Quality Improvement Study

Medicine®

OPEN

The potential for reduced radiation dose from deep learning-based CT image reconstruction

A comparison with filtered back projection and hybrid iterative reconstruction using a phantom

Ji Eun Lee, MD[a], Seo-Youn Choi, MD[a,*], Jeong Ah Hwang, MD[b], Sanghyeok Lim, MD[a], Min Hee Lee, MD[a], Boem Ha Yi, MD[a], Jang Gyu Cha, MD[a]

Abstract

The purpose of this phantom study is to compare radiation dose and image quality of abdominal computed tomography (CT) scanned with different tube voltages and tube currents, reconstructed with filtered back projection (FBP), hybrid iterative reconstruction (IR) and deep learning image reconstruction (DLIR) algorithms.

A total of 15 CT scans of whole body phantoms were taken with 3 different tube voltages and 5 different tube currents. The images were reconstructed with FBP, 30% and 50% hybrid IR adaptive statistical iterative reconstruction (ASIR-V), and low, medium and high strength DLIR algorithms. The image scanned with tube voltage/tube current of 120 kV/ 200 mA and reconstructed with FBP algorithm was chosen as the reference image. Five radiologists independently analyzed the images individually and also compared it with the reference image in overall, using the visual grading analysis. The mean score of each image was calculated and compared.

Using DLIR algorithms, the radiation dose was reduced by 65.5% to 68.1% compared with the dose used in the reference image, while maintaining comparable image quality. Using the DLIR algorithm of medium strength, the image quality was even better than the reference image with a reduced radiation dose up to 36.2% to 50.0%. The DLIR algorithms generated better quality images than ASIR-V algorithms in all the data sets. In addition, among the data sets reconstructed with DLIR algorithms, image quality was the best at the medium strength level, followed by low and high.

This phantom study suggests that DLIR algorithms may be considered as a new reconstruction technique by reducing radiation dose while maintaining the image quality of abdominal CTs.

Abbreviations: ASIR = adaptive statistical iterative reconstruction, CT = computed tomography, DLIR = deep learning image reconstruction, DLP = dose-length product, FBP = filtered back projection, IR = iterative reconstruction.

Keywords: artificial intelligence, CT, dose reduction, image reconstruction

Editor: Hyunjin Park.

This work was supported by the Soonchunhyang University Research Fund.

IRB was waived due to phantom study.

The authors have no conflicts of interests to disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

[a] Department of Radiology, Soonchunhyang University College of Medicine, Bucheon Hospital, Bucheon, [b] Department of Radiology and Center for Imaging Science, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea.

[*] Correspondence: Seo-Youn Choi, Department of Radiology, Soonchunhyang University College of Medicine, Bucheon Hospital, 170 Jomaru-ro, Wonmi-gu, Bucheon-si 420-767, Gyeonggido, Korea (e-mail: sychoi@schmc.ac.kr).

How to cite this article: Lee JE, Choi SY, Hwang JA, Lim S, Lee MH, Yi BH, Cha JG. The potential for reduced radiation dose from deep learning-based CT image reconstruction: a comparison with filtered back projection and hybrid iterative reconstruction using a phantom. Medicine 2021;100:19(e25814).

Received: 2 December 2020 / Received in final form: 31 March 2021 / Accepted: 14 April 2021

http://dx.doi.org/10.1097/MD.0000000000025814

1. Introduction

Due to its continuous technical evolution and wide availability, computed tomography (CT) has become more and more useful in the diagnosis and follow-up of almost all anatomical diseases.[1] This had resulted in the inevitable increase in ionizing radiation exposure, with reports mentioning up to an approximately 7-fold increase in the general population over the last 3 decades.[2] Accordingly, there is greater concern about the risks of radiation-induced cancers since ionizing radiation may be carcinogenic, especially in patients of younger age who are much more susceptible to radiation-induced injuries.[3–5] Consequently, CT dose reduction while maintaining image quality is a critical issue.

Several dose reduction techniques including automated tube current modulation, optimization of tube voltage, and iterative reconstruction (IR) algorithms have successfully been used.[6–9] Multiple studies have reported on the credible efficacy of IR in terms of dose reduction.[9–13] However, IR produces images with "plastic-looking" or "unnatural" impressions compared with the filtered back projection (FBP), which becomes more evident with greater IR strength.[8] In addition, the nonlinear and nonstationary features of the IR algorithms leads to increased contrast or dose dependence of the spatial resolution.[14] This may lead to the limited administration of IR algorithms in clinical practice.

