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FULL PAPER

Improving image quality with model-based iterative reconstruction at quarter of nominal dose in upper abdominal CT

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Objective: To evaluate the ability of a model-based iterative reconstruction (MBIR) for improving image quality in upper abdominal CT with quarter of the normal dose, in comparison with adaptive statistical iterative reconstruction (ASiR) at normal dose.

Methods: 40 upper abdominal patients were randomly divided into two groups: normal-dose group ($n = 20$) with tube current modulation for noise index (NI) of 10 HU and 40% ASiR reconstruction; low-dose group ($n = 20$) with NI = 20 HU in the delay phase and MBIR and 40%ASiR. Images in the delay phase were compared. The CT values and standard deviation (SD) values of the liver, spleen, pancreas, kidney, erector spine and fat were measured. Contrast-noise-ratio ($CNR = (CT_{tissue} - CT_{fat}) / (SD_{fat})$) of each measured organ were calculated and compared with one-way ANOVA among the three reconstruction groups. The subjective image scores of the three groups were assessed blindly by two experienced

physicians using a 5-point system and the score consistency was compared by the κ test.

Results: Dose reduction of 75 % was achieved for the low-dose scan. The subjective scores (95 % confidence intervals) of the three groups (NI 10–40 % ASiR, NI 20–40% ASiR and NI 20-MBIR) were 4.00 ± 0.79 (3.62–4.37), 3.35 ± 0.58 (3.07–3.62) and 3.90 ± 0.64 (3.60–4.19), respectively with no difference between the NI 10–40% ASiR and NI20-MBIR groups and good consistency between reviewers ($\kappa = 0.726$). MBIR had statistically lower SD values and higher contrast-to-noise ratio values in the liver, spleen, pancreas, kidney and erector spine than NI 10–40% ASiR and NI 20–40% ASiR (all $p < 0.05$).

Conclusion: At 75 % dose reduction, MBIR provides similar image quality compared to 40% ASiR at normal-dose.

Advances in knowledge: MBIR provides good image quality at 25 % of the normal dose.

INTRODUCTION

The public has been increasingly concerned about radiation exposure. Medical radiation exposure is no exception¹. CT has become more prevalent. Meanwhile, the dose received by the patient has increased. A survey shows that medical exposure constituted nearly half of the total radiation exposure of the US population from all sources in 2006, and CT was a major contributor.² As a non-invasive means of inspection, CT and MRI are the two major imaging modalities and have almost replaced exploratory laparotomy for diagnosing abdominal problems. Even though MRI has the advantage of no radiation dose issue, it is more expensive than CT and has contraindications for certain patients, e.g. patients with claustrophobia or foreign metal objects in the body. So CT examinations are still widely used and there is great desire to reduce

radiation dose for CT owing to the potential cancer risk caused by CT radiation.³

In the past, the most commonly applied methods to reduce radiation dose at CT include optimizing scan parameters, reasonable choice of scan length, and so on.^{4–6} Inappropriately reducing radiation dose can result in higher image noise, more image artifacts and lower diagnostic confidence.⁷ In recent years, advanced iterative reconstruction algorithms are introduced to reduce image noise and improve diagnostic confidence in low radiation dose situation. The adaptive statistical iterative reconstruction (ASiR) and model-based iterative reconstruction (MBIR) are two of the advanced iterative reconstruction algorithms that are introduced.^{1,8,9} ASiR algorithm uses both the noise model and object model

Table 1. The patient demographics and radiation dose comparison between the two groups

Parameters	Group A (NI = 10)	Group B (NI = 20)	<i>p</i> -value	Δ
Patient characteristics				
Gender (male/female)	16/4	14/6	0.465	–
Age (years)	56.10 ± 9.69	55.90 ± 9.86	0.947	–
BMI (kg·m ⁻²)	20.92 ± 2.82	21.22 ± 3.08	0.740	–
Radiation dose				
CTDIvol (mGy)	11.68 ± 3.97	2.91 ± 1.01	<0.001	75.09%
DLP (mGy·cm)	364.34 ± 122.45	90.91 ± 31.14	<0.001	75.05%
Effective dose (mSv)	5.46 ± 1.83	1.36 ± 0.46	<0.001	75.09%

