

Adaptive Statistical Iterative Reconstruction: Assessment of Image Noise and Image Quality in Coronary CT Angiography

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OBJECTIVE. The purpose of our study was to determine the effect of Adaptive Statistical Iterative Reconstruction (ASIR) on cardiac CT angiography (CTA) signal, noise, and image quality.

MATERIALS AND METHODS. We evaluated 62 consecutive patients at three sites who underwent clinically indicated cardiac CTA using an ASIR-capable 64-MDCT scanner and a low-dose cardiac CTA technique. Studies were reconstructed using filtered back projection (FBP), ASIR–FBP composites using 20–80% ASIR, and 100% ASIR. The signal and noise were measured in the aortic root and each of the four coronary arteries. Two blinded readers graded image quality on a 5-point Likert scale and determined the proportion of interpretable segments. All segments were included for analysis regardless of size.

RESULTS. In comparison with FBP (0% ASIR), the use of 20%, 40%, 60%, 80%, and 100% ASIR resulted in reduced image noise between groups (–7%, –17%, –26%, –35%, and –43%, respectively; $p < 0.001$) without difference in signal ($p = 0.60$). There were significant differences between groups (0%, 20%, 40%, 60%, 80%, and 100% ASIR) in the Likert scores (1.5, 2.1, 3.7, 3.8, 2.0, and 1.1, respectively; $p < 0.001$) and proportion of interpretable segments (88.7%, 89.3%, 90.5%, 90.4%, 88.0%, and 87.3%, respectively; $p < 0.001$). Reconstruction using 40% and 60% ASIR had the highest Likert scores and largest proportion of interpretable segments. In comparison with FBP, each was associated with higher Likert scores and increased interpretable segments ($p < 0.001$ for all).

CONCLUSION. ASIR resulted in noise reduction and significantly impacted image quality. When using a low tube current technique, cardiac CTA reconstruction using 40% or 60% ASIR significantly improved image quality and the proportion of interpretable segments compared with FBP reconstruction.

Coronary CT angiography (CTA) is well established in the evaluation of coronary artery disease [1–4]. Current limitations of coronary CTA include image noise and radiation dose. The recently published International Prospective Multicenter Study on Radiation Dose Estimates of Cardiac CT Angiography I (PROTECTION 1) [5] reported an effective radiation dose range of 8–18 mSv using standard 64-MDCT coronary CTA. As a result, a number of techniques and strategies have become available on newer CT platforms to enable dose reduction in coronary CT. These include sequential or prospective ECG triggering [6], reduced tube voltage scanning [7–9], and high-pitch helical scanning [10].

Recently, iterative reconstruction (Adaptive Statistical Iterative Reconstruction [ASIR],

GE Healthcare) has been introduced as a new reconstruction algorithm [11–14]. In comparison with filtered back projection (FBP), ASIR reduces image noise by iteratively comparing the acquired image to a modeled projection. This reconstruction algorithm is used to help deal with one of the primary issues of dose and tube current reduction for coronary CTA with FBP: increased image noise with decreased tube current. Although ASIR has been shown to reduce noise and improve image quality, permitting reduction in radiation dose in body CT [12], it has not been formally evaluated in coronary CTA.

Our hypothesis was that ASIR would reduce image noise and improve study quality and the proportion of interpretable segments when a low effective radiation dose and low tube current technique was used. Because image reconstruction can be performed using

both FBP and ASIR, we additionally sought to determine the optimal combination of ASIR and FBP.

Materials and Methods

This study retrospectively evaluated a consecutive series of patients who underwent coronary CTA studies at three sites. Inclusion criteria included adult patients (≥ 18 years) and studies limited to the heart. All studies were evaluated regardless of baseline heart rate or heart rhythm. Where applicable, sites were compliant with HIPAA. The study was approved by the institutional review board at each site.

The image reconstruction process on ASIR-capable scanners allows a mixture of FBP and ASIR images with adjustable increments ranging from 0% to 100%. Images with 0% ASIR represent reconstruction with FBP only, images with 1–99% ASIR represent a composite of ASIR with the inverse proportion using FBP, and 100% ASIR represents reconstruction with ASIR only. For example, 40% ASIR represents reconstruction with 40% ASIR and 60% FBP.

