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Comparison of image noise and image quality between full-dose abdominal computed tomography scans reconstructed with weighted filtered back projection and half-dose scans reconstructed with improved sinogram-affirmed iterative reconstruction (SAFIRE*)

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Abstract

Purpose: To retrospectively compare the image noise, signal-to-noise ratio (SNR), and subjective image quality between CT images acquired with a dual-source, split-dose imaging protocol reconstructed at full and half doses with weighted filtered back projection (wFBP) and an improved sinogram-affirmed iterative reconstruction algorithm (SAFIRE*).
Methods: Fifty-three consecutive patients underwent contrast-enhanced CT of the abdomen using a standardized dual-source, single energy CT protocol. Half-dose images were retrospectively generated using data from one detector only. Full-dose datasets were reconstructed with wFBP, while half-dose datasets were reconstructed with wFBP and SAFIRE* strengths 1–5. Region of interest analysis was performed to assess SNR and noise. Diagnostic acceptability, subjective noise, and spatial resolution were graded on a 10-point scale by two readers. Statistical analysis was carried out with repeated measures analysis of variance, Wilcoxon signed rank test, and Cohen's κ test.
Results: With the increasing strengths of SAFIRE*, a progressive reduction in noise and increase in SNR ($p < 0.01$) was observed. There was a statistically significant decrease in objective noise and increase in SNR in half-dose SAFIRE* strength 4 and 5 reconstructions compared to full-dose reconstructions using wFBP ($p < 0.01$). Qualitative analysis revealed a progressive increase in diagnostic acceptability, decrease in subjective noise and increase in spatial resolution for half-dose images reconstructed with the increasing strengths of SAFIRE* ($p < 0.01$).
Conclusions: Half-dose CT images reconstructed with SAFIRE* at strength 4 and 5 have superior image quality compared to full-dose images reconstructed with wFBP. SAFIRE* potentially allows dose reductions in the order of 50% over wFBP.

Key words: Abdominal imaging—Dual-source CT—Sinogram-affirmed iterative reconstruction—Radiation dose reduction

Purpose

There is considerable research and industry drive to reduce radiation dose in CT examinations, particularly given the recent trends in rising CT utilization. A study by Mettler et al. demonstrated that abdomen and pelvis CT studies contributed to almost half the cumulative dose of all CT scans in the United States [1]. One important strategy of radiation-dose reduction in CT is to improve iterative reconstruction (IR) algorithms, which have been shown to decrease noise and increase contrast in CT images [2–8]. Refinement in these algorithms may ultimately allow lower-dose CT scans to be

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performed that carry the same diagnostic information as higher-dose scans reconstructed with less-robust reconstruction algorithms [9–11].

Standard image reconstruction utilizes weighted filtered back projection (wFBP), a computationally not very demanding reconstruction algorithm. wFBP is prone to noise since any noise in the CT raw data is backprojected onto the final image without accounting for the actual CT system geometry and statistical properties of the raw data. IR techniques add refinement loops, which mathematically compare the raw data with model-based forward-projected image data [12, 13]. Vendors have produced multiple generations of IR algorithms, which employ different methods. Newer algorithms such as adaptive iterative dose reduction, iterative model reconstruction, model-based iterative reconstruction, and sinogram-affirmed iterative reconstruction are able to reconstruct more accurate images from the raw data, accounting for statistical noise, system characteristics, and X-ray physics [14–17].

An expansion to one such algorithm, sinogram-affirmed iterative reconstruction (SAFIRE, Siemens Healthcare, Erlangen, Germany), has been introduced as a research-only prototype, referred to as SAFIRE* in the remainder of this article. The main difference to SAFIRE is an improved regularization in the image domain using SAFIRE*, which accounts for a larger neighborhood of voxels used in this regularization step, offering potential improvements in image quality. There is currently a paucity of studies examining the noise- and dose-reduction capabilities of SAFIRE*.

The purpose of this study is to compare the image noise, signal-to-noise ratio (SNR), and subjective image quality between CT images reconstructed at full dose using wFBP as well as at half dose using wFBP and SAFIRE*.