BMI, body mass index; DLP, dose-length product; NI, noise index; CTDI_{vol}, CT dose index of volume;

^aRadiation dose reduction rate = [(Group B - Group A) / Group A] × 100%

to reduce the noise, and to make the image quality suitable for diagnosis at low radiation doses.^{7,10} MBIR adds the physics model and optical model of the CT system into the modeling for further noise and dose reduction. The purpose of this study was to evaluate the ability of MBIR for improving image quality in upper abdominal CT with quarter of the normal dose, in comparison with ASiR at normal dose.

METHODS AND MATERIALS

Patients

In this prospective study, all research procedures were approved by the Ethics Committee of the Affiliated Hospital of the Shaanxi University of Chinese Medicine. Written informed consent was obtained from all patients, or their legal representatives, prior to the inclusion. Exclusion criteria were: (1) iodine contrast medium allergy; (2) hyperthyroidism; (3) severe liver and kidney dysfunction; (4) severe non-compensatory cardiac insufficiency; (5) pregnant females and minors; (6) severe image artifacts impacting measurement. 40 patients were included in the study (mean age 56.00 ± 9.65 years; mean weight 59.77 ± 8.35 Kg), including 30 males and 10 females. These patients with abdominal lesions underwent the upper abdomen CT examinations between June 2016 and December 2016. Patients were divided into two groups randomly, each group with 20 patients (Group A and Group B). The demographics of each group after randomization are summarized in Table 1.

Scan technique

The scans of all patients were performed on a 64-slice CT scanner (Discovery CT750 HD; GE Healthcare, Waukesha, WI). All patients were scanned feet-first in supine position. The scan range was from the top of the diaphragm to the bottom of the kidney. The triple-phase, contrast enhanced CT scans were performed using 120 kVp tube voltage and automatic tube current modulation to achieve a pre-defined noise index (NI) in images. Patients were injected with non-ionic iodinated contrast agent (370 mg I/mL, Jiangsu Hengrui Medicine Co. Ltd., China) via the antecubital vein by using a power injector (Ulrich, German). The contrast injection rate was 3.5 ml s⁻¹, the total amount of contrast agent was 600 mgI/kg. The images of different reconstructions in the delay phase in both

the normal dose group (Group A, NI = 10 HU) and lower dose group (Group B, NI = 20 HU) were compared. The parameters of scanning, contrast agent injection and reconstruction of the two groups are shown in Table 2. The study process is summarized in Figure 1.

Image processing

The reconstruction schemes of Group A and Group B were as follows: Group A was reconstructed with 40% ASiR; Group B was reconstructed with both 40% ASiR and MBIR. The images were reconstructed at 5 mm slice thickness for routine diagnosis and at 0.625 mm slices thickness for study purpose to compare image spatial resolutions of different reconstruction algorithms in terms of organ and vessels boundaries and small anatomical structures.

Table 2. The parameters of scanning condition between the two groups

Parameters	Group A (<i>n</i> = 20)	Group B (<i>n</i> = 20)
Scanning parameters		
Tube voltage (kVp)	120	120
Tube current (noise index)	smart mA (NI = 10)	smart mA (NI = 20)
Rotation rate (s·r ⁻¹)	0.6	0.6
Detector configuration (no. of sections × mm)	64 × 0.625	64 × 0.625
Pitch	1.375:1	1.375:1
Reconstruction kernel	standard	standard
Scanning thickness (mm)	5	5
Injection parameters		
Total injection volume	600 mgI kg ⁻¹	600 mgI kg ⁻¹
Injection rate (ml·s ⁻¹)	3.5 ml s ⁻¹	3.5 ml s ⁻¹
Reconstruction parameters		
Thickness (mm)	5/0.625	5/0.625
Reconstruction algorithm	40% ASiR	40% ASiR and MBIR

Figure 1. Flow chart of the study process. ASiR, adaptive statistical iterative reconstruction; MBiR, model-based iterative reconstruction; NI, noise index.