With the increased use of machine learning as a subset of artificial intelligence, deep learning image reconstruction (DLIR) has emerged in CT imaging as a promising technique.[15] DLIR uses deep neural networks in the reconstruction flow, which consists of a training process to learn how to differentiate signal from noise and to suppress the noise without altering the structures, based on massive number of cases that cover different body sizes, anatomies, and scanning parameters. The goal of the DLIR algorithm is to develop images that is equivalent to the quality of FBP images scanned with high dose radiation, for FBP is the most ideal image reconstruction technique in high dose and optimal scan environment. The DLIR can be done in 3 selectable strength levels (low, medium, and high), which varies in the degree of noise.[16] To the best of our knowledge, the effect of DLIR algorithms in abdominal CTs at different tube voltages and tube currents has yet to be evaluated. This is important because it may help optimize radiation doses in abdominal CT examinations which have the highest radiation dose compared with other types of CT scans.[17]

Therefore, the purpose of this phantom study is to compare the radiation dose and image quality of abdominal CTs scanned with different tube voltages and tube currents, reconstructed with FBP, hybrid IR, and DLIR algorithms.

2. Materials and methods

Ethical approval was not necessary because of a phantom study.

2.1. Phantom

The trunk and bilateral thigh of the whole body phantom, PBU-60 (Kyoto Kagaku Co., Ltd, Japan), simulating a man of 165 cm and 50 kg was used in this study (Fig. 1). The phantom was made of radiological soft tissue substitute with an embedded life-size synthetic skeleton and organs such as the liver with portal and hepatic veins, kidneys, spleen, pancreas, stomach, sigmoid colon, rectum, and prostate. The phantom was placed on the CT bed in a head-first, supine position at the center of the gantry.

2.2. CT scanning

All CT images were acquired on a multi-detector Revolution CT (GE Healthcare). The phantom was scanned 15 times with 3 different tube voltages (80, 100, and 120 kV) and 5 different tube currents (20, 40, 60, 100, and 200 mA). All other CT parameters were fixed (rotation time: 1 second, pitch: 0.992, and reconstruction slice thickness: 2.5 mm). The obtained raw data was then processed on an advanced image processing station (AW4.7, GE Healthcare) into the standard FBP, hybrid IR Adaptive statistical iterative reconstruction (ASIR-V), and DLIR algorithms (TrueFidelity^{TM}). For the ASIR-V technique, 2 different levels of blending were chosen: 30% and 50%. As for the DLIR technique, 3 different reconstruction strength levels were chosen: low, medium, and high. Therefore, there were a total of 6 CT data sets for each scan.

2.3. Radiation dose measurement

The volume computed tomography dose index and dose-length product (DLP) for all of the 15 CT scans were obtained using the dose page on our picture archiving and communication system (PACS, Deja-View; Dong Eun IT, Bucheon-si, Republic of Korea) provided by the CT scanner.

2.4. Assessment of image quality with visual grading analysis

Five radiologists (JEL, JAH, SYC, MHL, and SL with 10 to 15 years of experience in abdominal imaging) independently reviewed all images in random order, blinded to the scanning parameters and the reconstruction algorithms, and graded the images on a scale from 1 (worst) to 5 (best) for each imaging features: subjective image noise, tissue interfaces, and visibility of hepatic vasculatures (Table 1). The tissue interfaces were evaluated by the severity of the blotchy irregular organ margin shown as small steps at the tissue interfaces, affecting the sharpness of the anatomical structures. Contrast of the structure was evaluated by testing the visibility of hepatic vasculatures (portal vein and hepatic vein branches) at the segmental level.[18] The mean score among the 5 readers was calculated.

The images scanned with a tube voltage of 120 kV, tube current of 200 mA, and reconstructed with the FBP algorithm were chosen as the reference image. For evaluation of the overall image quality, all images were compared in random order, side-by-side to the reference image by the same reviewers. Images were displayed using the soft tissue window setting (window/level of

Figure 1. The trunk and thigh of the PBU-60 (Kyoto Kagaku, Co., Kyoto, Japan) phantom.

400/40 Hounsfield units). All reviewers were blinded to the scanning parameters and the reconstruction algorithms. In assessment of the overall image quality, the image noise, sharpness of the organ margin, and detectability of small hepatic vessels were all taken into consideration and was graded according to the reviewers' opinion about the overall diagnostic acceptability. A 5-category relative visual grading analysis was used for the quantification of the subjective opinions (Table 1),[19] and the mean score among the 5 readers was calculated. The images were considered comparable or superior to the reference image when the mean score was equal to or greater than 3.