Our study cohort was 62 consecutive patients studied at the three participating sites. All patients who underwent coronary CTA were included over the period assessed were included. All studies were reconstructed using ASIR ranging from 0% to 100% in 20% increments: 0% (FBP only); 20%, 40%, 60%, and 80% (composite ASIR and FBP); and 100% (ASIR only). Reconstructions were performed during postprocessing from the original data set using the scanner terminal. Radiation dose for coronary CTA was determined by the dose-length product, and this was converted to mSv by multiplying by the conversion factor of $0.014 \text{ mSv} \times \text{mGy}^{-1} \times \text{cm}^{-1}$ [15].

Coronary CTA Acquisition

Patients received oral or IV β -blockers if needed to achieve a heart rate lower than 65 beats per minute, and were given 0.4 mg sublingual nitroglycerin immediately before the study, assuming no contraindications. All examinations were performed on the Discovery HD 750 scanner (GE Healthcare). Two sites used a triple-phase contrast protocol injected at a rate of 5–5.5 mL/s: 60 mL iodixanol (Visipaque, GE Healthcare) followed by 75 mL of a 50:50 mixture of iodixanol and saline and then a 50-mL saline flush; one site used a dual-phase protocol with 75 mL iodixanol followed by a 50-mL saline flush. A Medrad Stellant injector (Siemens Healthcare) was used for contrast injection. The scanning parameters included a rotation time of 350 milliseconds; $64 \times 0.625 \text{ mm}$ collimation; tube voltage, 100–120 kV; and 275–800 mA. Patients were preferentially scanned with

prospective triggering, and ECG-based dose modulation was used for all retrospectively gated studies. Although the scanning parameters were set on a patient-by-patient basis and at the discretion of the individual site, sites were aware of the potential of ASIR-enabled tube current reduction and parameters were set with the principle of as low as reasonably achievable (ALARA) in mind.

Quantitative Analysis

The signal and noise were measured in the aortic root and in the proximal portion of each of the four coronary arteries by a single reader. The aortic root was examined at the level of the left main coronary artery on an axial image using a 1.0-cm^2 region of interest to measure the Hounsfield-unit mean value (signal) and SD (noise); measurements using the largest possible region of interest were similarly made using axial images of the proximal left main, left anterior descending, left circumflex, and right coronary arteries. An automated tool was used to ensure that all measurements were performed in precisely the same location for all of the reconstructions on the PACS viewer (Inteleviewer, Intelepacs). To do this, the six reconstructions were viewed simultaneously in a row and an automated linked scroll function was used to ensure that all images were at the same level. The PACS system used provides coordinates when placing a region of interest Hounsfield-unit measurement and the exact coordinates provided were used for all of the ASIR reconstructions. The mean of the aorta and four coronary arteries was used to define the study signal, noise, and signal-to-noise ratio (SNR) for all patients (Fig. 1).

Qualitative Analysis

Qualitative image analysis was performed by two independent blinded and experienced coronary CTA readers (each with 5 years of coronary CTA experience) at a different time than the quantitative noise measurements. The 62 datasets were reconstructed with six reconstructions: FBP, composite ASIR and FBP, and ASIR. All of the reconstructed data sets were deidentified without any designation of the percentage ASIR used for reconstruction. Data sets were reviewed on an AW 4.4 Advantage Workstation (GE Healthcare).

Each reader reviewed all of the images for all reconstructions in a random and varied order. The use of axial data sets, maximum intensity projections, curved multiplanar reformats, and other postprocessing tools was left to the discretion of each reader. After blinded review of all of the data sets, each reader then assigned a Likert score for each data set on the basis of preferred image quality, with the focus on image noise, coronary wall definition, and low contrast resolution. The read-

ers were instructed to ignore issues, such as motion and poor gating, that could not be ascribed to the reconstruction algorithm.