Methods

Patient groups/exclusion criteria

57 consecutive patients (mean age: 60.5 ± 19.0 years; 30 male, 27 female) underwent contrast-enhanced CT of the abdomen and pelvis, in the emergency department of a level 1 trauma center using a standardized acquisition protocol. Clinical indications for these studies varied and were not used as a discriminating factor. Transverse and anteroposterior shoulder diameter were used and measured as a substitute for body mass index. Exclusion criteria included patients who were less than 18 years old ($n = 1$), and patients with significantly degraded image quality caused by motion artifacts ($n = 3$). Summary demographics are provided in Table 1.

Table 1. Summary demographics for the 53 subjects included in this study

Demographic	Value
Mean age (± 1 SD)	60.5 ± 19.0 years
Male (%)	27 (51)
Mean CTDIvol (± 1 SD)	9.5 (5.3)
Mean DLP (± 1 SD)	456 (257)
Mean AP diameter	24.4 (5.4)
Mean transverse diameter (± 1 SD)	34 (6.5)

SD standard deviation

CT acquisition

Patients underwent intravenous contrast-enhanced CT scans of the abdomen using a 128-slice dual-source CT scanner (SOMATOM Definition FLASH, Siemens Healthcare, Erlangen, Germany) and a detector configuration of 128 × 0.6 mm. A dual-source, single energy CT protocol was used, employing both tubes simultaneously with tube voltages of 100 kV and a quality reference mAs value of 162, with equal tube currents at both tubes in a split-dose approach. Patients were scanned in caudocranial direction, with rotation time of 1 s and pitch of 0.55. The scans were performed using intravenous contrast (Omnipaque 300 at 0.46 gI/kg) injected at a rate of 3.0 mL per second, with 70 s delay (portal venous phase). Automated exposure control (CARE Dose4D, Siemens Healthcare, Erlangen, Germany) was employed in all cases and met institutional standard of care. The data was then post-processed in a research-only mode for each SAFIRE* strength level.

Dual-source image reconstruction

Axial reformations with slice widths of 3 mm and increments of 3 mm were generated, mixing the raw data from detectors A and B to achieve 100% (full) dose levels and using data from detector A alone for 50% (half) dose levels. Image reconstruction was performed using a proprietary reconstruction engine (ReconCT version 9.2, Siemens Healthcare, Erlangen, Germany). Full-dose images were reconstructed using wFBP; half-dose images were reconstructed with wFBP and SAFIRE* strengths 1–5. A soft tissue deconvolution kernel was selected for wFBP and IR datasets (B30f and I30f, respectively). Dose length product (DLP) and volume Computed Tomography dose index ($CTDI_{vol}$) values were automatically generated by the CT system based on 32 cm phantom measurements and recorded from each individual CT dose report.

