR}=\frac{\mathrm{CTvalue}_{\mathrm{target}}\text{-}\mathrm{CTvalue}_{\mathrm{muscle}}}{\mathrm{SD}_{\mathrm{muscle}}}$$

Subjective image quality assessment

The six groups of reconstructed images were independently evaluated by two qualified radiologists (with 5 years and 10 years of experience in CT imaging) with no knowledge of the method of image reconstruction. A five-point scoring method was used to evaluate each of five characteristics: image noise, distortion, clarity of the portal vein, visibility of small structures and overall image quality [21, 22]. The specific scoring criteria for the five areas are shown in Table 1. The final image quality scores were obtained by consensus between the two radiologists if there were discrepancies in their scores through joint reading. An overall image quality of 3 points or above was considered to meet the needs of clinical diagnosis.

Statistical analysis

SPSS statistical software (Windows v.22.0, SPSS, Chicago, Illinois) was used for statistical analysis. All of the measured values are expressed as the mean ± SD. The Kolmogorov-Smirnov test was used to test the normality

Table 1 The subjective score criteria of image quality

Scores	Noise	Distortion	Clarity of portal vein	Visibility of small structures	Overall image quality
5 points	Minimal	None	Very clear and sharp	Very clear and sharp	Excellent
4 points	Less than average	Minor	Clear and sharp	Clear and sharp	Above average
3 points	Average	Moderate	Moderately clear and sharp	Moderately clear and sharp	Average
2 points	More than average	Major	Less clear and less sharp	Less clear and less sharp	Below average
1 point	Severe	Severe	Unclear and not sharp	Unclear and not sharp	Poor

of continuous data. The differences in general data (except for sex, which was tested using the χ^2 test), tube current and radiation dose between group A and group B were compared using the independent-samples t test. The objective parameters, including CT values, SD values, SNRs, and CNRs, were analyzed via using one-way ANOVA. The subjective scores were compared using the Kruskal‒Wallis H test. $P < 0.05$ was considered statistically significant. The Bonferroni correction was used for post hoc pairwise comparisons, and the significance level was adjusted to $P<0.05/15$. The consistency of the subjective scores of the two radiologists was analyzed using the kappa test, with kappa≥0.75 representing good consistency, 0.4≤kappa<0.75 representing general consistency, and kappa<0.4 representing poor consistency between the two reviewers.

Results

General clinical data and radiation dose

There was no statistically significant difference between the two groups in any of the general variables, including sex, age, height, weight, and BMI ($P>0.05$). Differences in mAs, CTDIvol, DLP, and ED between Group A and Group B were statistically significant ($P< 0.05$). The ED (1.53±0.37 mSv) in Group B was lower than that in Group A (5.09±0.91 mSv) by 69.94%. The specific clinical data and radiation dose parameters are shown in Table 2.

Objective image quality

As the Deep IR level increased from 1 to 5, the portal-phase CT values of the liver, spleen, portal vein and muscle in group B remained basically the same, whereas the SD value of the muscle gradually increased. The SNRs and CNRs of the liver, spleen and portal vein decreased as the reconstruction grade increased. The CT values of the liver, spleen, portal vein and muscle were numerically greater in Group B than in Group A, and the difference in the CT value of the portal vein was statistically significant ($P< 0.003$). The SNR and CNR in Group B were greater than those in Group A, and the differences between HIR and Deep IR at levels 1 to 3 were significant ($P<0.003$). The results are shown in detail in Table 3.

Table 2 Comparison of general data, scan parameters, and radiation dose measurements between the two groups

Parameters	Group A ($n=30$)	Group B ($n=30$)	χ^2 or t value	P value
General data				
Sex (male/female)	19/11	17/13	0.278	0.598
Age (years)	55.97 ± 10.90	59.47 ± 9.48	-1.327	0.190
Height (cm)	168.93 ± 6.66	167.97 ± 6.96	0.549	0.585
Weight (kg)	63.43 ± 10.09	60.40 ± 12.72	1.024	0.310
BMI (kg/m^2)	22.18 ± 3.03	21.29 ± 3.77	1.008	0.318
Scan parameters				
kV	100	80		
mAs	205.23 ± 28.23	153.57 ± 21.09	8.031	< 0.001
Radiation				
CTDIvol (mGy)	9.43 ± 1.30	3.29 ± 0.45	24.480	< 0.001
DLP (mGy*cm)	339.00 ± 60.45	101.91 ± 24.68	19.889	< 0.001
ED (mSv)	5.09 ± 0.91	1.53 ± 0.37	19.876	< 0.001