2.5. Statistical analysis

Our data are presented using a semi-quantitative, subjective image analysis which is well established as a clinically relevant method.[20] Descriptive statistics were used to present our results.

3. Results

3.1. Radiation dose

Compared with the radiation dose used in the reference image, the DLP was decreased by 70.0% for 120 kV/ 60 mA, 68.1% for 100 kV/ 100 mA, and 65.5% for 80 kV/ 200 mA data sets. In the data sets scanned with 100 kV/ 200 mA and 120 kV/ 100 mA, DLP was only decreased by 36.2% and 50% respectively, compared with the reference image (Table 2).

3.2. Assessment of image quality according to the reconstruction algorithm

As for the subjective image noise and tissue interfaces, the FBP algorithm resulted in the lowest mean scores, which increased gradually in order from ASIR-V 30%, ASIR-V 50%, DLIR-low, DLIR-medium to DLIR-high algorithm. The DLIR-high algorithm produced images with the lowest image noise and minimal irregular blotchy tissue interfaces, among the image sets scanned with same dose parameters (Table 3). As for the visibility of hepatic vasculatures, the mean scores were equal among ASIR-V 30%, ASIR-V 50%, DLIR-low, and DLIR-medium algorithms in each image sets, where the mean scores were slightly lower for FBP and DLIR-high algorithms (Table 3).

As for the overall image quality, in all data sets except for the 80 kV/ 20 mA, 80 kV/ 40 mA, and 100 kV/ 20 mA data sets where the radiation dose was extremely low resulting in clearly inferior overall image quality regardless of the reconstruction algorithm used, DLIR algorithms led to better overall image quality compared with the ASIR-V or FBP algorithms. Among the DLIR algorithms, medium strength level reconstruction resulted in the best overall image quality, followed by low and high strength level reconstruction (Table 4) (Figs. 2 and 3).

3.3. Assessment of image quality according to the scan parameter

Using DLIR of low or medium strength, the overall image quality was comparable to that of the reference image scanned at 120 kV/ 200 mA, even with scan parameters of 80 kV/ 200 mA or 100 kV/ 100 mA, resulting in 65.5% or 68.1% less radiation doses, respectively (Fig. 4). In addition, by using DLIR of medium strength, the overall image quality was even better than the reference image in the 100 kV/ 200 mA and 120 kV/ 100 mA data

Table 1

Scores and definition for visual grading analysis of the imaging features.

Score	Definition
Subjective image noise	
5	Minimal image noise
4	Less than average image noise
3	Average image noise
2	Above average image noise
1	Unacceptable image noise
Tissue interfaces	
5	Minimal irregular blotchy tissue interfaces
4	Less than average irregular blotchy tissue interfaces
3	Average irregular blotchy tissue interfaces
2	Above average irregular blotchy tissue interfaces
1	Irregular blotchy tissue interfaces
Visibility of hepatic vasculatures	
5	Excellent image contrast
4	Above average contrast
3	Acceptable contrast
2	Suboptimal contrast
1	Very poor contrast
Overall image quality (relative visual grading analysis)	
5	Test image is clearly superior to reference image
4	Test image is somewhat superior to reference image
3	Test image is equal to reference image
2	Test image is somewhat inferior to reference image
1	Test image is clearly inferior to reference image

Table 2

Scan voltage, current, and dose for each data set.

Current (mA)	Voltage (kV)					
	80		100		120	
	CTDIvol	DLP	CTDIvol	DLP	CTDIvol	DLP
20	0.5 (3.5)	26.03 (3.4)	0.93 (6.4)	48.23 (6.4)	1.45 (10.0)	75.54 (10.0)
40	1.0 (6.9)	50.06 (6.6)	1.85 (12.8)	96.46 (12.8)	2.9 (20.0)	151.07 (20.0)
60	1.5 (10.4)	78.1 (10.3)	2.78 (19.2)	144.68 (19.2)	4.35 (30.0)	226.61 (30.0)
100	2.5 (17.5)	130.16 (17.2)	4.63 (32.0)	241.14 (31.9)	7.25 (50.0)	377.68 (50.0)
200	4.99 (34.4)	260.32 (34.5)	9.25 (63.8)	482.28 (63.8)	14.49	755.36

CTDI = computed tomography dose index, DLP = dose–length product.

Note: data are mGy for CTDIvol and mGycm for DLP. The numbers in the parentheses represent the percentage of the radiation dose compared to the reference image (120 kV/ 200 mA). Phantom: 32 cm.

Table 3

Mean scores of the visual grading analysis for each imaging features.

