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DIAGNOSTIC NEURORADIOLOGY

Adaptive statistical iterative reconstruction reduces patient radiation dose in neuroradiology CT studies

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Abstract
Introduction Adaptive statistical iterative reconstruction (ASIR) can decrease image noise, thereby generating CT images of comparable diagnostic quality with less radiation. The purpose of this study is to quantify the effect of systematic use of ASIR versus filtered back projection (FBP) for neuroradiology CT protocols on patients' radiation dose and image quality.
Methods We evaluated the effect of ASIR on six types of neuroradiologic CT studies: adult and pediatric unenhanced head CT, adult cervical spine CT, adult cervical and intracranial CT angiography, adult soft tissue neck CT with contrast, and adult lumbar spine CT. For each type of CT study, two groups of 100 consecutive studies were retrospectively reviewed: 100 studies performed with FBP and 100 studies performed with ASIR/FBP blending factor of 40 %/60 % with appropriate noise indices. The weighted volume CT dose index ($CTDI_{vol}$), dose–length product (DLP) and noise were recorded. Each study was also reviewed for image quality by two reviewers. Continuous and categorical variables were compared by *t* test and free permutation test, respectively.
Results For adult unenhanced brain CT, CT cervical myelography, cervical and intracranial CT angiography and lumbar spine CT both $CTDI_{vol}$ and DLP were lowered by up to 10.9 % ($p<0.001$), 17.9 % ($p=0.005$), 20.9 % ($p<0.001$), and 21.7 % ($p=0.001$), respectively, by using ASIR compared with FBP alone. Image quality and noise were similar for both FBP and ASIR.
Conclusion We recommend routine use of iterative reconstruction for neuroradiology CT examinations because this approach affords a significant dose reduction while preserving image quality.

Keywords Computer tomography · Iterative reconstruction · Image quality · Radiation dose · Neuroradiology

Abbreviations

ASIR	Adaptive statistical iterative reconstruction
$CTDI_{vol}$	Weighted volume CT dose index
DLP	Dose–length product
FBP	Filtered back projection
NI	Noise index

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Introduction

Dose reduction in CT imaging has become a top priority because of concerns over the risks related to ionizing radiation [1, 2]. CT manufacturers have developed various techniques, including dose modulation, which have proven to be helpful in reducing patient dose [3]. As compared to conventional filtered back projection technique, iterative image reconstruction methods promise to drastically reduce image noise and artifacts, thereby allowing significant dose reduction. Adaptive statistical iterative reconstruction, or ASIR, is able to correct image data by modeling the photon statistics in X-ray attenuation. High levels of ASIR processing create a smooth image texture and noise characteristics unfamiliar to radiologists. In clinical practice, one can use variably blended images created with combined filtered back projection and ASIR techniques to produce different levels of ASIR. To date, the effect of implementing ASIR has been evaluated mostly for individual CT imaging protocols [4–7], and few studies evaluated the overall effect of its systematic use within a radiology department or section [8]. Thus, our goal was to retrospectively quantify the effect of systematic use of ASIR for neuroradiology CT protocols on patient dose and image quality.

Methods

Study design and imaging protocols

The Institutional Review Board approved this retrospective study, in compliance with the Health Insurance Portability and Accountability Act, with a waiver of consent. At our institution, all our CT imaging protocols include dose modulation. During CT acquisition, a computer algorithm alters the tube current applied to each CT section on the basis of a preset noise index. The noise index (NI) is a parameter indicative of the level of image noise considered to be acceptable to the radiologist for a given CT examination. A lower noise index translates into lower noise and thus into an improved signal-to-noise ratio. However, a lower noise index requires higher tube current for a given pitch and tube rotation time and therefore delivers higher patient radiation dose.

