ORIGINAL ARTICLE

Iterative Reconstruction for Head CT: Effects on Radiation Dose and Image Quality

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ABSTRACT: ***Background:*** Iterative reconstruction has been reported to reduce radiation dose in CT, while preserving and even improving image quality. The purpose of this study was to evaluate the effects of sinogram-affirmed iterative reconstruction (SAFIRE) on radiation dose reduction and image quality for noncontrast adult head CT and to compare SAFIRE with conventional filtered back-projection (FBP) reconstruction. ***Methods:*** Institutional review board approval was obtained for this retrospective analysis of head CT scans reconstructed with SAFIRE and/or FBP for 107 patients. Radiation dose parameters were recorded from scanner-generated CT dose reports. Signal-to-noise and contrast-to-noise ratios (SNR, CNR) were calculated from gray and white matter (GM, WM) attenuation measurements. Image noise, artifacts, GM-WM differentiation, small structure visibility, and sharpness were graded by two readers. Statistical analysis included the independent-samples t test for quantitative data, the related samples Wilcoxon signed-rank test for qualitative data, the coefficient of repeatability for intraobserver variation, and κ statistics for interobserver agreement. ***Results:*** Mean effective dose was significantly reduced with SAFIRE from 2.0 to 1.7 mSv ($p < 0.0001$). SAFIRE also significantly improved GM SNR, WM SNR, and GM-WM CNR ($p < 0.0001$). Significant reductions in image noise and posterior fossa artifact as well as improvements in GM-WM differentiation, small structure visibility, and sharpness were noted with SAFIRE ($P < 0.005$). ***Conclusions:*** SAFIRE for noncontrast adult head CT reduces patient radiation dose by 15% for the settings employed at our institution, while significantly improving multiple quantitative and qualitative measures of image quality.

RÉSUMÉ: Reconstruction itérative pour la tomodensitométrie de la tête : effets sur la dose de radiation et la qualité de l'image. ***Contexte:*** La reconstruction itérative réduirait la dose de radiation tout en préservant et même en améliorant la qualité de l'image. Le but de cette étude était d'évaluer les effets d'une reconstruction itérative avec filtrage des sinogrammes (sinogram-affirmed - SAFIRE) sur la diminution de la dose de radiation et sur la qualité de l'image pour la tomodensitométrie de la tête sans agent de contraste chez l'adulte et de comparer SAFIRE à la reconstruction par rétroprojection filtrée (FBP) conventionnelle. ***Méthode:*** Nous avons obtenu l'approbation du Comité d'éhique de l'institution pour cette étude rétrospective des scans de 107 patients reconstruits avec SAFIRE et/ou FBP. Les paramètres de la dose de radiation ont été recueillis des rapports de dose générés par le scanner. Les rapports signal-bruit et contraste-bruit (RSB, RCB) ont été calculés pour les mesures d'atténuation de la substance grise (SG) et de la substance blanche(SB). Le bruit, les artéfacts, la distinction SG-SB, la visibilité des petites structures et la netteté de l'image ont été évalués par deux lecteurs. L'analyse statistique a été réalisée au moyen du test de t pour échantillons indépendants pour les données quantitatives, du test des rangs signés de Wilcoxon pour échantillons appariés pour les données qualitatives, du coefficient de répétabilité pour la variation intra-observateur et de la statistique ƙ pour la concordance interobservateur. ***Résultats:*** La dose moyenne efficace était significativement réduite avec SAFIRE, de 2,0 à 1,7 mSv ($p < 0{,}0001$). SAFIRE améliorait significativement le RSB SG, le RSB SB et le RCB SG-SB ($p < 0{,}0001$). Des réductions significatives du bruit d'image et des artéfacts à la fosse postérieure ainsi qu'une meilleure distinction SG-SB, une amélioration de la visibilité de petites structures et de la netteté de l'image ont été notées avec SAFIRE ($p < 0{,}005$). ***Conclusions:*** SAFIRE, utilisé pour la tomodensitométrie de la tête avec les réglages utilisés chez l'adulte dans notre institution, diminue de 15% la dose de radiation à laquelle est exposé le patient tout en améliorant significativement plusieurs mesures quantitatives et qualitatives de la qualité de l'image.