Imaging features		Subjective image noise			Tissue interfaces			Hepatic vasculatures		
Current (mA)	Voltage (kV)	80	100	120	80	100	120	80	100	120
20	FBP	1	1	1	1	1	1	1	1	1
	ASIR-V 30%	1	1	1	1	1	1	1	1	1
	ASIR-V 50%	1	1	1	1	1	1	1	1	1
	DLIR-low	1.2	1.4	1.6	1.2	1.2	1.2	1	1	1
	DLIR-medium	1.4	1.6	2	1.2	1.2	1.2	1	1	1
	DLIR-high	1.6	1.8	2.4	1.2	1.2	1.2	1	1	1
40	FBP	1	1	1.2	1.2	1.4	1.8	1	1.2	1.8
	ASIR-V 30%	1	1	1.2	1.2	1.4	1.8	1	1.4	1.8
	ASIR-V 50%	1	1	1.4	1.2	1.4	2	1	1.4	1.8
	DLIR-low	1.4	1.6	2.4	1.6	1.8	2.4	1	1.4	1.8
	DLIR-medium	1.6	1.8	2.8	1.6	1.8	2.6	1	1.4	1.8
	DLIR-high	1.8	2	3	1.8	2	2.8	1	1.2	1.6
60	FBP	1	1	1.8	1.6	1.8	2.4	1.4	2.4	3.2
	ASIR-V 30%	1	1	1.8	1.6	1.8	2.6	1.6	2.4	3.4
	ASIR-V 50%	1	1.2	2	1.6	1.8	2.8	1.6	2.4	3.4
	DLIR-low	1.6	1.8	2.8	2	2.2	3.2	1.6	2.4	3.4
	DLIR-medium	1.8	2	3.4	2	2.4	3.6	1.6	2.4	3.4
	DLIR-high	2	2.2	3.8	2.2	2.4	3.6	1.4	2.2	3.2
100	FBP	1.4	1.6	2	2.8	3	3.4	2.8	4.4	4.6
	ASIR-V 30%	1.4	1.6	2.4	2.8	3.2	3.6	3	4.8	4.8
	ASIR-V 50%	1.4	1.8	2.4	2.8	3.4	3.6	3	4.8	4.8
	DLIR-low	2.2	2.4	3	3.6	3.6	3.8	3	4.8	4.8
	DLIR-medium	3	3.2	3.6	3.8	3.8	4	3	4.8	4.8
	DLIR-high	3.2	3.4	4.4	3.8	3.8	4	2.8	4.4	4.6
200	FBP	2	2	3	3.2	3.8	4	4.8	5	5
	ASIR-V 30%	2	2		3.4	4		4.8	5	
	ASIR-V 50%	2	2.2		3.4	4		4.8	5	
	DLIR-low	2.8	3		3.8	4		4.8	5	
	DLIR-medium	3.4	3.6		4	4.2		4.8	5	
	DLIR-high	4	4.2		4	4.2		4.6	4.8	

ASIR = adaptive statistical iterative reconstruction, FBP = filtered back projection, DLIR = deep learning image reconstruction.
*Data are the mean value of the scores given respectively by the 5 radiologists.

sets, with 36.2% and 50% lower radiation doses, respectively. When a tube voltage as low as 80 kV was used with a tube current of 100 mA and DLIR of medium strength as the reconstruction method, the mean score of the overall image quality was 2.8: 4 readers scored 3 and only 1 of the 5 readers scored 2 due to the relatively poor delineation of the small hepatic vessels while the image noise and sharpness of the organ margin was comparable to that of the reference image (Tables 3 and 4). In this case, the radiation dose was reduced by up to 82.5% compared to the reference image.

4. Discussion

In our study, a novel DLIR algorithm was assessed in comparison with the FBP and ASIR-V algorithms in the aspect of radiation dose and image quality using relative visual grading analysis. Our results showed that DLIR can reduce the radiation dose by approximately one-third while maintaining the image quality, and that DLIR of medium strength expressed images with the best quality among all the reconstruction techniques.

Multiple studies have reported that IR is useful for preserving image quality while decreasing radiation dose.[9,13,21–23] However, several issues with IR have also been noted, such as the contrast and dose dependence of the spatial resolution,[14] degradation of image texture, and impaired detection rate for low contrast resolution lesions in decreased radiation doses.[24] The DLIR algorithm developed by GE Healthcare (TrueFidelity™) uses the deep neural network, which is capable of learning by comparing a massive number of output images produced by low dose sinograms to the ground truth images–a high dose version of the same data reconstructed by FBP.[25] DLIR uses advanced computational power to handle significantly higher number of parameters, whereas IR relies on human management.[25] Therefore, DLIR is expected to outperform IR with better dose performance and image quality. As expected, our study results showed that the images reconstructed with DLIR exhibited the best image quality followed by those reconstructed with ASIR-V and FBP, regardless of the dose parameter.