ASIR was introduced in October 2011 on our 64-section CT scanner (Lightspeed VCT; General Eelectric Healthcare, Milwaukee, WI, USA). With ASIR, CT exams set to higher NI can yield images of comparable diagnostic image quality to that of studies without ASIR. Establishment of acceptable values for the NI with ASIR in our institution was accomplished over a 3-month period (from October 2011 to December 2011) by subjective review and consensus amongst the faculty in our neuroradiology division. The initial NI selected was that typically used for studies without ASIR. NI was increased by one unit compared to the value usually used for the corresponding protocol without ASIR. Image sets with all possible ASIR factors—10 %, 20 %, 30 %, 40 %, 50 %, 60 %,70 %, 100 % (ASIR/filtered back projection blending values of 10 %/90 %, 20 %/80 %, 30 %/70 %, 40 %/60 %, 50 %/50 %, 60 %/40 %, 70 %/30 %, 80 %/20 %, 90 %/10 %, 100 %/0 %). If at least one of these image datasets yielded an acceptable image quality comparable to that of images without ASIR, then the noise index was increased by one more unit, and the same process was repeated (NI gradually increased) until the image quality was deemed to be inferior to that of images without ASIR. In the latter situation, independently of the ASIR factor used, then the NI was brought back down one unit. This became the new,

Table 1 Imaging protocols

Parameters	Unenhanced head CT in adult patients		Unenhanced head CT in pediatric patients		CT myelography of the cervical spine in adult patients		Cervical and intracranial CT angiography in adult patients		Soft tissue neck CT in adult patients		CT of the lumbar spine in adult patients	
	No ASIR	ASIR	No ASIR	ASIR	No ASIR	ASIR	No ASIR	ASIR	No ASIR	ASIR	No ASIR	ASIR
Detector configuration[a]	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625	64×0.625
Slice thickness (mm)	2.5	2.5	2.5	2.5	1.25	1.25	0.625	0.625	2.5	2.5	2.5	2.5
Reconstruction interval (mm)	2.5	2.5	2.5	2.5	0.625	0.625	0.375	0.375	2	2	2	2
Pitch	0.984:1	0.984:1	0.984:1	0.984:1	1.375:1	1.375:1	0.984:1	0.984:1	1.375:1	1.375:1	1.375:1	1.375:1
Rotation time (s)	1	1	1	1	0.8	0.8	0.5	0.5	0.8	0.8	0.8	0.8
Peak voltage (kVp)	120	120	80	80	120	120	120	120	120	120	140	140
Noise index	4	5	100	100	12	17	4	5	9	16	12	17
Minimal tube current (mA)	100	100	30	30	100	100	200	200	100	100	150	150
Maximal tube current (mA)	350	350	300	300	200	200	350	350	200	200	250	250
ASIR factor	–	40 %	–	40 %	–	40 %	–	40 %	–	40 %	–	40 %

[a] Number of sections×section thickness in millimeters

Table 2 Radiation dose for unenhanced head CT in adult patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	164.8±11.8 (130.0–197.5)	166.8±14.8 (135.0–235.0)	+1.2 % (−1.1 %, +3.5 %) [0.292]
$CTDI_{vol}$ (mGy)	64.1±6.8 (26.1–85.1)	57.1±7.2 (38.5–82.5)	−10.9 % (−14.0 %, −7.9 %) [<0.001]
DLP (mGy×cm)	1,330.2±140.0 (549.5–1,663.6)	1,190.9±145.4 (696.5–1,657.8)	−10.5 % (−13.5 %, −7.5 %) [<0.001]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t*-test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

"ASIR protocol" noise index. The ASIR factor that yielded the best image quality was also recorded and implemented as part of the "ASIR protocol".

We retrospectively evaluated our six most frequent types of neuroradiologic CT studies: unenhanced head CT in adult and pediatric patients, cervical spine CT myelography in adult patients, CT angiography of the cervical and intracranial vessels in adult patients, neck soft tissue CT in adult patients, and lumbar spine CT studies in adult patients (Table 1). For each type of CT study, we included two groups of 100 consecutive patients each: The first group underwent CT with a 64-section CT scanner with *x*–*y*–*z* dose modulation before the introduction of ASIR (using filtered back projection only), and the second group with the same setup after introduction of ASIR and calibration of the CT protocols using the process described above (also with *x*–*y*–*z* dose modulation). Patient demographic data were recorded. The CT studies performed during the two periods of NI adjustment—October 2011 through December 2011 (3 months of practice before enrollment of patients in the second group)—were not included in the present study. The in-plane resolution (field of view and matrix) for each type of CT study was kept the same for the two groups of patients.