Keywords: Head CT, iterative reconstruction, radiation dose, image quality

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An estimated 4.4 million CT scans were performed in 2011-2012 in Canada.[1] Although CT scans have been reported to compose only 17% of all diagnostic imaging tests employing ionizing radiation, they account for 49% of the collective radiation dose administered by all radiographic and nuclear medicine procedures.[2] Recent literature has highlighted the need for CT radiation dose reduction given the potential risk of secondary carcinogenesis.[3,4] A number of dose-reduction strategies have already been adopted into CT scanner design, including tube current modulation and automatic exposure control.[5] More recent clinical implementation of iterative reconstruction has provided additional optimization of patient dose relative to conventional filtered back-projection (FBP) techniques.[6]

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Opportunities for dose reduction are limited in FBP given the trade-off between image noise and sharpness and the resultant loss of image quality at lower tube current settings.[7] Iterative reconstruction introduces a correction loop with image regularization into the reconstruction process, which reduces noise with maintained or improved image resolution by offering some degree of decoupling of noise and spatial resolution.[8] Technological advances have enabled workflow-efficient iterative reconstruction on CT workstations and all major CT vendors have developed software for clinical use.[9] One of the newest commercially available algorithms, sinogram affirmed iterative reconstruction (SAFIRE) (Siemens Healthcare, Forchheim, Germany), performs iterations in the raw data (sinogram) and image domains to optimize image noise and sharpness.[7,9] Recent studies have reported that SAFIRE offers substantial radiation dose savings in imaging of the chest, abdomen, and head.[7,10-12]

The purpose of this study was to further evaluate the effects of SAFIRE on radiation dose reduction and quantitative and qualitative measures of image quality for noncontrast adult head CT for the scanning parameters employed at our institution and to validate the technique for local clinical use.

Methods

Patients

Institutional review board approval was obtained for this retrospective study. Between June 1 and June 15, 2012, 168 consecutive adult patients underwent noncontrast head CT scans for any indication with SAFIRE reconstruction immediately after a software upgrade. Following appropriate sample size/power calculations, a test group of the first 50 consecutive patients in this group was selected for the quantitative CT dataset analysis. The control group for the quantitative CT dataset analysis comprised 50 patients from a consecutive series who underwent noncontrast CT head examinations for any indication with FBP reconstruction between May 16 and 28, 2012, before the software upgrade on the same CT scanner. Subjects within the control group were age-matched within 5 years of the test group to limit confounding secondary to age-related white matter changes. For the qualitative CT dataset analysis, the test population comprised 14 of the 168 patients imaged between June 1 and 15, 2012, who had previously undergone noncontrast CT head examinations for any indication between May 19, 2011, and May 20, 2012, with FBP reconstruction before the software upgrade on the same CT scanner. Five patients were included in both the quantitative and qualitative arms of the study.

CT Data Acquisition and Reconstruction

Imaging was performed on a Siemens SOMATOM Definition Flash CT scanner (Siemens Healthcare). Acquisition and reconstruction parameters are listed in Table 1.

Quantitative CT Dataset Analysis

One reader (MRB, second-year radiology resident) blinded to patient identity, scan date, and reconstruction algorithm, performed two independent sets of circular region of interest (ROI) attenuation measurements in Hounsfield units (HU) on head CT images for the 50 patients in the control group (FBP) and the 50 patients in the test group (SAFIRE). Region-of-interest (ROI) attenuation measurements were performed in the lentiform nucleus for gray matter (GM) and in the internal capsule for white matter (WM). Both mean and standard deviation (SD) values were recorded for each ROI measurement. These values were subsequently used to calculate signal-to-noise and contrast-to-noise ratios (SNR, CNR). The SNR represents the quality of the signal intensity within a given tissue, whereas the CNR reflects tissue differentiation based on photon attenuation with respect to background noise.[13] The SNR of a given tissue is defined as its mean attenuation (HU) divided by the SD.[14] The CNR of adjacent tissues, in this case GM and WM, is defined as the difference in their mean tissue attenuations divided by the square root of the sum of their variances.[14]