Objective image quality analysis

All images were transferred into an AW4.6 post-processing workstation (GE Healthcare) for analysis and comparison. All images were initially presented with a soft-tissue window width/window level preset of 360/70 HU. The regions of interest (ROIs) were drawn in liver, spleen, pancreas, kidney, erector spine and subcutaneous fat at the same measured level on axial sectional images in each patient to measure CT number and standard deviation (SD). The average was calculated from the measurements from the three consecutive slices. The ROIs were drawn by two attending physicians who received training on how to draw ROIs before drawing. The ROIs were placed in the following anatomical structures: liver parenchyma at the level of the porta hepatis; spleen parenchyma at its largest cross-section; kidney parenchyma at the level of the renal hilum; pancreas at the level of the part of body; erector spinae at the right renal hilum. Care was taken to make sure similar ROIs were used for the same organ in different patients. The ROIs had areas ranging from 20 to 50 mm² and were positioned over area as homogenous as possible avoiding the edge, vessels and lesions. The standard deviation of the subcutaneous fat was used as the background noise for the three reconstruction groups.

The contrast-to-noise ratio (CNR) in this study was calculated according to the following formula:

$$\text{CNR} = (\text{CTnumber}(\text{organ}) - \text{CTnumber}(\text{fat}))/\text{SD}(\text{fat})$$

The CT dose index of volume (CTDI_{vol}) and dose length product (DLP) for each patient was recorded in the dose report to calculate the effective dose (ED) using the formula of $\text{ED} = \text{DLP} \times K$ where $K = 0.015 \text{ mSv-mGy}^{-1}\text{-cm}^{-1}$ was used for the upper abdominal area.

Subjective image quality analysis

Two attending physicians (QT and YY with 4 and 6 years experience, respectively in CT abdominal imaging) blindly and independently evaluated the subjective image quality. A 5-point score system was used to evaluate image quality, including image noise and spatial resolution in terms of organ and vessels boundaries and small anatomical structures. The evaluation criteria are shown in Table 3 from 1 to 5.^{3,11} Before evaluating the images, the two attending physicians studied the scoring criteria together, and make sure the consistency of the scoring criteria. After the reading, if the consistency of subjective scores by the two attending physicians was good or excellent, the data from the physician with 6 years of experience were used, otherwise, average valued from the two physicians were used. Images were divided into 2 reading sessions with 10 patients from each of the 2 scan groups in each reading session and separated by a week in between sessions. In each session, the images of the three reconstructions were mixed and randomized and the reviewers were not aware of the dose level and reconstruction type of the images. The sharpness of organ and vessel boundaries were observed in the three-dimensional reformatted images from the 0.625 mm slice thickness axial images.

Table 3. Subjective evaluation criteria of image quality

Score level	Evaluation criterion
5	Excellent, limited perceived image noise, very clear and sharp small anatomical structures and organ boundaries
4	Good, mild image noise, clear small anatomical structures and organ boundaries
3	Acceptable, moderate image noise, small anatomical structures and organ boundaries can be identified
2	Not acceptable, heavy image noise, the identification of small anatomical structures and organ boundaries become difficult
1	Non-diagnostic, severe image noise, small anatomical structures cannot be identified

Statistical analysis

Statistical analysis was performed using commercially available software (v. 20.0 for Windows, SPSS Inc.), with $p < 0.05$ indicating statistically significant difference. Continuous variables and the subjective scores were expressed as mean $\pm$ SDs and 95% confidence intervals. The multiple logistic regression analysis was used to compare the patient demographics between two groups. The single-sample K-S and Levene's tests were used to test the goodness of fit and homogeneity of variance of the measurements, respectively. The independent samples student's t -test was used to test the parameters when data were consistent with normal distribution and homogeneity of variance, otherwise the Mann-Whitney U test was used to test the parameters. Dunnett test was used to test subjective score. κ test was used to evaluate the consistency of subjective scores by two attending physicians, the κ values were defined as follows: κ value >0.75 , excellent agreement;

0.60–0.74, good agreement; 0.40–0.59, fair agreement; and κ value <0.40 , poor agreement.