Image noise, image quality, low contrast resolution, and spatial resolution were all evaluated with a single grade on a 5-point scale ranging from 1 (worst) to 5 (best) assigned on the basis of the worst segment. The scores assigned were relative to the other ASIR reconstructions after the review of all of the data sets with the reader blinded to the reconstruction technique. The mean value of the Likert scores from the two readers was used for analysis.

The Likert scale was defined as 1: poor, impaired image quality limited by excessive noise or poor vessel wall definition; 2: adequate, reduced image quality with poor vessel wall definition or excessive image noise, limitations in low contrast resolution remain evident; 3: good, impact of image noise, limitations of low contrast resolution and vessel margin definition are minimal; 4: very good, good attenuation of vessel lumen and delineation of vessel walls, relative image noise is minimal, coronary wall definition and low contrast resolution well maintained; and 5: excellent, excellent attenuation of the vessel lumen and clear delineation of the vessel walls, limited perceived image noise.

In addition, study interpretability was assessed. Both readers were blinded to the percentage of ASIR used for image reconstruction. Each reported the proportion of segments that were deemed interpretable for each study compared with the number of existing segments. Studies were evaluated using a standard 17-segment model [16]. Importantly, all segments present were included regardless of size. A third blinded reader with 3 years of coronary CTA experience was used to achieve consensus for any segments with discordance. Diagnostic study quality was graded at a per-segment level with a segment deemed diagnostic if it could be assessed for the presence and degree of stenosis.

Statistical Analysis

It was of interest to determine if signal, noise, SNR, proportion of interpretable segments, or study quality by the Likert scale differed by percentage of ASIR used in reconstruction (0%, 20%, 40%, 60%, 80%, and 100%). Because each patient examination received multiple levels of ASIR reconstruction, a mixed-model analysis was conducted to account for repeated observations within patients. Because 40% and 60% ASIR had the highest image quality as defined by both proportion of interpretable segments and qualitative Likert scale, additional comparisons were performed between FBP and 40% ASIR and between FBP and 60% ASIR.

Repeated measures analysis of variance was conducted separately for each outcome (signal, noise,