Radiation dose

Radiation dose to the patient was calculated for each study by means of the two standard dose indicators—volume CT dose index ($CTDI_{vol}$) and dose–length product (DLP)—that were calculated by the CT scanner for each CT study and automatically saved to a dose report onto our picture archiving and communication system. The $CTDI_{vol}$ parameter is representative of the average dose delivered within the reconstructed section. The $CTDI_{vol}$ represents the weighted CT dose index divided by the pitch and describes the average dose throughout a 160-mm-diameter circular Plexiglas phantom, incorporating the central dose weighted by a 1/3 factor and the peripheral dose weighted by a 2/3 factor. The DLP can be related to energy imparted to organs and can thus be used to assess the overall radiation burden of a given examination. It is equal to the product of the $CTDI_{vol}$ and the length of the scan in centimeters [9].

Image analysis

For each patient group and study type, quantitative image noise and subjective image quality were evaluated. Quantitative noise was determined by using a previously reported method [3, 10]: the standard deviation of the CT attenuation in a 100-200-mm^2 region of interest that was drawn in the background defined as the air surrounding the patient, as far as possible from the patient. For the lumbar spine studies, air was not included in the majority of the images; therefore, noise was recorded in fat in the posterior pararenal space, avoiding vascular structures.

Table 3 Radiation dose for unenhanced head CT in pediatric patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	146.0±18.8 (94.5–242.5)	150.5±23.1 (97.5–290.0)	+3.1 % (−1.0 %, +7.1 %) [0.135]
$CTDI_{vol}$ (mGy)	42.2±18.3 (3.5–71.5)	40.9±11.6 (14.0–57.9)	−3.2 % (−13.3 %, +6.9 %) [0.528]
DLP (mGy×cm)	816.4±389.6 (62.8–1904.5)	807.5±267.4 (201.1–1287.2)	−1.1 % (−12.5 %, +10.3 %) [0.851]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t* test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

Table 4 Radiation dose for CT myelography of the cervical spine in adult patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	169.4±36.9 (116.3–484.0)	186.0±19.8 (153.8–210.6)	+9.8 % (−5.7 %, +25.3 %) [0.212]
$CTDI_{vol}$ (mGy)	11.8±4.3 (6.0–29.2)	9.7±4.0 (5.3–33.2)	−17.9 % (−27.7 %, −8.0 %) [<0.001]
DLP (mGy×cm)	270.8±100.1 (137.0–673.5)	231.1±99.2 (117.8–826.8)	−14.7 % (−24.9 %, −4.4 %) [0.005]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t* test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

Two neuroradiologists (D.O. and C.L.S.) reviewed all the CT studies for image quality in a random order. The reviewers were blinded as to whether or not ASIR had been utilized. The studies were graded by using a five-point Likert scale on a variety of criteria (a score of 1 indicated that the study was unacceptable; a score of 3, that the study was average but diagnostic; and a score of 5, that the study was excellent). Grading addressed the ability to define low-contrast (such as gray/white matter and basal ganglia differentiation and thyroid texture) and high-contrast structures (such as cortical bone definition) and the sharpness of tissue interfaces. This grading system is similar to those utilized in previous studies (Tables E1–E5, Supplemental Material) [3].

Statistical analyses

For each type of CT study, differences between the two groups of patients in terms of demographic data, radiation dose descriptors, image quality, and noise were evaluated for statistical significance (stat 9.2; StataCorp, College Station, Texas 77845 USA). Unpaired *t* tests were used to compare continuous variables between groups; the statistical significance level was set at 0.05. The Likert image analysis scores for the different image quality assessments were analyzed separately by way of paired distribution free permutation tests and by way of two-sample distribution free permutation tests. The paired permutation tests were utilized to conduct inter-reader comparisons, while the two-sample permutation tests were utilized to conduct intra-reader image comparisons of image studies without versus with ASIR. With regard to hypothesis testing, a two-sided Bonferroni $p \leq 0.05$ decision rule was utilized as the null hypothesis rejection criterion so that simultaneous statements of statistical inference could be made across reader and across imaging method.