The DLIR algorithm developed by GE Healthcare (TrueFidelity™) provides 3 selectable reconstruction strength levels: low, medium, and high.[25] In the case of ASIR-V, blending with the traditional FBP was performed in 10% increments according to the user preference.[8] In previous reports comparing IR of different levels,[16,26] higher levels of IR induced exaggerated noise reduction, leading to excessive image smoothing or unnatural images compared with the FBP, which radiologists favor and are used to. Consequently, high level IR algorithms have limited usage in clinical practice. In the case of DLIR, Greffier et al[27] reported that with the increase of DLIR levels, the detectability of simulated lesions on this phantom study increased

Table 4

Mean scores of the relative visual grading analysis for overall image quality with 120 kV/ 200 mA as the reference image.

Imaging feature		Overall image quality		
Current (mA)	Voltage (kV)	80	100	120
20	FBP	1	1	1
	ASIR-V 30%	1	1	1
	ASIR-V 50%	1	1	1
	DLIR-low	1	1	1
	DLIR-medium	1	1	1.2
	DLIR-high	1	1	1
40	FBP	1	1	1
	ASIR-V 30%	1	1	1
	ASIR-V 50%	1	1	1.2
	DLIR-low	1	1	2.2
	DLIR-medium	1	1.2	2.2
	DLIR-high	1	1	2
60	FBP	1	1	1.6
	ASIR-V 30%	1	1	2
	ASIR-V 50%	1	1	2
	DLIR-low	1.6	2	2
	DLIR-medium	2	2.2	2.8
	DLIR-high	1.8	2	2
100	FBP	1.4	2	2.4
	ASIR-V 30%	1.8	2	3
	ASIR-V 50%	1.8	2	3
	DLIR-low	2.6	3	3
	DLIR-medium	2.8	3	3.8
	DLIR-high	2.2	2	2.6
200	FBP	2	2.2	**3**
	ASIR-V 30%	2	2.4	
	ASIR-V 50%	2.2	2.8	
	DLIR-low	3	3.2	
	DLIR-medium	3	3.8	
	DLIR-high	2.6	2.8	

ASIR = adaptive statistical iterative reconstruction, FBP = filtered back projection, DLIR = deep learning image reconstruction.

*Data are the mean value of the scores given respectively by the 5 radiologists.

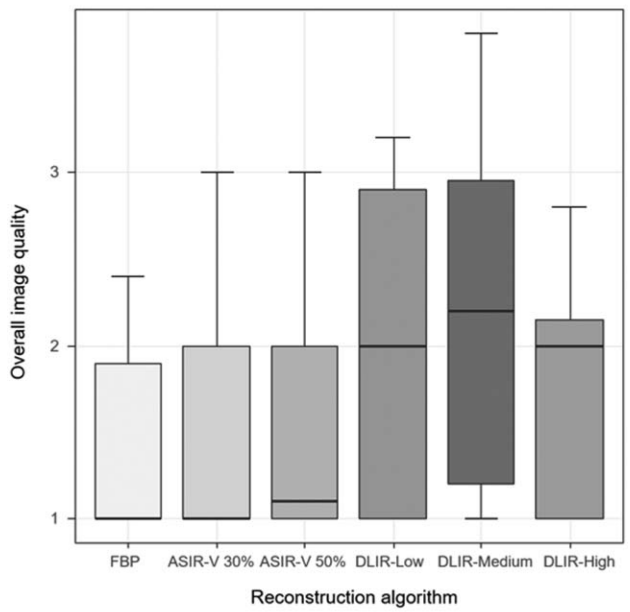

Figure 2. Graph shows the mean overall image quality score for each reconstruction algorithm of all the 14 image sets. A score of 3 was given when the image quality of the test image was equally good compared to the reference image, 2 for somewhat inferior, and 1 for clearly inferior image quality. The mean overall image quality score of the DLIR algorithms were superior to that of the adaptive statistical iterative reconstruction (ASIR-V) or filtered back projection (FBP) algorithms. Among the DLIR algorithms, the mean overall image quality score was highest for the DLIR of medium strength, followed by DLIR-low and DLIR-high.

as well. However, in our study, medium-level DLIR resulted in the best overall image quality, followed by low and high level reconstructions. This was due to the stronger noise reduction performance of the DLIR compared to FBP or ASIR-V, which increased progressively from low to high reconstruction strength level. The tissue interfaces were also smoother as the reconstruction strength level increased in DLIR algorithm. On the other hand, the aggressive noise reduction of DLIR-high algorithm, so called "oversmoothing" of the images resulted in rather unfamiliar plastic image textures, and smudging of the smaller hepatic vasculatures in liver segments, leading to decreased image contrast and overall, inferior image quality compared to that of the low level reconstruction. This result was achieved in consensus among all of the 5 readers of our study.