RESULTS

Patient characteristics

There were no significant differences between the two groups in the basic demographic data ($p > 0.05$). In Group A, there were five cases with liver cancer, four cases with kidney cancer, three cases with liver metastases, two cases with hydronephrosis, two cases with kidney cysts, one case with gallbladder polyps, one case with pancreatic cancer, one case with duodenal tumor and one case without lesion; In Group B, there were three cases with liver cysts, three cases with pancreatic cancer, three cases hepatic hemangioma, two cases with kidney cysts, one case with pancreatic cysts, one case with penile cancer, two cases with colon cancer, four cases with liver cancer and one case with gastric stromal tumors.

Radiation dosage

The standard of care data acquisition and reconstruction in our institution for abdominal CT using NI = 10 HU protocol and 40% ASiR (Group A) had a mean volumetric CT dose index (CTDIvol) of 11.68 ± 3.97 mGy, (median CTDIvol: 10.89 mGy) and a mean dose-length product of 364.34 ± 122.45 mGy-cm. The mean CTDIvol of 2.91 ± 1.01 mGy (median CTDIvol: 2.71 mGy) in Group B decreased by 75% compared with Group A, and the difference was statistically significant ($p < 0.001$). Radiation dose comparison is shown in Table 1.

The objective measurement comparison between three different reconstructions

The SD and CNR values of liver, spleen, pancreas, kidney and erector spine under the three different reconstruction algorithms

Table 4. The SD and CNR of different organs with three different reconstruction methods

	Iterative Reconstruction	Liver mean $\pm$ SD (95% CI)	Spleen mean $\pm$ SD (95% CI)	Pancreas mean $\pm$ SD (95% CI)	Kidney mean $\pm$ SD (95% CI)	Erector spine mean $\pm$ SD (95% CI)
SD	NI10-ASiR	20.11 $\pm$ 4.61 (17.95–22.27)	20.38 $\pm$ 2.82 (19.06–21.70)	24.50 $\pm$ 4.96 (32.19–36.82)	40.85 $\pm$ 10.32 (21.57–27.79)	21.74 $\pm$ 5.81 (15.25–19.02)
	NI20-ASiR	39.28 $\pm$ 7.56 ^a (35.74–42.81)	39.89 $\pm$ 6.31 ^a (36.93–42.84)	24.68 $\pm$ 6.65 ^a (36.02–45.68)	41.04 $\pm$ 10.12 ^a (36.30–45.78)	18.52 $\pm$ 5.12 ^a (30.22–36.61)
	NI20-MBIR	16.63 $\pm$ 1.42 ^a (13.96–15.29)	13.69 $\pm$ 2.01 ^a (12.75–14.63)	17.13 $\pm$ 4.02 ^a (19.01–24.45)	33.42 $\pm$ 6.83 ^a (16.12–20.92)	12.68 $\pm$ 2.97 ^a (11.29–14.07)
	p -value ^b	<0.001	<0.001	<0.001	<0.001	<0.001
CNR	NI10-ASiR	9.63 $\pm$ 1.66 (8.85–10.41)	9.59 $\pm$ 1.72 (8.78–10.40)	8.73 $\pm$ 1.63 (7.97–9.50)	7.67 $\pm$ 1.78 (13.09–15.46)	7.99 $\pm$ 1.54 (7.27–8.71)
	NI20-ASiR	5.17 $\pm$ 0.93 ^a (4.73–5.61)	5.37 $\pm$ 1.13 ^a (4.84–5.90)	4.84 $\pm$ 0.82 ^a (4.45–5.22)	4.81 $\pm$ 1.59 ^a (7.32–8.92)	4.67 $\pm$ 0.90 ^a (4.24–5.09)
	NI20-MBIR	12.49 $\pm$ 3.03 ^a (11.01–13.91)	12.97 $\pm$ 3.42 ^a (11.37–14.58)	12.27 $\pm$ 3.27 ^a (10.28–13.19)	9.83 $\pm$ 3.37 ^a (16.98–22.24)	11.12 $\pm$ 2.75 ^a (9.83–12.41)
	p -value ^b	<0.001	<0.001	<0.001	<0.001	<0.001

ASiR, adaptive statistical iterative reconstruction; MBIR, model-based iterative reconstruction; CI, confidence interval; CNR, contrast-to-noise-ratio; SD, standard deviation;

^a $p < 0.05$ for paired comparison, NI10-ASiR vs NI20-ASiR and NI10-ASiR vs NI20-MBIR.