Results

Study patients

There were no significant demographic differences between the two groups of patients imaged with and without ASIR (Table E6, Supplemental Material). This was true for the six types of CT studies that were assessed.

Imaging studies

For all six types of CT studies, application of ASIR allowed the noise index to increase by one unit or more. For all six types of CT studies, the final ASIR factor that was preferred by the neuroradiology faculty and was selected for the "ASIR protocol" was 40 %, which means a blending of 40 % of ASIR and 60 % of filtered back projection. ASIR factors higher than 40 % yielded images that were deemed too glazy by the

Table 5 Radiation dose for cervical and intracranial CT angiography in adult patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	356.2±45.5 (160.0–435.8)	360.8±38.9 (107.3–445.5)	+1.3 % (−2.0 %, +4.6 %) [0.441]
$CTDI_{vol}$ (mGy)	14.9±11.2 (10.0–67.7)	10.7±2.7 (9.3–28.8)	−28.0 % (−43.2 %, −12.7 %) [<0.001]
DLP (mGy×cm)	574.2±299.4 (60.7–2,539.1)	454.3±105.4 (343.6–1,140.2)	−20.9 % (−31.8 %, −10.0 %) [<0.001]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t* test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

Table 6 Radiation dose for soft tissue neck CT in adult patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	243.4±33.0 (108.0–306.0)	255.3±48.3 (122.5–404.0)	+4.9 % (−0.2 %, +10.0 %) [0.062]
$CTDI_{vol}$ (mGy)	11.5±5.4 (5.9–35.1)	10.3±6.2 (5.5–39.1)	−10.5 % (−26.0 %, +5.0 %) [0.184]
DLP (mGy×cm)	342.8±140.2 (136.6–981.3)	316.6±160.4 (136.9–911.1)	−7.6 % (−21.2 %, +5.9 %) [0.268]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t* test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

neuroradiology faculty and perception of anatomical and pathological structures were inferior compared to that of images obtained without ASIR.

Radiation dose

Radiation doses for the different imaging protocols are reported in Tables 2, 3, 4, 5, 6, and 7. When ASIR was used, both $CTDI_{vol}$ and DLP were lowered by up to 10.9 % ($p<0.001$), 17.9 % ($p=0.005$), 20.9 % ($p<0.001$), and 21.7 % ($p=0.001$) for unenhanced head CT in adults (Table 2), CT myelography of the cervical spine in adult patients (Table 4), cervical and intracranial CT angiography in adult patients (Table 5), and CT of the lumbar spine in adult patients (Table 7), respectively, which was statistically significant. Regarding pediatric unenhanced head CT (Table 3) and soft tissue neck CT in adult patients (Table 6), $CTDI_{vol}$ and DLP were lowered by up to 3.2 % ($p=0.851$) and 10.5 % ($p=0.268$), respectively, when ASIR was used, but the difference failed to reach statistical significance.

Image quality and noise

Image noise was significantly lower with ASIR than image noise without ASIR for unenhanced head CT in adult and pediatric patients. The image noise was not affected by the use of ASIR in the remainder of the studies (Tables E7). Image quality between studies performed with and without ASIR was overall similar, as assessed by the two reviewers (Tables E8–E13 and Fig. 1). According to one reviewer, the cortical bone definition (high-contrast feature) was decreased with ASIR for unenhanced head CT in adult and pediatric patients (Table E8-9) and CT myelography of the cervical spine in adult patients (Table E10), however, none of these were noted across both reviewers. Irrespective of the imaging method, the mean of the distribution of the Likert image quality scores differed from reader to reader in the majority of studies with Reader #1 having a tendency to rate image quality lower than Reader #2 (Tables E8–E13).