Optimal tube voltage is one of the most important factors in the dose optimization of CTs.[6] With higher tube voltage, image noise may be reduced, but increased radiation dose is inevitable. Furthermore, lower tube voltage increases the X-ray absorption of iodine which improves iodine enhancement and potentially decreases the amount of contrast material used.[28] Conventionally, tube voltage of 120 kV has been widely used for abdominal CTs for optimal soft-tissue imaging.[29] However, in contrast-enhanced abdominal CTs, the desire to lower the tube voltage in order to obtain better image contrast for the higher attenuation of iodine as well as decreased radiation dose exists.[6] In our study, with the help of medium level DLIR, comparable image quality was sustained even with decreased tube voltage up to 100 kV or even 80 kV when a tube current higher than 100 mA was used. Although our phantom study proceeded without contrast enhancement, only 1 reviewer scored 2 for the overall image quality due to the relatively faint delineation of small hepatic vessels, while the other 4 reviewers gave a score of 3 for the 80 kV/ 100 mA image. We speculate that the usage of contrast enhancement may improve this issue with the visibility of small vessels. Accordingly, we expect that our study may open the possibility of further reducing tube voltage to 100 kV or more, without degrading image quality. However, further prospective human studies are needed to support our results.

There were several limitations to our study. First, we used a phantom with only simple anatomical structures and rather homogenous density that did not take into consideration the differences in actual patient's body habitus. Second, our study used a single CT scanner with a given DLIR algorithm, making it difficult to apply our results fully to scanners from other manufacturers. Third, although there was a significant trend in the results, comparison of the overall image quality was performed using a scoring system dependent on the subjective judgment of each radiologist. Therefore, further prospective clinical studies must be performed using objective quantitative parameters to confirm our results.

In conclusion, DLIR algorithms can be used as a new reconstruction technique to reduce radiation dose while maintaining image quality in abdominal CTs.

Figure 3. Axial abdominal CT images acquired with a scanning parameter of 80 kV/ 100 mA using different reconstruction algorithms: (A) FBP, (B) ASIR-V 30%, (C) ASIR-V 50%, (D) DLIR-low, (E) DLIR-medium, and (F) DLIR-high. The images reconstructed with DLIR algorithms (D-F) resulted in better image quality than those reconstructed with FBP (A) and ASIR-V algorithms (B-C) due to the reduced image noise. However, the mean score was best for DLIR-medium which was 2.8, and decreased to 2.2 for DLIR-high due to excessive image smoothing.

Author contributions

Conceptualization: Ji Eun Lee, Seo-Youn Choi, Jeong Ah Hwang, Boem Ha Yi, Jang Gyu Cha.
Data curation: Ji Eun Lee, Seo-Youn Choi.
Formal analysis: Ji Eun Lee, Seo-Youn Choi, Jeong Ah Hwang, Sanghyeok Lim, Min Hee Lee.
Investigation: Ji Eun Lee, Seo-Youn Choi, Jeong Ah Hwang, Sanghyeok Lim, Min Hee Lee.
Methodology: Ji Eun Lee, Seo-Youn Choi.
Project administration: Seo-Youn Choi.
Supervision: Seo-Youn Choi.
Validation: Ji Eun Lee, Seo-Youn Choi.