Effect of ASIR on Coronary CT Angiography

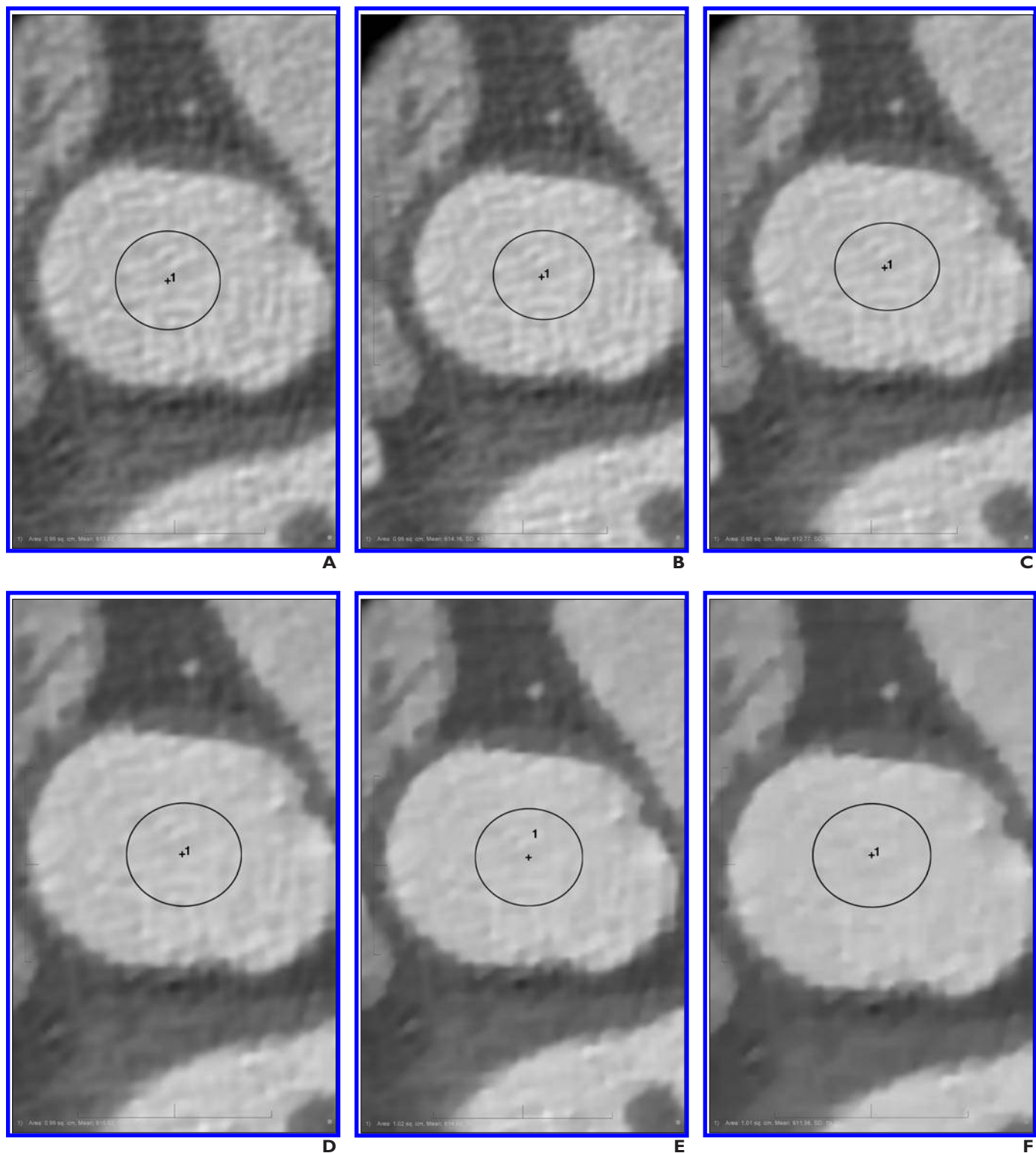


Fig. 1—58-year-old woman with atypical chest pain.

A–F, Transaxial CT angiography images of ascending aorta (window width, 1,540; window level, 142) reconstructed using increasing increments of adaptive statistical iterative reconstruction (ASIR) (GE Healthcare): 0% (filtered back projection) (**A**), 20% (**B**), 40% (**C**), 60% (**D**), 80% (**E**), and 100% (**F**). Images show linear decrease in image noise with increasing increments of ASIR, with noise measurements of 57.0 (**A**), 43.7 (**B**), 36.1 (**C**), 30.5 (**D**), 24.7 (**E**), and 19.8 (**F**), respectively.

SNR, proportion of interpretable segments, and image quality) against the percentage of ASIR. A 0.05 significance level was used for all repeated measures and analysis, and a Tukey's multiple comparison correction test was used to look at pairwise differences between percentages of ASIR. SAS version 9.2 statistical software was used for all analyses.

Results

The mean age of the 62 patients at our three sites was 57.5 years (age range, 29–81 years), 60% were men and 40% were women, and the mean body mass index (BMI) was $24.2 \pm 9.6 \text{ kg/m}^2$. Of the 62 examinations 51 (82%) were performed with prospective ECG-triggering (axial scanning) and 11 (18%) with retrospectively gated helical acquisitions. The median effective radiation dose was 2.0 mSv

(interquartile range, 1.1–4.0 mSv). The median dose for the 51 prospectively triggered studies was 1.4 mSv (total range, 0.48–5.0 mSv) and for the retrospectively gated studies, the median effective dose was 12.0 mSv (total range, 5.0–16.4 mSv).

Signal and Noise

An increased percentage of ASIR was associated with a linear reduction in noise, no change in signal, and a linear improvement in SNR (Table 1). In comparison with FBP (0% ASIR), the mean noise reduction was 7%, 17%, 26%, 35%, and 43% for reconstructions with 20%, 40%, 60%, 80%, and 100% ASIR, respectively (Fig. 1). Thus, as the percentage of ASIR increases the noise significantly decreases, with 100% ASIR giving the greatest noise reduction.