Discussion

At our institution, application of ASIR for all six types of neuroradiology CT studies allowed us to maintain image quality and increase noise index by at least one unit which translated into significant dose savings in four of the six types of neuroradiology CT studies, including unenhanced adult head CT, adult cervical and lumbar CT myelography, and adult cervical and intracranial CT angiography. The application of ASIR was achieved by rendering an ASIR factor of 40 % (a blend of 40 % ASIR and 60 % filtered back projection); the optimal value for our neuroradiology CT studies by consensus judgment. Higher ASIR factors may provide further radiation dose savings by allowing higher noise index, however, lend the images a

Table 7 Radiation dose for CT of the lumbar spine in adult patients

Parameter	No ASIR[a]	ASIR[a]	ASIR vs. no ASIR[b]
Scan range (mm)	269.0±82.3 (31.5–640.0)	278.8±64.3 (200.0–596.0)	+3.6 % (−4.0 %, +11.3 %) [0.353]
$CTDI_{vol}$ (mGy)	22.6±8.2 (8.2–47.4)	18.0±6.3 (10.0–40.9)	−20.4 % (−29.4 %, −11.4 %) [<0.001]
DLP (mGy×cm)	779.3±395.0 (366.5–2,462.0)	609.9±316.5 (−452.8–2332.1)	−21.7 % (−34.6 %, −8.9 %) [0.001]

[a] Data are means ± standard deviations, with ranges in parentheses

[b] Data are relative differences expressed as percentages, with 95 % confidence intervals (also expressed as percentages) in parentheses and *p* values in square brackets as assessed with unpaired *t* test. Relative difference for comparing ASIR vs. no ASIR protocols was calculated as the absolute value for the ASIR protocol minus the absolute value for the no ASIR protocol, with this difference then divided by the absolute value for the no ASIR protocol. Absolute values are shown in the first two columns of the table