Qualitative CT Dataset Analysis

Qualitative analysis of images obtained with FBP and SAFIRE was performed on the 14 patients who had head CT scans with both FBP and SAFIRE reconstruction. Two readers (MRB, second-year radiology resident; JSS, subspecialty-trained neuroradiologist) were trained in the qualitative grading system before reviewing the study datasets. Readers graded study datasets according to randomized lists on a PACS workstation (Barco, Kortrijk, Belgium). The "demographic toggle" function was employed to ensure appropriate blinding to patient identity, scan date, and reconstruction algorithm. Qualitative variables and their grading system are listed in Table 2.[13] For visual assessment of image noise, ratings ≥2 represented diagnostic quality studies. Posterior fossa artifact comprised beam

Table 1: CT data acquisition and reconstruction parameters

	FBP	SAFIRE
kVp	120	120
mAs	300	225-276 (ref 320)
Gantry rotation (s)	1	1
Collimation (mm)	40 × 0.6	40 × 0.6
Pitch	0.55	0.55
CAREDOSE 4D	On	On
FOV (cm)	23	23
Matrix	512 × 512	512 × 512
Slice thickness (mm)	5	3
Reconstruction algorithm	H37s medium smooth	J37s medium smooth (SAFIRE 3)

FBP = filtered back-projection; FOV = field of view; SAFIRE = sinogram-affirmed iterative reconstruction.

Table 2: Qualitative variables and grading system

Variables	Motion artifact	Image noise Posterior fossa artifact	GM-WM differentiation Small structure visibility Image sharpness
Scale	1 = no 2 = yes	1 = unacceptable 2 = above average 3 = average 4 = less than average 5 = minimal	1 = very poor 2 = suboptimal 3 = acceptable 4 = above average 5 = excellent

GM = gray matter; WM = white matter.

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hardening and partial volume averaging. GM-WM differentiation was assessed at the level of the centrum semiovale. Small structure visibility included evaluation of Virchow-Robin spaces at the level of the basal ganglia and intracranial vasculature. Image sharpness was rated according to the visibility of the margins of the subarachnoid space.

Radiation Dose

CT dose index volume ($CTDI_{vol}$) and dose-length product (DLP) were recorded from scanner-generated CT dose reports for all patients. An effective dose per unit dose-length product of 0.0021 mSv/(mGy·cm) for the head was used to calculate effective dose for a 70-kg adult patient.[5]

Statistical Analysis

Statistical analysis was performed with the PASW Statistics 18.0 software package (IBM Corporation, Somers, NY). Numerical data are presented as the mean (SD, range). Intraobserver variation for the repeated attenuation measurements was assessed with the coefficient of repeatability.[15] Interobserver agreement for the qualitative variables was assessed with a quadratic-weighted kappa value.[16] The independent samples t-test and the related samples Wilcoxon signed-rank test were employed for significance testing of quantitative and qualitative data, respectively. Significance was taken at $p < 0.05$.

Preliminary measurements of the quantitative variables assessed in this study (SNR, CNR, $CTDI_{vol}$, DLP, and effective dose) were performed to estimate study power.[17] The sample size of 50 provided greater than 95% power with $\alpha = 0.05$ representing the Type I error probability.

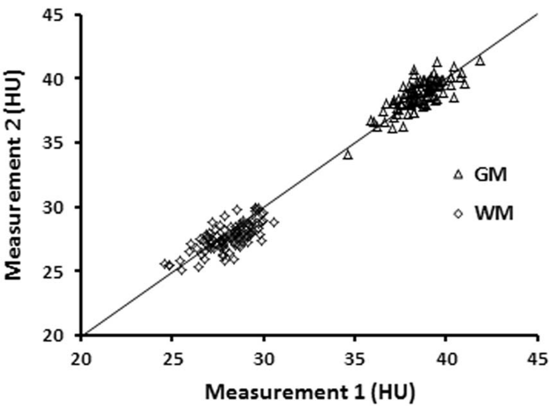

Figure 1: Intraobserver variation for GM and WM attenuation values. Measurement 1 versus measurement 2 with the line of equality.