^b p values for the one-way ANOVA test for all groups.

Figure 2. Histograms of SD and CNR in different organs with different reconstruction methods. It shows that MBIR algorithm further reduces image noise and improves image quality at 75% reduced radiation dose, when compared with the 40% ASiR reconstruction with normal radiation dose.

are listed in Table 4. The NI20-MBIR images had lower SD values and higher CNR values in the liver, spleen, pancreas, kidney and erector spine in comparison with the NI20-ASiR and NI10-ASiR images (all $p < 0.05$) (Table 4 and Figure 2). On the other hand, the NI20-ASiR images had higher SD values and lower CNR values in the liver, spleen, pancreas, kidney and erector spine compared with the NI10-ASiR images (all $p < 0.05$)

The subjective image quality score comparison between three different reconstructions

There was good consistency in the subjective score between the two radiologists with κ value of 0.726. The subjective image quality scores of the three different reconstruction methods (NI20-MBIR, NI10-ASiR and NI20-ASiR) were 3.90 ± 0.64 (95% CI, 3.60–4.19), 4.00 ± 0.79 (95% CI, 3.62–4.37) and 3.35 ± 0.58 (95% CI, 3.07–3.62), respectively. All reconstructions yielded acceptable image quality with subjective image quality scores greater than or equal to 3 (moderate). There was no significant difference in the quality score between NI20-MBIR and NI10-ASiR images ($p = 1.00$), indicating similar image quality between the 75% lower radiation dose MBIR and the normal dose ASiR. On the other hand, NI20-MBIR had significantly higher image quality score than NI20-ASiR ($p = 0.030$), indicating the ability of MBIR to improve image quality compared with state-of-the-art ASiR at the same dose. Examples of MBIR images at 25% of the normal radiation dose are shown in Figures 3 and 4

DISCUSSION

In this prospective study of 40 patients, we compared image quality of abdominal CT scans at different dose levels reconstructed with two iterative reconstruction algorithms ASiR and MBIR. The radiation dose for the MBIR images was 2.91 ± 1.01 mGy, 75% lower than the normal dose of 11.68 ± 3.97 mGy. Our results showed that at only 25% of the normal radiation dose, MBIR could still significantly reduce image noise and improve CNR compared with the normal dose ASiR. The subjective image quality scores of NI20-MBIR images were similar to NI10-ASiR images ($p > 0.05$) but were statistically higher than the NI20-ASiR images. So, although all images in the three reconstructions were acceptable, MBIR images either had same image quality scores

at 25% radiation dose or higher image quality scores (improved image quality) at same radiation dose.

The filtered back-projection (FBP) reconstruction algorithm has been widely used in clinical practice with its quick reconstruction speed, but its ability to reduce radiation dose is limited. Iterative reconstruction algorithms are developed to improve image quality while reducing radiation dose. Currently, different forms of iterative reconstruction techniques are used in CT. These iterative reconstruction techniques can reduce image noise, thus improve the image quality at lower dose levels. Iterative reconstruction algorithms are reported to reduce dose up to 40–60% compared to using the standard FBP algorithm.^{12,13} The ASiR has been one of the most widely studied iterative reconstruction algorithms and is currently widely used in clinical practice. Compared with FBP, ASiR provides clinically acceptable images at a lower radiation dose.¹⁴ ASiR can use different levels to adjust the image quality, from 0 to 100%. High ASiR levels will cause the image to be over uniform, and there will be "artificial texture".^{15,16} The choice of ASiR level will directly affect the image quality.¹⁷ In

Figure 3. A, B: One patient at reduced dose with noise index of 20 HU with 40% ASiR and MBIR, respectively. The scores of the visibility of NI20 ASiR (a) was 3, that means the image was accepted, moderate image noise, small anatomical structures and organ boundaries can be identified. The scores of the visibility of NI20 MBIR (b) was 4, that means the image was good, mild image noise, clear small anatomical structures and organ boundaries. ASiR, adaptive statistical iterative reconstruction; HU, Hounsfield unit; MBIR, model-based iterative reconstruction; NI, noise index.