Note Data are presented as the number or mean ± SD

Subjective image quality

The intergroup differences in the five subjectively evaluated measures of the six reconstructed images were statistically significant ($P< 0.001$), and the results are shown in Table 4, and Fig. 1. The image noise scores of Group B were higher than those of group A. The lower the level of Deep IR was, the lower the image noise. The subjective scores of image noise in Group B were higher than those in Group A. The scores of Deep IR levels 4 and 5 in Group B were significantly better than those in Group A in terms of distortion, clarity of the portal vein, visibility of small structures and overall image quality ($P< 0.003$). Deep IR at levels 1 and 2 increased the distortion and reduced the overall image quality ($P< 0.003$). (Figures 2, 3 and 4). There was good agreement between the two reviewers (the kappa value was between 0.73 and 0.91).

Discussion

Dose optimization is highly important for eliminating the possible adverse effects of ionizing radiation exposure from CT. In this study, we employed the Deep IR algorithm to further reduce the radiation dose by using the combined low tube-voltage and tube-current technique. Our results indicated that our protocol with Deep IR algorithm could significantly reduce the radiation dose (5.09±0.91 mSv vs. 1.53±0.37 mSv) in portal-phase abdominal CT while improving the image quality. Specifically, Deep IR at levels 4 and 5 enabled a 69.69% reduction in the radiation dose while still providing improved SNR, CNR, and subjectively scored image quality. It demonstrates the potential of deep learning techniques to improve patient safety and diagnostic utility in abdominal CT evaluation.

The radiation dose is known to be proportional to the square of the tube voltage [23]. A previous showed that [24] when the tube current is constant and the tube voltage is reduced from 120 kV to 100 kV, the radiation dose can be reduced by 33%; The radiation dose can be reduced by 65% when the tube voltage is reduced from 120 kV to 80 kV, and the radiation dose can be effectively reduced by reducing the tube voltage. Seung et al. [25] showed that the use of 80 kV could reduce the radiation dose by 45.2% with comparable or improved image quality in patients with abdominal tumors. Li et al. [26] used 80 kV scans combined with deep learning image reconstruction (DLIR) for late arterial-phase abdominal

Table 3 Comparison of CT, SNR and CNR values between the HIR and deep IR algorithms

		Group A	Group B					F value	*P* value
		HIR	Deep IR 5	Deep IR 4	Deep IR 3	Deep IR 2	Deep IR 1		
CT value									
	Liver	119.38 ± 14.82	125.58 ± 19.64	125.54 ± 19.60	125.53 ± 19.56	125.49 ± 19.55	125.47 ± 19.49	0.530	0.753
	Spleen	128.14 ± 17.4	145.97 ± 22.46	146.00 ± 22.45	145.97 ± 22.42	146.02 ± 22.37	146.02 ± 22.33	3.400	0.006
	Portal vein	177.32 ± 26.31	213.91 ± 24.70*	210.63 ± 24.30*	213.93 ± 24.71*	214.04 ± 24.69*	214.03 ± 24.76*	10.516	< 0.001
	Muscle	65.24 ± 6.43	68.74 ± 8.68	68.71 ± 8.60	68.64 ± 8.64	68.67 ± 8.54	68.39 ± 8.03	0.863	0.507
SNR									
	Liver	9.27 ± 1.82	13.03 ± 2.91	15.68 ± 3.52	20.36 ± 4.56*	30.60 ± 6.83*	63.62 ± 18.69*	165.013	< 0.001
	Spleen	9.28 ± 2.13	16.14 ± 2.45	19.13 ± 2.86*	24.34 ± 3.65*	35.76 ± 6.85*	64.82 ± 18.23*	174.953	< 0.001
	Portal vein	11.04 ± 2.41	20.32 ± 2.99	23.91 ± 4.15	30.97 ± 5.28*	44.71 ± 9.03*	82.58 ± 30.50*	110.337	< 0.001
	Muscle	5.41 ± 0.98	7.43 ± 1.50	8.80 ± 1.82	11.16 ± 2.37*	15.82 ± 4.48*	29.86 ± 12.35*	78.315	< 0.001
CNR									
	Liver	4.48 ± 1.49	6.23 ± 2.39	7.39 ± 2.89	9.41 ± 3.73	13.28 ± 5.80*	24.79 ± 12.88*	43.272	< 0.001
	Spleen	5.22 ± 1.71	8.23 ± 2.35	9.76 ± 2.84	12.40 ± 3.66*	17.76 ± 6.81*	32.78 ± 14.15*	64.709	< 0.001
	Portal vein	9.23 ± 2.40	15.65 ± 3.40	18.16 ± 4.40	23.59 ± 5.44*	33.83 ± 11.41*	62.96 ± 25.12*	81.536	< 0.001
SD									
	Muscle	12.36 ± 1.99	9.48 ± 1.45*	8.01 ± 1.27*	6.33 ± 1.12*	4.67 ± 1.48*	2.72 ± 1.25*	169.660	< 0.001