Quantitative analysis of image noise

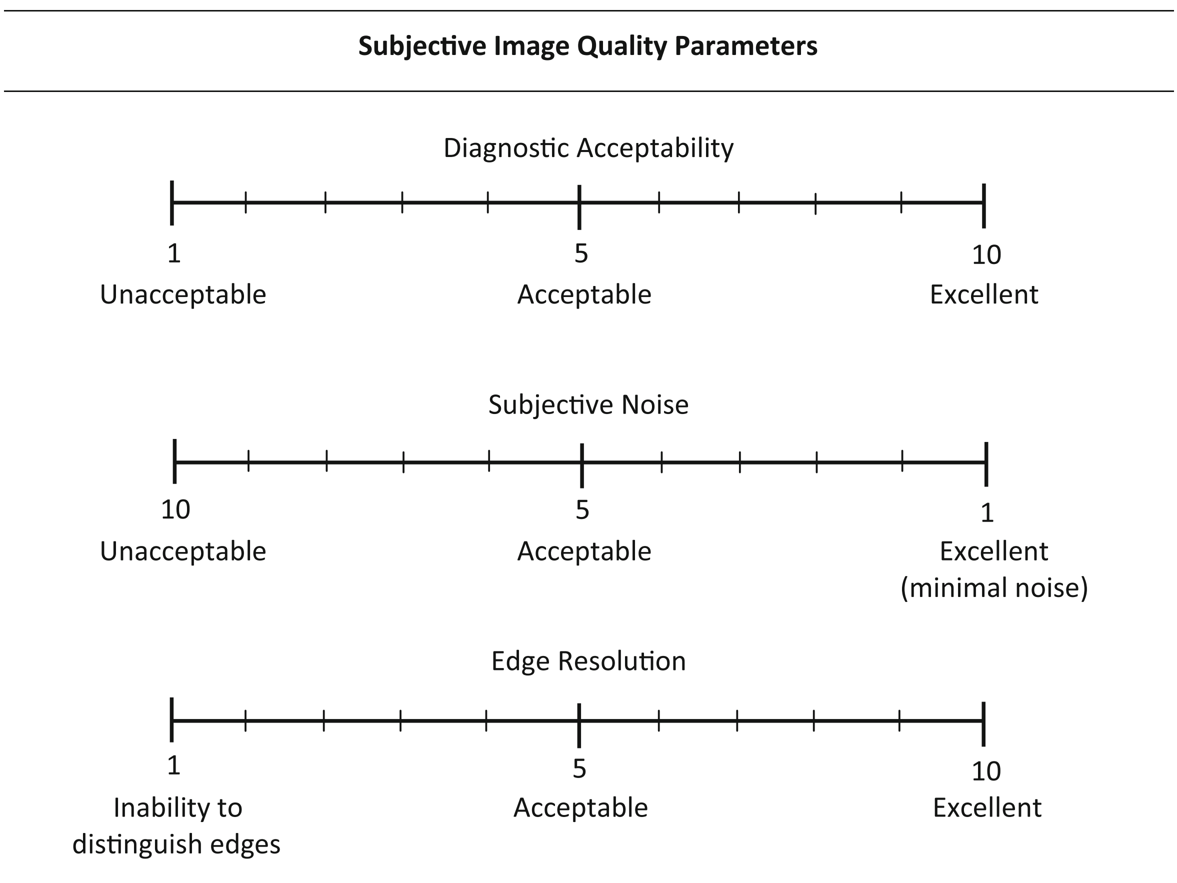
Circular regions of interest (ROIs) (area: 1 cm^2) were placed in four structures within the abdomen by a single reader, with 2 years of experience, in the following structures: the liver at the level of the diaphragm, the liver at the level of the porta hepatis, the erector spinae muscle group at the level of the renal hilum, and the psoas muscle at the level of the iliac crest. In each structure, efforts were made to place the ROI in as homogeneous an area as possible, such as away from vasculature, tissue planes, and intramuscular fat. For each patient, the ROIs were first created in the full-dose wFBP data and then copied over to the half-dose CT data to ensure the measured regions were identical across all datasets for a single patient.

Mean attenuation in Hounsfield units (HU) and standard deviation of the attenuation in the ROI was recorded for all datasets. The standard deviation in the ROI served as an objective measure of noise. Signal-to-noise ratio was calculated by dividing the mean attenuation by standard deviation for each ROI.

Qualitative analysis of image quality

Qualitative interpretation was performed for all datasets by an emergency radiologist with 8 years of experience (Reader 1), and a diagnostic radiology resident with 2 years of experience (Reader 2). All images were reviewed in Digital Imaging and Communications in Medicine (DICOM) format using soft-tissue window settings only (window width: 400 HU, window level: 40 HU) on a 27-inch iMac 4 K Retina display (Apple Computers, Cupertino, CA) using open-source DICOM image viewing software (OsiriX, version 5.5.1). Subjective image-quality parameters and grading system were adapted from the European Guidelines on Quality Criteria for CT document [18] and included diagnostic acceptability, subjective noise, and edge resolution. Diagnostic acceptability was graded from unacceptable (score of 1) to excellent (score of 10). Subjective image noise was graded according to the extent of "graininess", with scores ranged from unacceptable (score of 10) to excellent (score of 1), with acceptable (score of 5) indicating satisfactory depiction of small anatomic structures. Edge resolution was scored from 1 (indicating unacceptable ability to distinguish edges) to 10 (representing excellent ability to resolve edges). Complete scales are summarized in Table 2.