Figure 4. (c): Normal dose with noise index of 10 HU with 40% ASiR. The scores of the visibility of NI10 ASiR (c) was 5, that means the image was excellent, limited perceived image noise, very clear and sharp small anatomical structures and organ boundaries.

our study, we used 40% level for ASiR based on our own experience which is consistent with other scholars.^{3,15}

MBIR reconstruction algorithm has been gradually entered into clinical applications and focused by radiologists on dose reduction.¹⁸ MBIR is a full model-based iterative reconstruction algorithm, and combines a more complex modeling includes noise statistics model, physics model, object model and optical model. In theory, MBIR can further reduce the noise while sharpening the edges and offers considerably better image quality than FBP and ASiR. However, because the natural contrast of the abdomen is worse than the chest, MBIR algorithm has been used by radiologists to maintain or improve the low contrast resolution in CT scans with reduced radiation dose in the abdomen as a first consideration. It has been shown that MBIR reduces image noise and improves image quality in abdominopelvic CT images acquired with dose reductions of up to 62% in cadaveric study.¹⁹ In our study, the dose reduction was further increased to 75%, and subjective image quality and objective CNR were compared with ASiR images at the normal dose. It is worth pointing out that even though subjective image quality is related to diagnostic confidence, it is not the direct measure of diagnostic accuracy. How does MBIR affecting the diagnostic accuracy at such a low radiation dose needs further evaluation. Also, it is well known that CNR, the primary objective metric of image quality used in our study, is substantially limited in appropriately assessing image quality for iterative reconstruction algorithms. This is

because resolution and noise texture are totally ignored by CNR. A recent study by Solomon et al²⁰ estimating the dose reduction potential of an iterative algorithm showed that using CNR as the bases of such an estimation would have substantially over-estimated the amount you could reduce dose without affecting detectability of low-contrast liver lesions. Other researches have also pointed out^{21,22} that the dose reduction potential of IR is highly dependent on the diagnostic task, because IR techniques affect the noise and spatial resolution properties in a non-linear manner. In the diagnostic tasks involving high-contrast objects, such as bony anatomy, IR can reduce image noise allows for marked dose reduction. However, in diagnostic tasks involving low-contrast objects, IR does not have the ability to improve spatial resolution properties, such as small liver lesions. Because abdomen lacks natural contrast, the current version MBIR can reduce noise, but has little advantage in improving resolution. So, in this study, although the MBIR images had less image noise, the resolution in the MBIR images were not improved compared to ASiR. This may be a reason why MBIR is slowly getting accepted clinically even though the objective measures showed better image quality with MBIR at much lower radiation dose. Next generation MBIR is being developed that will have the option to improve spatial resolution while reducing image noise, but its clinical benefit is yet to be demonstrated.

One of the other important reasons for the limited MBIR clinical practice is its long processing time, so it is limited from the applications in emergency settings.⁹ In our study, patients were selected for non-emergency situations, so the rate of reconstruction was not considered.

Several limitations of this study must be considered. First, it is limited by a relatively small cohort. We will do a larger-scale prospective study to confirm our findings. Second, we selected only one ASiR level, the impact of different ASiR levels on image quality was not assessed using a low radiation dose. Another limitation of our study was that we limited the analysis to image quality and did not compare ASiR and MBIR in terms of diagnostic accuracy for the disease, which will be our future work. Finally, we did not classify our patients according to weight, but in this study all patient data were used for both ASiR and MBIR reconstruction.

In summary, this study demonstrates that at 75% dose reduction, MBIR provides similar image quality compared to 40% ASiR at normal-dose.

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