Note * represents P < 0.003 (0.05/15) with different levels of Deep IR in comparison to HIR. The data are presented as the mean ± standard deviation (SD). SNR: signal-to-noise ratio; CNR: contrast-to-noise ratio

CT of patients with a low BMI, and the results showed that DLIR could significantly reduce the image noise and improve the overall image quality of low-dose abdominal CT while reducing the radiation dose by 57%. Many studies [27, 28] have shown that 100 kV combined with HIR can obtain high-quality abdominal images. 100 kV and HIR are routinely used for scanning in our institution. In Group B, not only did the tube voltage decrease from 100 kV to 80KV, but the tube current also decreased from 205 mAs to 154 mAs. The results showed that the combination of reducing the tube voltage and tube current with the image reconstruction algorithm can better reduce the radiation dose (by 69.94%) while ensuring the same or better abdominal image quality.

X-ray energy decreases and approaches the K edge of iodine (33.2 keV). Through the photoelectric effect, X-ray energy interacts more with iodine-based materials, which can cause greater X-ray attenuation and greater contrast enhancement. Yu et al. [29] conducted a phantom experiment and showed that the iodine attenuation value of 80 kV CT increased by 70% and 100%, on average, compared with that of 120 kV CT and 140 kV CT. Zamboni et al. [30] found that pancreatic cancer was more obvious when a low kV was used. The results of this study showed that the CT values of all organs in Group B were greater than those in Group A, and the CT values of the portal vein were significantly greater than those in Group A, which is 33 HU greater that those in Group A. Sufficient CT values can increase the contrast of images and optimize the display of vessels. In addition, patients in both groups were treated with high-concentration iodine contrast agent (370 mgI/ml). Iezzi et al. [31] found that the use of a high-concentration contrast agent and low kV can maintain the image quality of the abdominal aorta and reduce the radiation dose by 74%. A low tube voltage combined with a high concentration of iodine contrast agent can not only reduce the radiation dose, but also improve the image quality of solid organs and ensure the SNR. In this study, the SNRs and CNRs of the liver, spleen and portal vein in Group B were greater than those in Group A, which effectively enhanced the display of parenchymal organs, vessels and their branches and improved the contrast between the portal vein and its surrounding tissues.

A decrease in tube voltage and tube current produces remarkable image noise and is sensitive to hardening artifacts, especially in abdominal CT with low soft tissue contrast, and an increase in image noise leads to a decrease in image quality, thus affecting the diagnostic accuracy [6]. The Deep IR algorithm can automatically identify useful signals and noise in images, which can not only remove fringe artifacts in low-dose images but also achieve image denoising so that the reconstructed image has better contrast and detail display [32]. In this

Table 4 Comparison of subjective scores between HIR and different levels of deep IR