Results

The quantitative study population consisted of 100 adult patients; 50 underwent noncontrast CT head examinations with FBP (mean [SD] age, 57.1 [20.0] years; range, 22-92 years; 31 women, 19 men) and 50 underwent noncontrast head CT examinations with SAFIRE (mean [SD] age, 56.4 [19.9] years; range, 21-91 years; 27 women, 23 men). There were no significant differences in age ($p = 0.853$) or gender ($p = 0.418$) between the FBP or SAFIRE groups.

The qualitative study population consisted of 14 adult patients (four women, 10 men) who underwent noncontrast CT head examinations with FBP and SAFIRE. The mean age at the time of the FBP examination was 63.2 (22.1, 24-92) years. The mean time was between the FBP and SAFIRE examinations was 202 (147, 18-381) days. One patient developed bilateral subdural hygromas in the interval between studies.

Quantitative CT Dataset Analysis

The mean ROI area for attenuation measurements was 22.8 (0.8, 18.3-26.3) mm^2. Each ROI contained approximately 110 voxels. Mean GM attenuation values for the FBP and SAFIRE populations were 38.1 (1.1, 34.1-40.0) HU and 39.3 (1.0, 36.3-41.8) HU, respectively. For WM, the attenuation values were 28.3 (1.1, 25.2-30.6) HU for FBP and 27.5 (1.1, 24.6-29.9) HU for SAFIRE. The coefficient of repeatability for the two sets of attenuation measurements was 1.8 (95% confidence interval: 1.5-2.0). Figure 1 demonstrates relatively tight clustering of the GM and WM attenuation values about the line of equality.

Figures 2a and 2b displays boxplots of the GM SNR and WM SNR stratified by reconstruction technique. The mean GM SNR significantly increased from 10.2 (1.1, 7.4-13.1) for FBP to 15.8 (2.2, 12.7-22.4) for SAFIRE ($p < 0.0001$). Similarly, the mean WM SNR increased from 7.4 (0.9, 5.4-9.1) for FBP to 10.0 (1.3, 7.3-14.4) for SAFIRE ($p < .0001$). Figure 3 displays a boxplot of

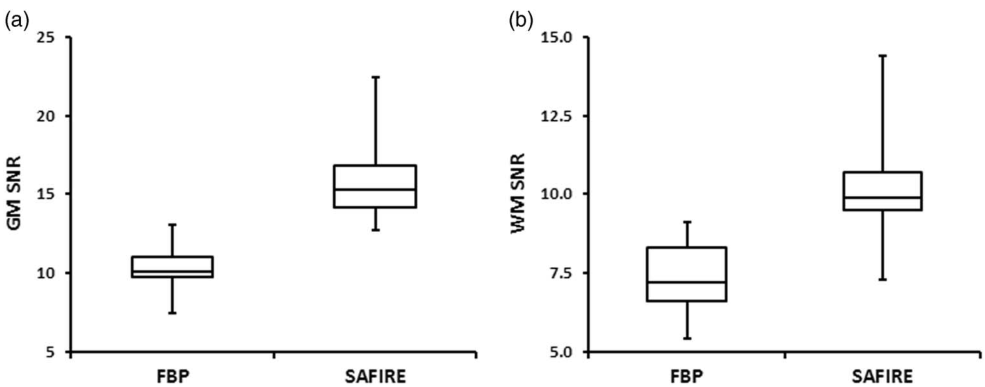

Figure 2: Boxplots of GM SNR (a) and WM SNR (b) with FBP and SAFIRE. The horizontal line within the box is the median value; the box defines the 25th to 75th quartile with whiskers to the minimum and maximum values.