Table 2. Subjective image quality parameters and grading system. Adapted from the European Guidelines on Quality Criteria for CT



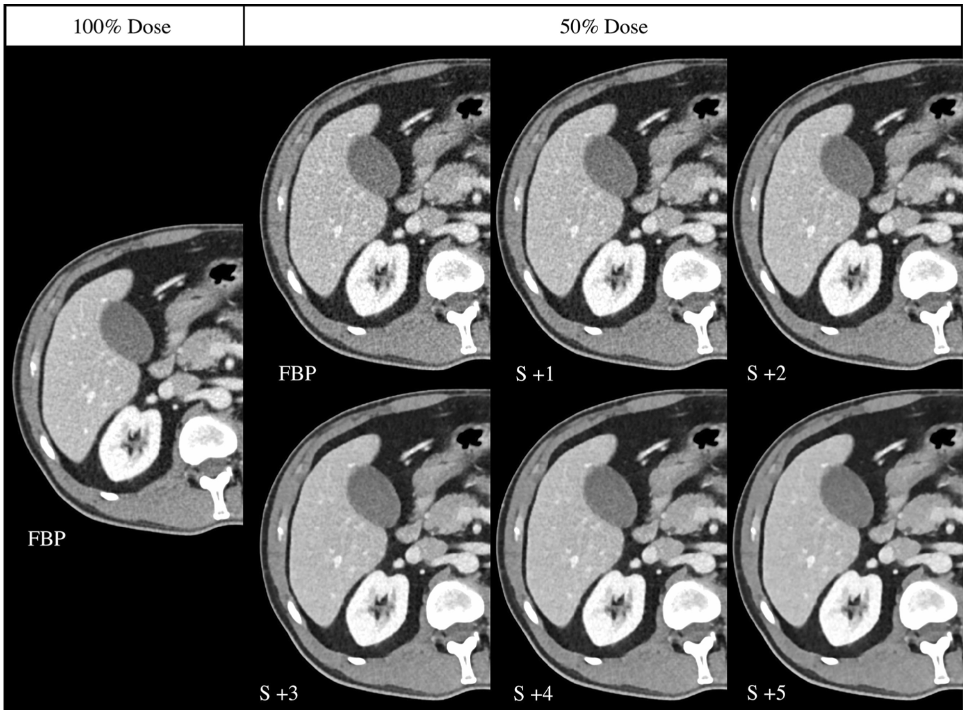


Fig. 1. Transverse abdominal CT images in a 56-year-old male reconstructed with wFBP at 100% dose, wFBP at 50% dose, and SAFIRE* strengths 1–5 at 50% dose. With the increasing strength of SAFIRE*, there was a trend for decreased noise and increased diagnostic acceptability. *S+* SAFIRE*.

Table 3. Summary of quantitative and qualitative analyses for full-dose wFBP reconstructions (100%-wFBP), half-dose wFBP reconstructions (50%-wFBP), and half-dose SAFIRE* reconstructions (50%-SAFIRE*) with strengths 1–5

	100%-wFBP	50%-wFBP	50%-SAFIRE*				
			Strength 1	Strength 2	Strength 3	Strength 4	Strength 5
Quantitative analysis							
Objective noise (HU)	18 ± 4	25 ± 6	23 ± 4	20 ± 4	17 ± 4	14 ± 3	11 ± 3
SNR	5.4 ± 0.2	3.8 ± 0.1	4.1 ± 0.1	4.7 ± 0.2	5.5 ± 0.2	6.7 ± 0.2	8.7 ± 0.3
Qualitative accuracy							
Diagnostic accuracy							
Reader 1	6.5 ± 0.8	4.6 ± 1.0	5.3 ± 0.1	5.9 ± 0.8	6.8 ± 0.9	7.7 ± 1.0	8.3 ± 1.2
Reader 2	6.4 ± 0.8	4.5 ± 1.0	5.4 ± 0.8	6.1 ± 0.8	6.7 ± 0.9	7.5 ± 1.0	8.0 ± 1.1
Subjective noise							
Reader 1	6.1 ± 0.7	8.2 ± 0.7	7.4 ± 0.1	6.7 ± 0.9	5.9 ± 0.9	4.7 ± 0.9	2.9 ± 0.9
Reader 2	5.9 ± 0.7	7.9 ± 0.7	7.1 ± 0.9	6.4 ± 1.0	5.5 ± 1.0	4.5 ± 1.0	3.3 ± 1.0
Edge resolution							
Reader 1	7.1 ± 0.8	5.4 ± 0.9	5.8 ± 0.9	6.6 ± 0.8	7.4 ± 0.8	8.3 ± 0.8	9.3 ± 0.7
Reader 2	7.1 ± 0.7	5.2 ± 0.7	6.1 ± 0.8	6.7 ± 0.8	7.4 ± 0.7	8.3 ± 0.7	9.0 ± 0.7