	Group A	Group B					H-value	*P* value
	HIR	**Deep IR 5**	**Deep IR 4**	**Deep IR 3**	**Deep IR 2**	**Deep IR 1**		
Noise	3.63 ± 0.49	3.87 ± 0.35	3.93 ± 0.25	4.33 ± 0.48*	4.97 ± 0.18*	5.00*	138.235	< 0.001
Distortion	4.47 ± 0.51	4.83 ± 0.38*	4.83 ± 0.38*	4.37 ± 0.67	3.43 ± 0.57*	2.20 ± 0.48*	126.248	< 0.001
Clarity of portal vein	3.80 ± 0.66	4.87 ± 0.35*	4.87 ± 0.35*	4.90 ± 0.31*	4.30 ± 0.60	3.37 ± 0.56	111.808	< 0.001
Visibility of small structures	4.30 ± 0.70	4.97 ± 0.18*	4.97 ± 0.18*	4.83 ± 0.38*	3.87 ± 0.51	2.73 ± 0.64*	130.984	< 0.001
Overall image quality	4.50 ± 0.51	4.93 ± 0.25*	4.97 ± 0.18*	4.60 ± 0.50	3.60 ± 0.50*	2.43 ± 0.57*	136.110	< 0.001

Note * represents $P < 0.003$ (0.05/15) with different levels of Deep IR in comparison to HIR. The data are presented as the mean ± standard deviation (SD)

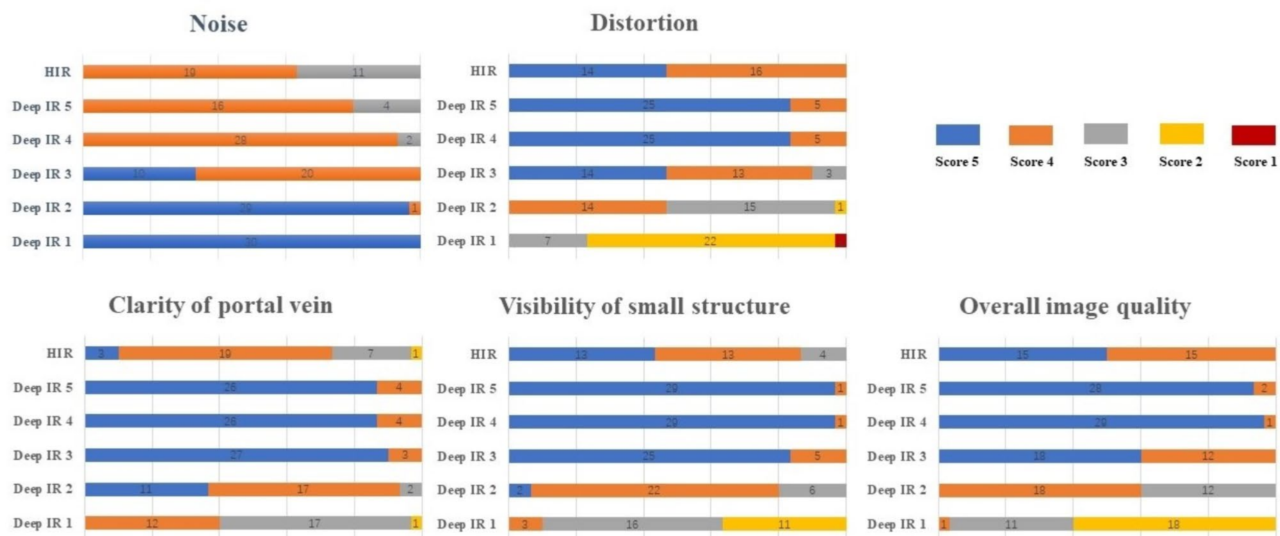

Fig. 1 Subjective image quality score

study, compared with the HIR algorithm, the Deep IR algorithm significantly improved the SNRs and CNRs of abdominal organs and the portal vein at all reconstruction levels. The lower the Deep IR reconstruction level was, the higher the SNR and CNR. However, there was a discrepancy between objective image quality and subjective scoring results. Although higher SNR and CNR were obtained on Deep IR images with lower reconstruction strengths, readers more preferred those images with higher strengths. This was because Deep IR with low strengths provide lower image noise compared to that with high strengths; thereby obtaining better objective image quality. Nevertheless, it should be noted that such objective metrics, such as SNR and CNR are simple metrics related with image noise, which may not be sufficient for assessing image quality thoroughly [22, 33, 34]. In this study, when the Deep IR algorithm was applied at strength levels 1 and 2, although the image noise was significantly reduced, the reconstructed images were subject to distortion and other alterations due to blurring effects and texture changes, resulting in lower subjective scoring. On the basis of subjective and objective evaluation, appropriate Deep IR reconstruction levels can effectively improve the image quality of abdominal parenchymal organs and the clarity of the portal vein, and Deep IR grades 4 and 5 have the best performance.