The use of 40% or 60% ASIR was associated with a significant reduction in noise when directly compared with FBP ($p < 0.001$ for each).

There was no significant difference in the mean signal between groups. In comparison with FBP, the signal of images using 40% and 60% ASIR was similar ($p = 0.49$). There was a significant increase in the SNR with increased use of ASIR. In comparison with FBP, there was a mean increase in SNR of 8%, 21%, 36%, 58%, and 81% for reconstructions using 20%, 40%, 60%, 80%, and 100% ASIR, respectively. The use of 40% or 60% ASIR was associated with a statistically significant increase in the ratio when compared with FBP ($p < 0.001$ for each).

Further analyses were also performed evaluating the impact of ASIR on patients

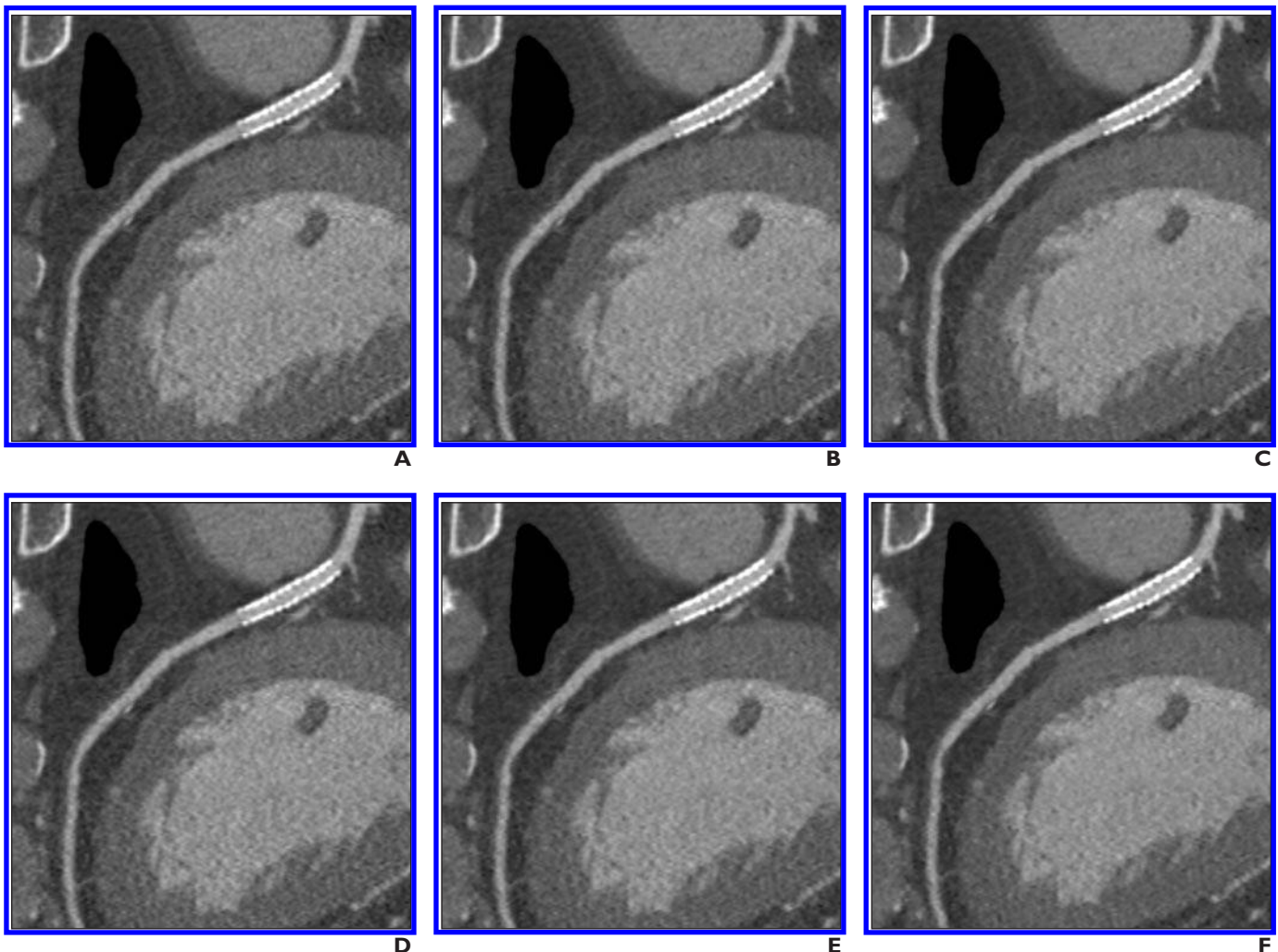


Fig. 2—Multiplanar reformation images of left anterior descending artery reconstructed with increasing percentage of adaptive statistical iterative reconstruction (ASIR) (GE Healthcare) in 52-year-old man with recurrent chest pain after coronary artery stenting. **A–F**, Images have been reconstructed in 20% increments of ASIR: 0% (**A**), 20% (**B**), 40% (**C**), 60% (**D**), 80% (**E**), and 100% (**F**). Note progressive decrease in image noise with increasing ASIR but also blurring of vessel margin of 100% ASIR reconstruction referred to as having “plastic” appearance by one reader.

TABLE 1: Scanning Variables by Percentage Adaptive Statistical Iterative Reconstruction (ASIR)^a Used for Reconstruction

Variable	Percentage ASIR Used for Image Reconstruction						<i>p</i>
	0%	20%	40%	60%	80%	100%	
Signal (HU)	394.2±142.4	392.4±194.2	392.6±193.4	391.0±193.2	398.0±201.1	388.5±192.3	0.60
Noise (HU)	36.2±20.4	33.6±19.2	30.2±17.2	26.7±15.6	23.6±14.1	20.5±12.5	<0.001