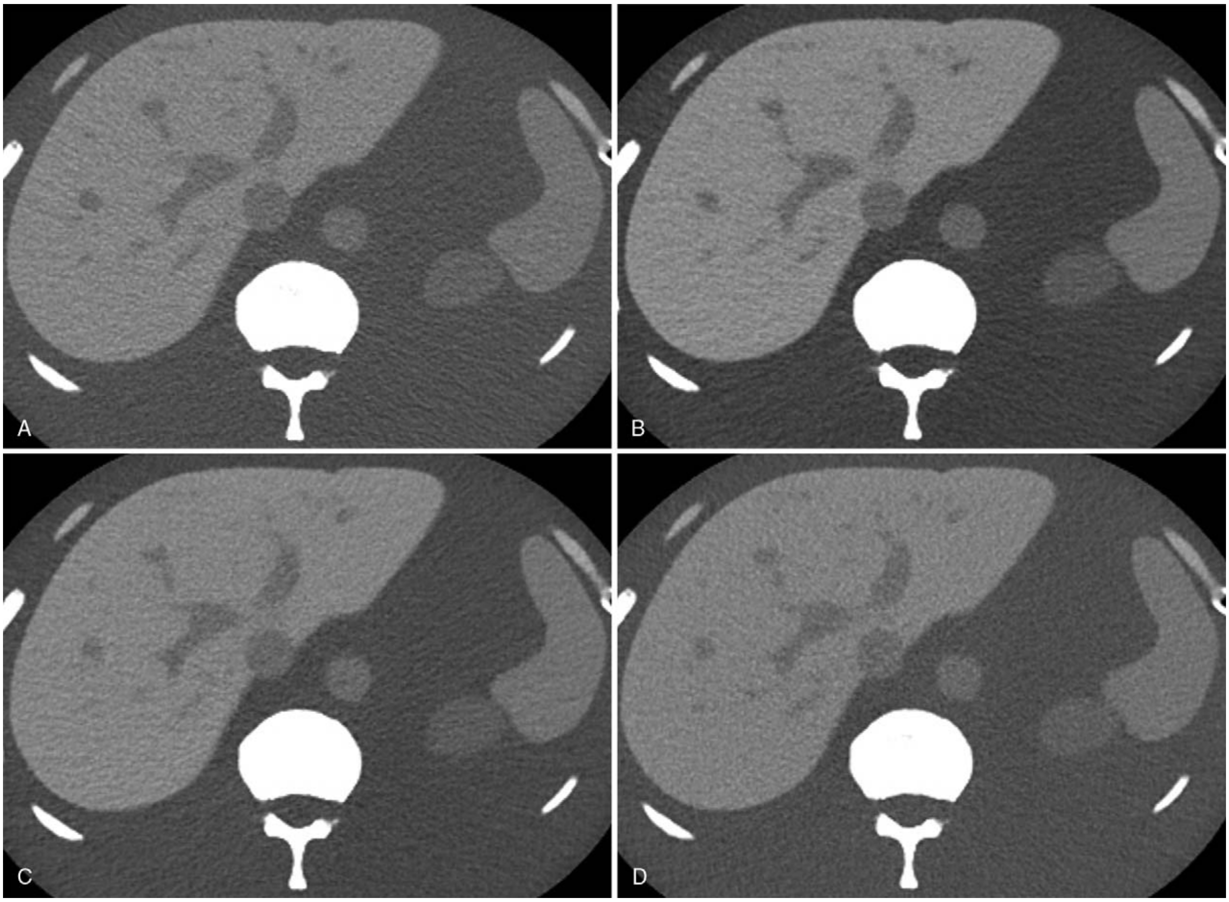

Figure 4. (A) Axial images of abdominal CTs acquired with the scanning parameter of 120kV/ 200mA and reconstructed with FBP, which was chosen as the reference image. Axial images of abdominal CTs using the DLIR-medium algorithm with comparable image quality to the reference image (mean score: 3), scanned with different parameters: (B) 80kV/ 200mA, (C) 100kV/ 100mA, and (D) 120kV/ 100mA.

Writing – original draft: Ji Eun Lee, Seo-Youn Choi.
Writing – review & editing: Ji Eun Lee, Seo-Youn Choi.