The results of this study have significant clinical implications, and the combined use of low tube voltage, low tube current and Deep IR techniques may improve patient safety by reducing radiation exposure while improving image quality of abdominal CT and angiography. This is particularly beneficial for patients who require regular follow-up, those who require multiphase, large-scale perfusion scans, and those who are sensitive to radiation. This study also provides a reference for the subsequent research on enhanced abdominal CT scanning with lower doses and more advanced reconstruction algorithms.

Some limitations still exist in this study. First, this was a single-center study with a relatively small sample size. Second, the maximum BMI of the patients in this study was 32, and the feasibility of improving abdominal image quality in patients with high BMIs needs to be further studied. Finally, only the image quality of the portal venous phase of the abdomen was studied, and the sensitivity and specificity of lesion detection and

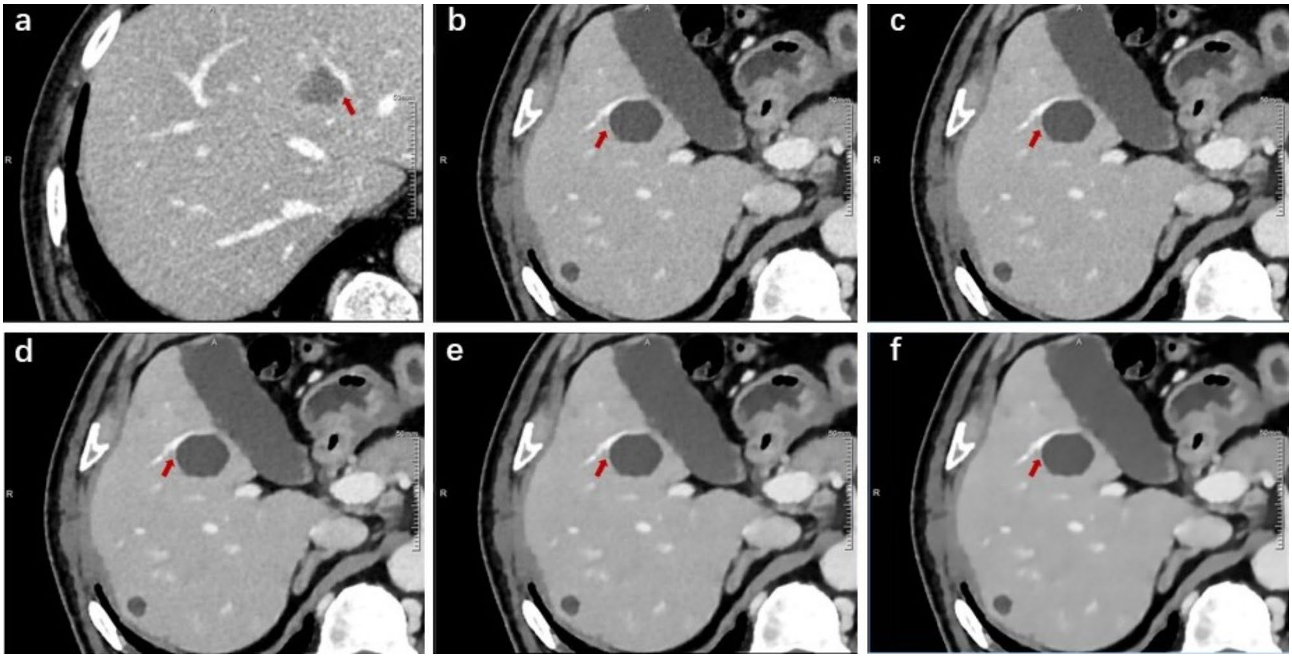

Fig. 2 **a** Image from a 64-year-old man reconstructed with HIR. The vessel and lesion are moderately clear and sharp, and the noise and overall image quality were rated 3 and 4, respectively. **b**-**f** Images from a 65-year-old man reconstructed with Deep IR at levels 5 (**b**), 4 (**c**), 3 (**d**), 2 (**e**) and 1 (**f**). The vessel and lesion were very clear and sharp; the noise of the images **b**-**f** was rated as 4, 4, 4, 5 and 5, respectively; and the overall image quality of images **b**-**f** was rated as 5, 5, 4, 4 and 3, respectively