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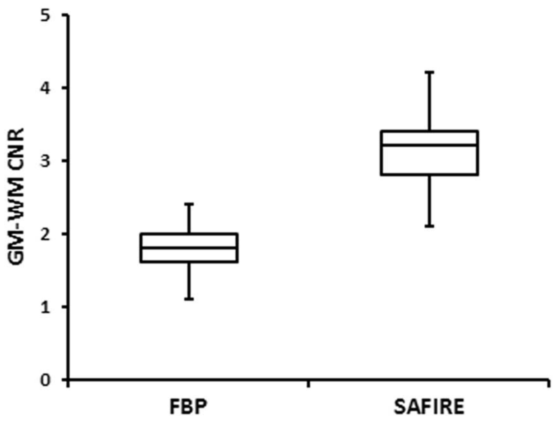

Figure 3: *Boxplot of GM-WM CNR with FBP and SAFIRE. The horizontal line within the box is the median value; the box defines the 25th to 75th quartile with whiskers to the minimum and maximum values.*

Table 3: Mean qualitative rankings (n = 12)

	FBP	SAFIRE	p
	Mean (SD)	Mean (SD)	
Image noise	2.3 (0.5)	4.0 (0.3)	0.002
Posterior fossa artifact	2.8 (0.3)	4.1 (0.4)	0.002
GM-WM differentiation	2.6 (0.6)	4.0 (0.6)	0.002
Small structure visibility	2.5 (0.5)	4.0 (0.5)	0.003
Image sharpness	2.5 (0.4)	4.2 (0.4)	0.002

FBP = filtered back-projection; GM = gray matter; SAFIRE = sinogram-affirmed iterative reconstruction; SD = standard deviation; WM = white matter.

the GM-WM CNR stratified by reconstruction technique. There was also a significant improvement in GM-WM CNR with SAFIRE, which increased from 1.8 (0.3, 1.1-2.4) to 3.1 (0.4, 2.1-4.2) ($p < 0.0001$).

Qualitative CT Dataset Analysis

There was perfect agreement between the readers for the presence of motion artifact, and two of the 14 patients were excluded from analysis secondary to motion artifact on the FBP scans. Readers either agreed or were within 1 unit of each other for 114/120 (95%) of the rankings in the remaining 12 patients. Measures of interobserver agreement were: image noise, 0.82 (very good); posterior fossa artifact, 0.50 (moderate); GM-WM differentiation, 0.60 (moderate); small structure visibility, 0.71 (good); and image sharpness, 0.65 (good). Mean reader qualitative rankings are listed in Table 3. Image noise and posterior fossa artifact were significantly reduced with SAFIRE ($p = 0.002$). Similarly, GM-WM differentiation, small structure visibility, and image sharpness were significantly improved with SAFIRE ($p < 0.005$). Examples of FBP and SAFIRE non-contrast head CT images are displayed in Figures 4a and 4b, respectively.

Radiation Dose

The mean $CTDI_{vol}$ and DLP values for FBP were 55.9 (1.0, 55.6-59.4) mGy and 951.4 (58.6, 849-1144) mGy·cm. These values were significantly reduced to 47.4 (2.4, 42.3-51.9) mGy and 802.9 (76.9, 654-959) mGy·cm for SAFIRE ($P < 0.0001$). Using the effective dose per unit dose-length product, the mean effective doses for FBP and SAFIRE were calculated as 2.0 (0.1, 1.8-2.4) mSv and 1.7 (0.2, 1.4-2.0) mSv, respectively, corresponding to a dose reduction of 15% with SAFIRE ($p < 0.0001$).