Signal-to-noise ratio	11.8±4.0	12.8±4.4	14.3±5.0	16.1±5.8	18.7±7.1	21.3±8.2	<0.001
Relative quality (Likert scale)	1.5±0.7	2.1±0.9	3.7±1.4	3.8±1.4	2.0±0.83	1.1±0.4	<0.001
Interpretable segments (%)	88.7	89.3	90.5	90.4	88.0	87.3	<0.001

Note—Except where indicated, data are mean ± SD. Variables are provided for varying reconstruction combinations from 0% ASIR (only filtered back projection) to 100% ASIR (only ASIR reconstruction). The *p* value compares differences in the least-square mean between groups.

^aASIR is a product of GE Healthcare.

of varying body habitus. The data were analyzed for patients with BMI less than 25, 25–30, and greater than 30 kg/m². For each BMI subset, there was no difference in signal between ASIR groups (*p* = 0.64, 0.12, 0.20, respectively), with an incremental decrease in noise (*p* < 0.001 for all groupings) and increase in SNR with increased ASIR (*p* < 0.001).

Image Quality

Image quality as assessed by the Likert scale showed a significant difference between groups, with the highest values noted for reconstructions using 40% and 60% ASIR (Table 1). In comparison with FBP, both 40% and 60% ASIR were associated with a statistically significant increase in relative image quality as defined by the Likert scale (*p* < 0.001 for each) (Fig. 2).

Image quality was also assessed by the percentage of segments deemed interpretable on each study by the blinded readers. There was a significant difference between groups in the percentage of interpretable segments, with the highest proportions of interpretable segments observed using 40% and 60% ASIR reconstructions (Table 1). When 40% and 60% reconstructions were compared directly to FBP, each was associated with a significant increase in per-segment interpretability (*p* < 0.001 for each).