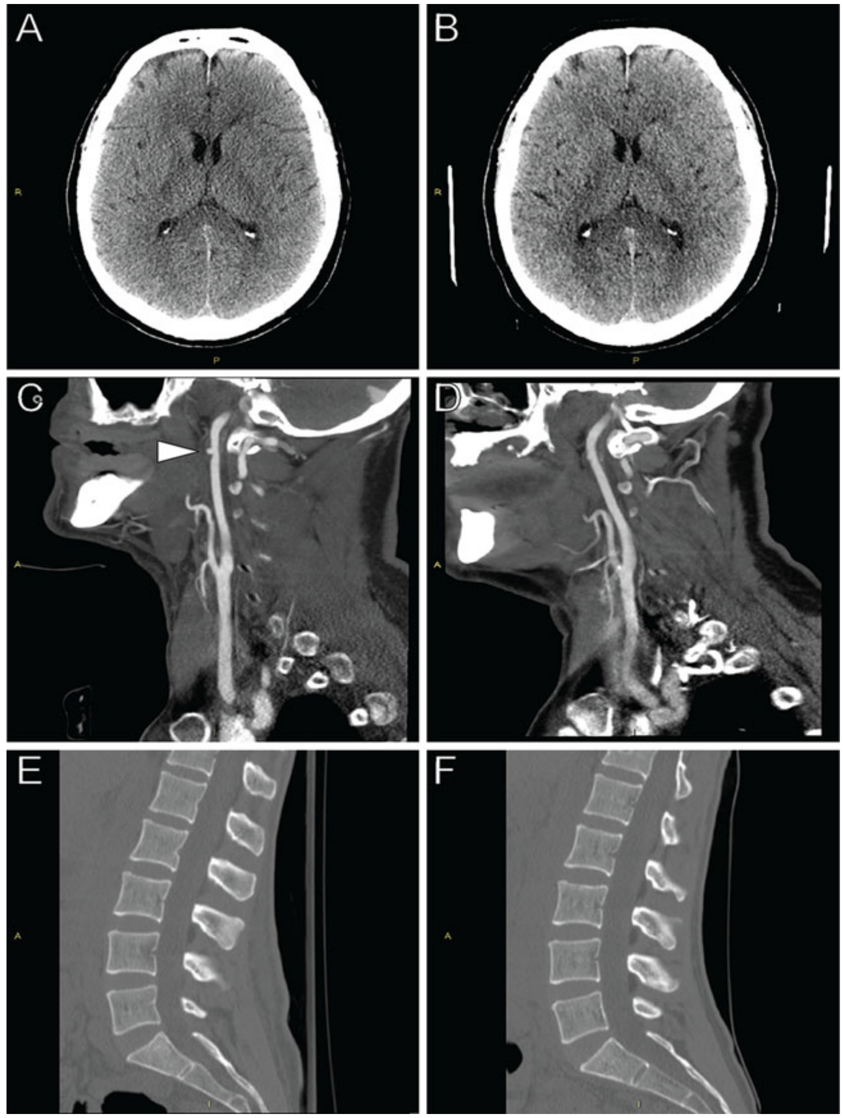

Fig. 1 Representative adult unenhanced head CT (**a** and **b**), cervical CT angiography (**c** and **d**), and lumbar spine CT sagittal reformatted images (**e** and **f**) obtained from the same patients without (**a**, **c**, **e**) and with use of ASIR (**b**, **d**, **f**). *Arrowhead* on *panel* **c** denotes traumatic pseudoaneurysm that has partially resolved on the subsequent study (**d**)

shinier, more glazed appearance. The "amount" of ASIR applied is a matter of personal choice and each institution has to find the optimal ASIR factor for their daily interpretation of neuroradiology CT studies. Our study supports the routine use of ASIR for neuroradiology CT examinations.

The degree of radiation dose reduction varied significantly amongst study types: one end of the spectrum was 28 % dose reduction for adult intracranial and cervical CT angiography with no significant dose reduction for pediatric head CTs at the other end of the spectrum. The reason for this difference between study types may be related to the fact that lower tube current was already used in pediatric studies before implementation of ASIR, resulting into a smaller margin of potential improvement with ASIR. Interestingly, the quantitative image noise was reduced by ASIR for pediatric head CT examinations as compared to images without ASIR. This may indicate that in the search for the optimal ASIR factor and noise index, improved image quality may have been preferred over a more aggressive dose reduction.

We used multiple criteria, including assessment of low and high-contrast anatomical and pathological structures/features for each type of neuroradiology study to assess diagnostic utility and found that the image quality was overall equivalent between studies performed with and without ASIR. In two types of studies, however, the high-contrast imaging criteria evaluated, namely the cortical bone definition, was less with ASIR compared to FBP alone. Differences between absolute quality score values with ASIR and without ASIR did not appear clinically relevant, but were statistically significant because of the large sample size. Nevertheless, the potential for a diminished high-contrast definition with ASIR is a potential pitfall that needs to be considered.

There were limitations to our study. First, ASIR yields images with a shinier appearance than with FBP, possibly compromising our ability to blind the reviewers. Furthermore, because our study was performed with CT scanners from one manufacturer only, our results need to be confirmed in studies that evaluate CT scanners from other vendors. Also, we did not investigate the effect of iterative reconstruction on all our CT protocols, but rather limited our evaluation to the types of CT studies most frequently performed in our division. Although the ideal study design to assess the effect of ASIR on imaging parameters would be to perform regular imaging on the same subjects while varying the noise index and ASIR factor, this approach cannot be utilized secondary to ethical concerns.

In conclusion, we recommend routine use of iterative reconstruction for neuroradiology CT examinations, because this approach affords a significant dose reduction while preserving image quality. Implementation of iterative reconstruction requires a fine-tuning process to identify optimal blend between iterative reconstruction and filtered back projection for each type of CT study performed.

Conclusions

Routine use of iterative reconstruction is recommended for neuroradiology CT examinations, because this approach affords a significant dose reduction while preserving image quality.

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Conflict of interest We declare that we have no conflict of interest.

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