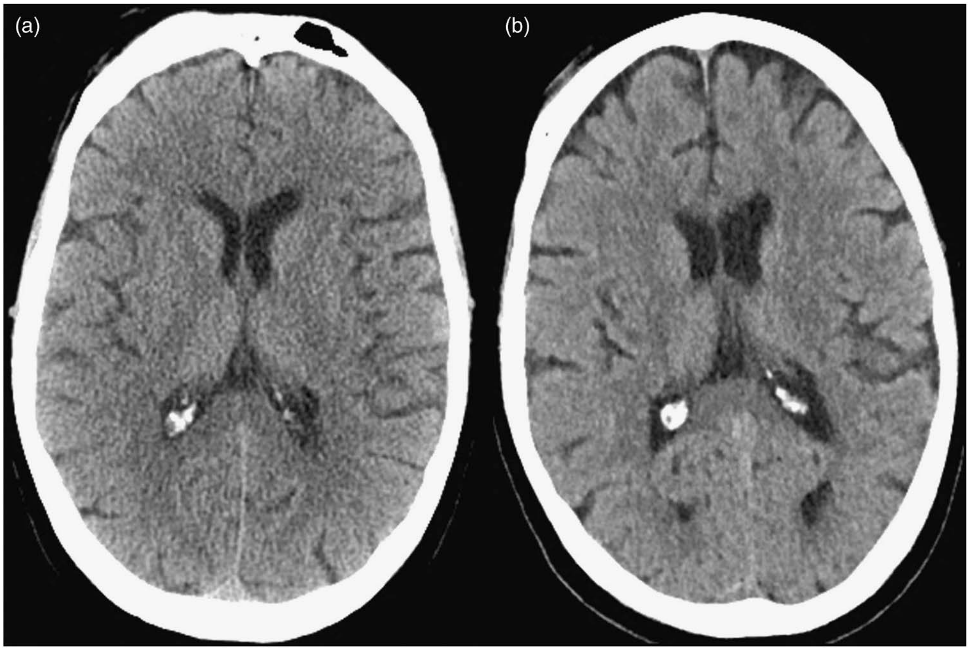

Figure 4: *A 41-year-old man with a seizure disorder. (a) Axial noncontrast head CT image (width, 80 HU; level, 40 HU) reconstructed with FBP from a raw CT dataset acquired with a tube current of 300 mAs. (b) Axial noncontrast head CT image (width, 80 HU; level, 40 HU) reconstructed with SAFIRE from a raw CT dataset acquired with a tube current of 247 mAs. The scans were performed 1 month apart.*

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Discussion

Several other recent studies have also assessed the efficacy of iterative reconstruction for head CT and have shown that image quality can be preserved and even improved with concomitant radiation dose reduction.[8,12,13,18,19] Iterative reconstruction has been reported to reduce patient dose for head CT by 15-30% for iterative reconstruction in image space (Siemens Healthcare),[8] 24-31% for adaptive statistical iterative reconstruction (ASiR) (GE Healthcare, Milwaukee, WI),[13,18,19] and 20% for SAFIRE.[12] Reported mean effective doses for head CT in adults range from 2.2-2.7 mSv for FBP to 1.5-2.0 mSv for different iterative methods.[8,12,13,18] Our results of 2.0 mSv for FBP and 1.7 mSv for SAFIRE are in good agreement with these values.

We identified significant improvements in SNR and CNR for the acquisition parameters in our study. Korn et al.[12] report 28%, 31%, and 25% increases in GM SNR, WM SNR, and GM-WM CNR with SAFIRE at reduced-dose head CT (255 mAs) in comparison to routine-dose scans (320 mAs). Higher values of 55%, 35%, and 72% in our study likely relate to a combination of a lower tube current for our routine-dose scans (300 mAs) and a relatively higher quality reference mAs setting for our reduced-dose SAFIRE scans (320 mAs). An earlier report on image quality at different ASiR levels for routine- and reduced-dose head CT scans found that reduced-dose head CT scans had significantly higher SNR at ASiR levels ≥60% and CNR at ASiR levels ≥40%.[13] Although differences exist between the ASiR and SAFIRE algorithms, our results at a medium strength SAFIRE setting of 3 are comparable.

Subjective measures of CT image quality are similarly dependent on radiation dose and the method of image reconstruction. Furthermore, the generalizability of our results to the literature is limited by the lack of standardized ratings scales and variables.[8,12,13,18,19] We employed the 5-point rating scales and variables of Rapalino et al.,[13] who similarly identified significant reductions in image noise and artifacts with improved GM-WM differentiation at ASiR levels ≥ 60% in reduced-dose head CT scans with respect to routine-dose head CT without ASiR. Although we report a reduction in posterior fossa artifact for SAFIRE, this finding may be in part be attributable to the narrower slice thickness of 3 mm, which would be expected to reduce partial volume averaging through the skull base. Korn et al.[12] also report significantly reduced image noise, GM-WM differentiation, and distinctness of the posterior fossa contents with SAFIRE in reduced-dose head CT scans. Although our results of improved small structure visibility with SAFIRE have not previously been reported, this finding may relate to the use of a lower tube current for the routine-dose scan (300 mAs).