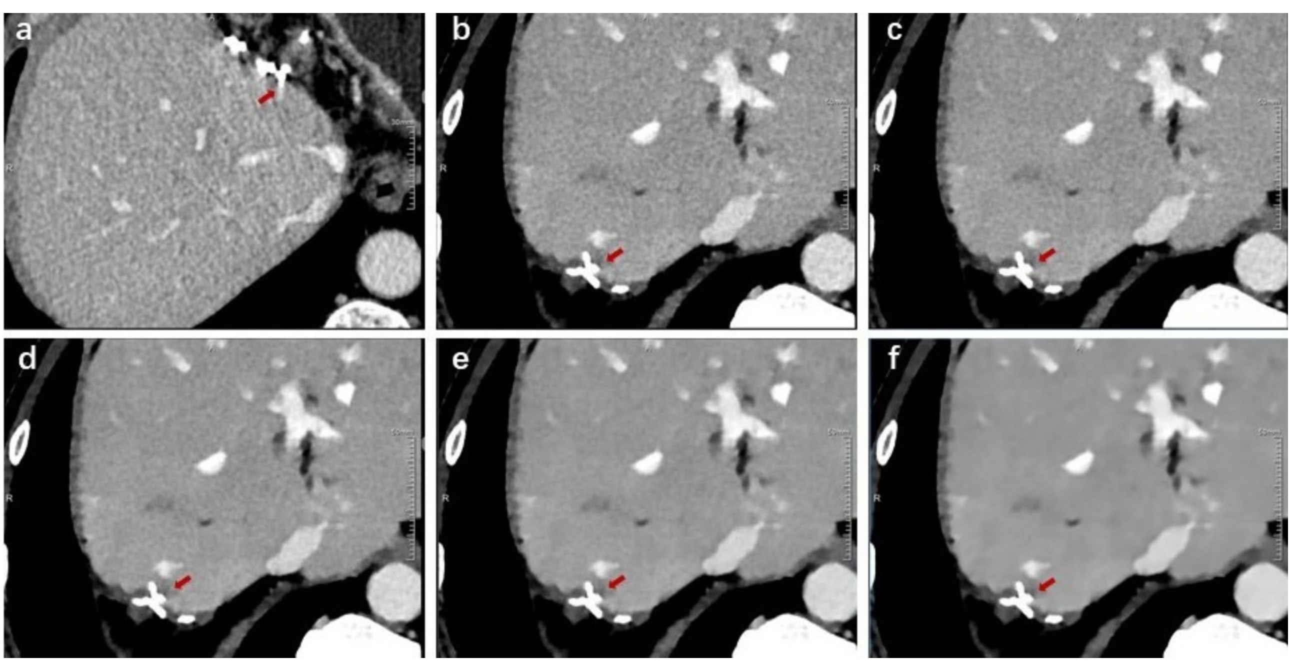

Fig. 3 **a** Image from a 60-year-old woman reconstructed with HIR. The metal boundary was minor distortion, and rated the distortion as 4. **b-f** Images from a 65-year-old man reconstructed with Deep IR at levels 5 (**b**), 4 (**c**), 3 (**d**), 2 (**e**) and 1 (**f**). The metal boundary was not distorted, and the distortion **b-f** was rated as 5, 5, 5, 4 and 3, respectively