SNR signal-to-noise ratio

Statistical analysis

Statistical tests were performed with a commercially available medical statistical package (PASW version 20, SPSS Inc, Chicago, IL, USA). Statistical analysis was done with repeated measures analysis of variance and Wilcoxon signed rank test. Agreement between scoring of qualitative parameters was compared using Cohen's κ test of inter-observer agreement. All data are presented as mean ± standard deviation unless otherwise stated.

Results

Fifty-three patients were included in this study. There was no statistically significant difference in age between the male patients (N = 27, mean age = 64.0 ± 20.2 years) and female patients (N = 26, mean age = 58.1 ± 18.2 years). A summary of the patient demographics and scan dosimetry is included in Table 1.

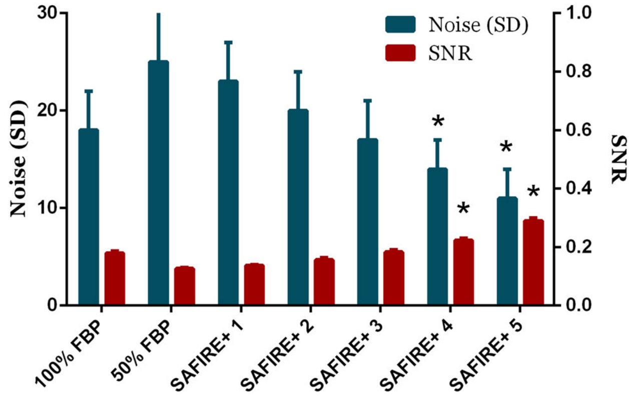


Fig. 2. Comparison of quantitative noise (standard deviation of HU) and signal-to-noise ratio (SNR). An asterisk (*) indicates a statistically significant result compared to wFBP reconstructions at 100% dose. All reconstructions with SAFIRE* were done at 50% dose.

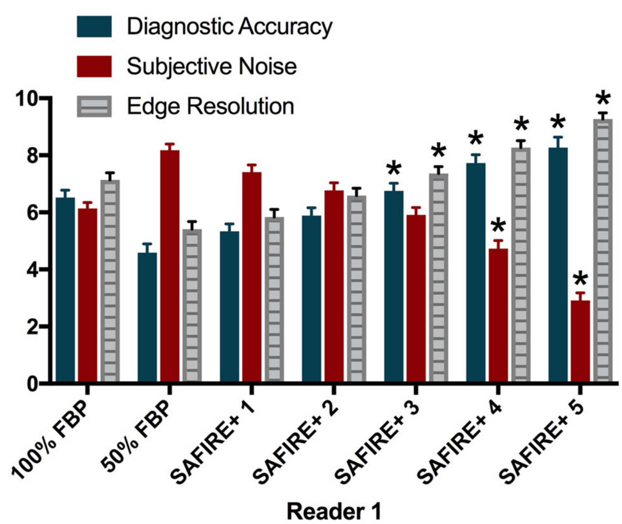


Fig. 3. Summary of Reader 1's comparison of diagnostic acceptability, subjective noise, and edge resolution. An asterisk (*) indicates a statistically significant result compared to wFBP reconstructions at 100% dose. All reconstructions with SAFIRE* were done at 50% dose.

Image quality—quantitative analysis

An example of the image quality using all reconstruction methods, i.e. full-dose wFBP images (100%-wFBP), half-dose wFBP images (50%-wFBP) and half-dose SAFIRE* images (50%-SAFIRE*) with strengths 1–5, is shown in Fig. 1 in one representative study patient. There was a statistically significant increase in noise and decrease in SNR when using 50%-wFBP compared to 100%-wFBP ($p < 0.01$). Compared to 100%-wFBP, 50%-SAFIRE* strengths 1–5 demonstrated a mean noise reduction of 8%, 20%, 32%, 44%, and 56%, respectively ($p < 0.01$), and a mean SNR increase of 8%, 24%, 45%, 76%, and