The difference in slice thickness between the FBP (5 mm) and SAFIRE (3 mm) groups may have contributed to an underestimation of the potential CT dose reduction offered by SAFIRE for the SNR values reported in this study. Radiation dose is proportional to the mAs or the number of photons used to acquire a CT dataset. These quantities have traditionally been expressed in relation to SNR, pixel volume, and slice thickness whereby the number of photons used to create a CT dataset is proportional to the square of the SNR divided by the product of the pixel volume and the slice thickness.[20] For example, increasing the slice thickness from 3 to 5 mm for a given reconstruction algorithm with a fixed pixel volume provides a theoretical dose reduction of up to 40% if the mAs required to maintain a fixed SNR is appropriately reduced at the time of scanning. The SNR values measured from the SAFIRE datasets in this study may be achievable at 1 mSv with a slice thickness of 5 mm, or 60% of the reported 1.7 mSv dose with a slice thickness of 3 mm. In comparison to the 2.0 mSv FBP dose, this represents a dose savings of up to 50%. The inherent reduction in image noise in iterative reconstruction also offers an additional opportunity for radiation dose optimization. Using the relationship described previously at a fixed pixel volume, estimated mean effective doses of 0.9 mSv for 3-mm SAFIRE datasets and 0.6 mSv for 5-mm SAFIRE datasets may be obtained for the mean SNR values reported for the 5-mm FBP datasets in this study. These values are 45% and 30%, respectively, of the reported 2.0 mSv FBP dose. However, these estimates require experimental verification for modern CT scanners, and the diagnostic quality of such low-dose datasets would also need to be confirmed.

Although we only evaluated noncontrast adult head CT scans, SAFIRE may be considered for additional head and neck CT applications. Children would benefit from reduced doses given heightened concerns of radiosensitivity and lifetime cumulative dose in this population.[19] A role for iterative reconstruction in contrast-enhanced head CT has previously been described,[8] and further reductions in radiation dose may be also achievable in CT angiography and dedicated bone imaging where GM-WM CNR is less important.[21] SAFIRE could be considered for CT brain perfusion imaging, but has the potential to delay the initiation of tissue plasminogen activator therapy in the setting of acute ischemic stroke because of slightly longer reconstruction times.[12]

There are limitations to this study. First, a fixed tube current of 300 mAs for the FBP scan protocol in comparison to a quality reference mAs setting of 320 mAs for SAFIRE likely resulted in an underestimation of the dose reduction offered by SAFIRE for head CT because previous studies have employed fixed tube currents of 320-340 mAs for FBP.[8,12,18] Second, the 3-mm slice thickness for the SAFIRE datasets may also have contributed to an underestimation of the achievable dose reduction with respect to 5-mm FBP datasets as described previously. The reduced posterior fossa artifact for the SAFIRE datasets may be attributable in part to the narrower slice thickness, given the expected reduction in partial volume averaging through the skull base. Third, routine-dose datasets (300 mAs) could not be reconstructed with SAFIRE to assess image quality at a fixed tube current because of the retrospective study design. Despite this limitation, measures of image quality with SAFIRE would likely be improved at higher radiation doses. Similarly, reduced-dose datasets were not reconstructed with FBP, but would likely have been noisier than the routine-dose scans with FBP reconstruction and reduced-dose scans with SAFIRE. Fourth, the characteristic appearance of SAFIRE images may have limited reader blinding for the qualitative CT dataset analysis,[13] which would also benefit from a larger sample size. Finally, the diagnostic accuracy of SAFIRE in the clinical setting was not assessed because this study focused on the characterization of image quality.

In conclusion, SAFIRE for noncontrast adult head CT reduces patient radiation dose by 15% for the scanner settings employed at our institution. Additional dose reduction is likely achievable given the significant improvements in SNR, CNR, and multiple qualitative measures of image quality with reduced-dose SAFIRE. Further research is also required to validate the technique for multiple head and neck applications. Future advances may also facilitate adoption of this technique into more computationally demanding applications such as CT brain perfusion imaging for acute ischemic stroke.

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