References

[1] Lell MM, Wildberger JE, Alkadhi H, et al. Evolution in computed tomography: the battle for speed and dose. Invest Radiol 2015;50:629–44.
[2] Furlow B. Radiation dose in computed tomography. Radiol Technol 2010;81:437–50.
[3] Brenner DJ. Should we be concerned about the rapid increase in CT usage? Rev Environ Health 2010;25:63–8.
[4] Hall EJ, Brenner DJ. Cancer risks from diagnostic radiology. Br J Radiol 2008;81:362–78.
[5] Kendall GM, Bithell JF, Bunch KJ, et al. Childhood cancer research in oxford III: the work of CCRG on ionising radiation. Br J Cancer 2018;119:771–8.
[6] Kaza RK, Platt JF, Goodsitt MM, et al. Emerging techniques for dose optimization in abdominal CT. Radiographics 2014;34:4–17.
[7] Kalra MK, Maher MM, Toth TL, et al. Strategies for CT radiation dose optimization. Radiology 2004;230:619–28.
[8] Geyer LL, Schoepf UJ, Meinel FG, et al. State of the art: iterative CT reconstruction techniques. Radiology 2015;276:339–57.
[9] Sagara Y, Hara AK, Pavlicek W, et al. Abdominal CT: comparison of low-dose CT with adaptive statistical iterative reconstruction and routine-dose CT with filtered back projection in 53 patients. AJR Am J Roentgenol 2010;195:713–9.
[10] Greffier J, Macri F, Larbi A, et al. Dose reduction with iterative reconstruction in multi-detector CT: what is the impact on deformation of circular structures in phantom study? Diagn Interv Imaging 2016;97:187–96.
[11] Klink T, Obmann V, Heverhagen J, et al. Reducing CT radiation dose with iterative reconstruction algorithms: the influence of scan and reconstruction parameters on image quality and CTDIvol. Eur J Radiol 2014;83:1645–54.
[12] Ning P, Zhu S, Shi D, et al. X-ray dose reduction in abdominal computed tomography using advanced iterative reconstruction algorithms. PLoS One 2014;9:e92568.
[13] Xin X, Shen J, Yang S, et al. Improved image quality of low-dose CT combining with iterative model reconstruction algorithm for response assessment in patients after treatment of malignant tumor. Quant Imaging Med Surg 2018;8:648–57.
[14] Verdun FR, Racine D, Ott JG, et al. Image quality in CT: from physical measurements to model observers. Phys Med 2015;31:823–43.
[15] Willemink MJ, Noel PB. The evolution of image reconstruction for CT-from filtered back projection to artificial intelligence. Eur Radiol 2019;29:2185–95.
[16] Chen LH, Jin C, Li JY, et al. Image quality comparison of two adaptive statistical iterative reconstruction (ASiR, ASiR-V) algorithms and filtered back projection in routine liver CT. Br J Radiol 2018;91:20170655.
[17] Berrington de Gonzalez A, Mahesh M, Kim KP, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. Arch Intern Med 2009;169:2071–7.
[18] Singh S, Kalra MK, Hsieh J, et al. Abdominal CT: comparison of adaptive statistical iterative and filtered back projection reconstruction techniques. Radiology 2010;257:373–83.
[19] Ludewig E, Richter A, Frame M. Diagnostic imaging–evaluating image quality using visual grading characteristic (VGC) analysis. Vet Res Commun 2010;34:473–9.

[20] Bath M, Mansson LG. Visual grading characteristics (VGC) analysis: a non-parametric rank-invariant statistical method for image quality evaluation. Br J Radiol 2007;80:169–76.
[21] Singh S, Kalra MK, Gilman MD, et al. Adaptive statistical iterative reconstruction technique for radiation dose reduction in chest CT: a pilot study. Radiology 2011;259:565–73.
[22] Pauchard B, Higashigaito K, Lamri-Senouci A, et al. Iterative reconstructions in reduced-dose CT: which type ensures diagnostic image quality in young oncology patients? Acad Radiol 2017;24: 1114–24.
[23] Gaddikeri S, Andre JB, Benjert J, et al. Impact of model-based iterative reconstruction on image quality of contrast-enhanced neck CT. AJNR Am J Neuroradiol 2015;36:391–6.
[24] McCollough CH, Yu LF, Kofler JM, et al. Degradation of CT low-contrast spatial resolution due to the use of iterative reconstruction and reduced dose levels. Radiology 2015;276: 499–506.
[25] Hsieh J, Liu E, Nett B, et al. A new era of image reconstruction: TrueFidelityTM: Technical white paper on deep learning image reconstruction. [Internet]. July 2019; https://www.gehealthcare.ru/-/jssmedia/040dd213fa89463287155151fdb01922.pdf.
[26] Kwon H, Cho J, Oh J, et al. The adaptive statistical iterative reconstruction-V technique for radiation dose reduction in abdominal CT: comparison with the adaptive statistical iterative reconstruction technique. Br J Radiol 2015;88:20150463.
[27] Greffier J, Hamard A, Pereira F, et al. Image quality and dose reduction opportunity of deep learning image reconstruction algorithm for CT: a phantom study. Eur Radiol 2020;30:3951–9.
[28] Nakamoto A, Yamamoto K, Sakane M, et al. Reduction of the radiation dose and the amount of contrast material in hepatic dynamic CT using low tube voltage and adaptive iterative dose reduction 3-dimensional. Medicine 2018;97:e11857.
[29] Kalender WA, Buchenau S, Deak P, et al. Technical approaches to the optimisation of CT. Phys Med 2008;24:71–9.