Discussion

Image reconstruction for CT has traditionally been performed using FBP. FBP is fast and mathematically simplistic, thus requiring limited computational power to perform. However, there is a noise penalty that results from the simplicity of reconstruction using FBP [12–14]. Iterative reconstruction is currently used in PET and was used in the early days of CT [14], but until recently it has not

been available for use in modern CT due to its complexity and the computational power required. ASIR, unlike FBP, reconstructs CT data sets by fully modeling the system statistics. The reconstruction process is iterative in nature to overcome the mathematic complexity introduced by the added modeling (Paden et al., presented at the 2008 annual meeting of the Radiological Society of North America) [11–14]. ASIR does not assume that the measured signal is free of noise due to x-ray photon statistics or electronic noise but rather uses more accurate statistical modeling during the reconstruction process [14]. This enables improved noise properties in the reconstructed images, while maintaining spatial resolution and other image quality parameters.

In this study, the use of ASIR resulted in significant noise reduction, no change in signal, and improved SNR. Although the largest reduction in noise was observed with 100% ASIR, reconstruction with 40% and 60% ASIR appeared to provide optimal image quality on the basis of the assessment of the blinded readers. Importantly, in comparison with FBP, reconstructions with 40% or 60% ASIR resulted in improved study quality and interpretability in these low-dose examinations. These findings suggest that ASIR may be useful in patients who would otherwise have significant noise—such as obese patients—and may permit improved imaging of plaque, the arterial lumen, and other structures. This is consistent with the large difference in image quality that was observed, with the mean relative Likert value of 1.3 for FBP reconstructions increasing to 3.7 for 40% ASIR, likely reflecting this significant decrease in image noise and improved SNR.

Furthermore, the noise reduction properties of ASIR may permit the use of lower tube current with stable image noise and quality when compared with FBP using stan-

dard tube current, despite the reduction in absolute photon number. This may represent a valuable method of radiation dose reduction that would be additive to existing dose reduction strategies. Because tube current reduction is related to the square of the noise reduction, our measured 17% noise reduction with 40% ASIR reconstruction would theoretically permit a tube current reduction of approximately 30–40%, resulting in a proportional decrease in the effective radiation dose without altering image noise. Additionally, future versions of iterative reconstruction may further improve the statistical modeling and may provide additional decreases in image noise and radiation dose.

The present findings suggest that imaging with a composite of both FBP and ASIR may be optimal. It is interesting that there was a degradation of qualitative image quality using increased ASIR, with the mean Likert score for 100% ASIR being lower than that for FBP. Reconstructions with high proportions of ASIR are significantly different in appearance from traditional FBP, with a different noise texture and significantly smoothed borders, which was described by one reader as a “plastic” appearance. It is possible that the lack of reader familiarity with the appearance of these images resulted in artificially decreased diagnostic confidence for segment interpretation and lower Likert scores, which could result in incorrectly lower image quality and segment interpretability in these studies. Further study comparing the diagnostic performance and accuracy between these different reconstructions may be warranted.

There are several limitations to our study. First, although blended ASIR–FBP provided superior image quality than FBP, this was in the setting of relatively low-dose and low tube current examinations. The applicability of

these findings for higher effective dose examinations is uncertain. Additionally, although a high proportion of pure ASIR reconstructions were perceived to have lower image quality, this may be due to the large difference in appearance when compared with traditional FBP reconstructions and the lack of reader familiarity with these images.

Furthermore, although the study measured image quality using a defined Likert scale and by assessing segment interpretability, additional study is needed to evaluate the diagnostic performance of reconstructions using varying proportions of ASIR. Finally, our segment interpretability range of 87–91% reflects our inclusion of all segments regardless of size, unlike most published studies that have limited evaluable coronary segments to those of 1.5 mm or larger.

In conclusion, ASIR permitted significant noise reduction in clinical coronary CTA examinations, and when a low-dose technique was used 40–60% ASIR improved image quality and segment interpretability in comparison with FBP. ASIR may improve image quality in patients with significant image noise and is promising as a valuable technique to reduce the radiation dose associated with coronary CTA.

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The reader's attention is directed to the related commentary, which begins on page 647, and the related article, titled "Estimated Radiation Dose Reduction Using Adaptive Statistical Iterative Reconstruction in Coronary CT Angiography: The ERASIR Study," which begins on page 655.

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