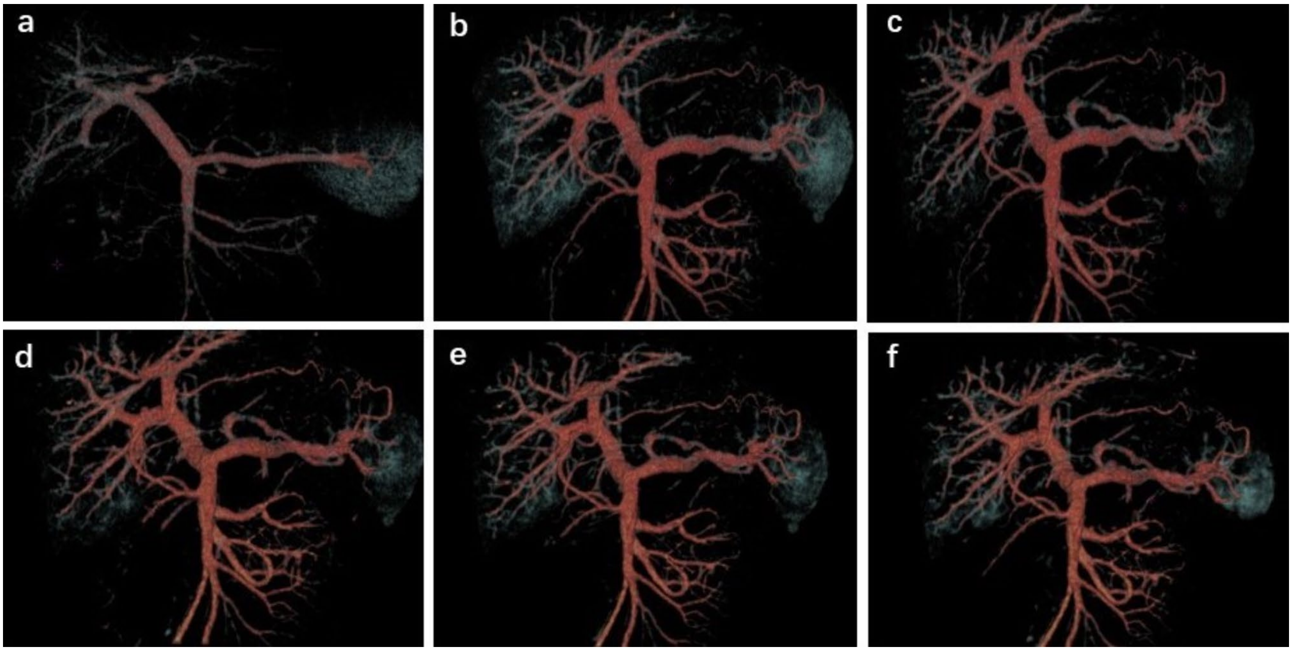

Fig. 4 **a** Volume render (VR) image from a 64-year-old man reconstructed with HIR. The branches of the portal vein are moderately clear, and the clarity of the portal vein was rated 3. **b-f** VR images from a 42-year-old man reconstructed with Deep IR at levels 5 (**b**), 4 (**c**), 3 (**d**), 2 (**e**) and 1 (**f**). The branches of the portal vein are very clear in the images, and the clarity of the portal vein in images **b-f** was rated 5, 5, 5, 5 and 4, respectively

differentiation were not evaluated in this study. The next step will be extended to the arterial phase and delayed phase of the abdomen to achieve the goal of multiphase enhanced CT with a low radiation dose.

Conclusion

The Deep IR algorithm can meet the clinical requirements and reduce the radiation dose by 69.94% in portal venous phase abdominal CT with a low tube voltage of 80 kV and a low tube current. Deep IR at levels 4–5 can significantly improve the image quality of the abdominal parenchymal organs and the clarity of the portal vein.

Abbreviations

Deep IR	Deep Learning Iterative Reconstruction Algorithm
CT	Computer Tomography
AEC	Automatic Exposure Control
HIR	Hybrid Iterative Reconstruction
SD	Standard Deviation
ROI	Regions of Interest
SNR	Signal-to-Noise Ratio
CNR	Contrast to Noise Ratio
MBIR	Model-Based Iterative Algorithm
CTDIvol	Volume CT Dose Index
DLP	Dose Length Product
ED	Effective Dose
DLIR	Deep Learning Image Reconstruction

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Author contributions

SZ and CJ wrote the main manuscript text. JY, BZ, ZL, and YL contributed to the conception of the study. QT, AL, and WH performed the data analyses. JY, WZ, and XH helped perform the analysis with constructive discussions. YX, YW, and RW prepared the figures and tables. All of the authors read and approved the final manuscript.

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Data availability

Authors declares that all data and material will be available for further research and verification by contacting corresponding author.

Declarations

Ethics approval and consent to participate

The current study was approved by a Research Ethics Committee of the First Affiliated Hospital of Xi 'an Jiaotong University [Code: XJTU1AF2021LSB-02]. We declare that all research phases performed in accordance with the Declaration of Helsinki-Ethical Principles for Medical Research Involving Human Subjects. Research participants were informed about the study and informed consent was obtained and the voluntary nature of the participation was explained to participants, and they were assured about anonymity and confidentiality of data collected.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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