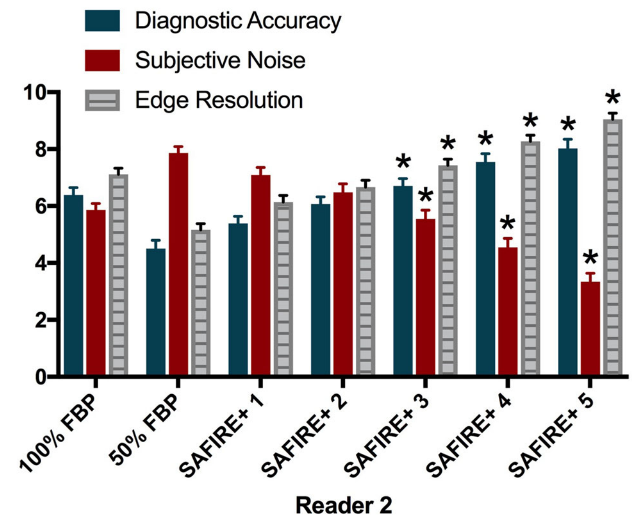


Fig. 4. Summary of Reader 2's comparison of diagnostic acceptability, subjective noise, and edge resolution. An asterisk (*) indicates a statistically significant result compared to wFBP reconstructions at 100% dose. All reconstructions with SAFIRE* were done at 50% dose.

129%, respectively ($p < 0.01$). With the increasing SAFIRE* strength, a trend of increasing SNR and decreasing noise ($p < 0.05$) was observed.

Compared to 100%-wFBP, there was a statistically significant decrease in objective noise and increase in SNR for 50%-SAFIRE* strengths 4 and 5 ($p < 0.01$). Objective noise was reduced by 22% and 29% for 50%-SAFIRE* strengths 4 and 5, respectively; mean SNR increase was 24% and 61% for 50%-SAFIRE* strengths 4 and 5, respectively. Quantitative results are summarized in Table 3 and Fig. 2.

Image quality—qualitative analysis

Qualitative analysis revealed a progressively increasing diagnostic acceptability, a decreasing subjective noise, and an increasing spatial resolution for increasing strengths of 50%-SAFIRE* ($p < 0.01$). Compared to 50%-wFBP, both readers determined that all 50%-SAFIRE* strengths demonstrated statistically significant increased diagnostic acceptability, decreased subjective noise, and increased edge resolution ($p < 0.01$). 50%-SAFIRE* strengths 1–5 resulted in increased diagnostic acceptability score by 15–20%, 28–35%, 48–49%, 67–68%, and 78–80%, respectively; decreased subjective noise score by 10%, 17–18%, 28–29%, 42%, and 57–65%, respectively; and increased edge resolution score by 7–19%, 22–29%, 37–44%, 53–60%, and 72–75%, respectively.

Compared to 100%-wFBP, both readers determined that 50%-SAFIRE* strengths 3–5 demonstrated increased diagnostic acceptability and increased edge resolution ($p < 0.01$), while Reader 1 found SAFIRE* strength 4 and 5 demonstrated decreased subjective noise ($p < 0.01$), and Reader 2 found SAFIRE* strength 3-5 demonstrated decreased subjective noise ($p < 0.01$). Qualitative results are summarized in Fig. 3 for Reader 1, and Fig. 4 for Reader 2. Cohen's κ ranged between moderate to very good agreement for diagnostic acceptability (κ = 0.511- 0.934), between fair to very good for edge resolution (κ = 0.411–0.853), and was in moderate agreement for subjective noise (κ = 0.519–0.619).

Discussion

In this study, the use of SAFIRE* in half-dose CT scans led to a statistically significant decrease in noise and increase in SNR compared to weighted filtered back projection images. Mean noise reduction ranged from 8% to 56% for 50%-SAFIRE* strengths 1 and 5, respectively. Furthermore, with the increasing SAFIRE* strength, we observed progressive improvement in noise and SNR. The findings represent important results for low-dose CT scans, such as in obese patients, as the use of SAFIRE* can improve image noise. Our results are in line with the work by Schabel et al. which also demonstrated improved SNR for half-dose abdominal CT scans reconstructed with IR methods compared to full-dose wFBP scans [6].

Importantly, we demonstrated that half-dose CT scans reconstructed with SAFIRE* had comparable if not reduced image noise, particularly at strengths 4 and 5, compared to full-dose CT scans reconstructed with wFBP. At SAFIRE* strength 5, there was on average a 29% reduction in image noise and a 61% increase in SNR compared to full-dose wFBP images. These results not only suggest that half-dose CT scans are achievable while maintaining the level of image noise, but that there is potential for even lower-dose CT scans given the favorable noise characteristics.

Qualitative results further support the improvements in image quality with SAFIRE* over wFBP. Compared to 50%-wFBP, all 50%-SAFIRE* strengths demonstrated improved image quality. In addition, with the increasing SAFIRE* strength, there was progressive improvement in diagnostic acceptability, subjective noise, and edge resolution. Compared to 100%-wFBP, 50%-SAFIRE* strengths 3–5 demonstrated statistically significant improvements in diagnostic acceptability and edge resolution, while both readers also agreed that SAFIRE* strengths 4 and 5 additionally demonstrated statistically significant improvements in subjective noise. Previous work by Hardie et al. demonstrated that CT examinations performed at half dose, reconstructed with SAFIRE, were nearly equivalent to full-dose scans reconstructed with wFBP [10]. While SAFIRE* may represent an improvement over SAFIRE in regards to subjective image quality, a study with a direct comparison of the two reconstruction methods would be beneficial.

Previous papers on older IR techniques demonstrated degradation in subjective image quality at higher strengths, which produced a 'blocky' or 'plastic' appearance [4, 7, 10]. It is known that this change in noise texture affects subjective image quality and diagnostic performance [19–21]. However, our results indicate there is preservation of subjective image quality even at higher strengths of SAFIRE*. These results are in line with work on current generation IR techniques [22–25], which demonstrate improved subjective image quality of model-based methods over other IR methods. In addition, the ability to adjust the strength of SAFIRE* would allow readers to generate images with an acceptable tradeoff between noise texture and SNR.

This study was limited by its retrospective nature. Data were previously acquired using a split-dose dual-source technique, which only allowed for the comparison of half-dose to full-dose scans. This design has a number of advantages, including no extra radiation to patients and contemporaneous data acquisition of half-dose and full-dose image sets. Prospective studies or studies that use an asymmetric split-dose technique would be able to elucidate the effects of different degrees of dose reduction on image quality. Furthermore, the entire study population was assessed with half-dose scans, which does not accurately characterize the dose-reduction potential of SAFIRE* at a different body habitus. Silva et al. previously outlined a greater dose-reduction potential in nonobese patients using a different IR algorithm [12]. Nevertheless, our patient population was in a relatively narrow size range, and future studies incorporating low- or high-BMI patients are warranted. In addition, subjective image quality was only measured by reader scoring. Other groups have attempted to overcome the semiquantitative nature of this analysis through the use of noise quality metrics [20, 26], use of task-based methods [13], or forced choice comparisons [27]. Finally, these findings can be furthered by testing for diagnostic accuracy (using a cohort of patients with similar indications for scanning) and for additional testing of low contrast detectability.

In conclusion, SAFIRE* offers improved image quality in comparison with weighted filtered back projection for abdominal CT scans at the same radiation dose. SAFIRE* also shows promise for radiation-dose reduction, as half-dose CT datasets reconstructed with higher strengths of SAFIRE* maintained image quality compared to full-dose CT datasets reconstructed with wFBP. Unlike previous generations of IR, increased image-quality scores were demonstrated at higher SAFIRE* strengths. SAFIRE*, which is only available as a research prototype, shows promising results for potential clinical use in abdominal CT.

Compliance with ethical standards

Conflict of interest The University of British Columbia has a master research agreement with Siemens. Stephen Choy declares he has no conflict of interest. Dennis Parhar declares he has no conflict of interest. Kevin Lian declares he has no conflict of interest. Heiko Schmiedeskamp is an employee of Siemens Medical Solutions USA. Luck Louis declares he has no conflict of interest. Timothy O'Connell has received speaker fees from Siemens. Patrick McLaughlin declares he has no conflict of interest. Savvas Nicolaou declares he has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Hospital institutional review board approval was obtained for this retrospective study. The need for informed consent was waived.

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