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Performance of Iterative Image Reconstruction in CT of the Paranasal Sinuses: A Phantom Study

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ABSTRACT

BACKGROUND AND PURPOSE: CT in low dose technique is the criterion standard imaging modality for evaluation of the paranasal sinus. Our aim was to evaluate the dose-reduction potential of a recently available sinogram-affirmed iterative reconstruction technique, regarding noise, image quality, and time duration when evaluating this region.

MATERIALS AND METHODS: CT was performed on a phantom head at different tube voltages (120 kV, 100 kV) and currents (100 mAs, 50 mAs, 25 mAs). Each protocol was reconstructed (in soft tissue and bony kernel) by using standard filtered back-projection and 5 different SAFIRE strengths, and image noise was evaluated. Subjective image quality was evaluated on noise-aligned image triplets acquired at tube currents of 100% (FBP), 50% (SAFIRE), and 25% (SAFIRE) by using a 5-point scale (1 = worst, 5 = best). The time duration for image reconstruction was noted for calculations with FBP and SAFIRE.

RESULTS: SAFIRE reduced image noise by 15%–85%, depending on the iterative strength, rendering kernel, and dose parameters. Noise reduction was stronger at a bone kernel algorithm both in 1- and 3-mm images ($P < .05$). Subjective quality evaluation of the noise-adapted images showed preference for those acquired at 100% tube current with FBP (4.7–5.0) versus 50% dose with SAFIRE (3.4–4.4) versus 25% dose with SAFIRE (2.0–3.1). The time duration for FBP image sets was 2.9–6.6 images per second versus SAFIRE with 0.9–1.6 images per second.

CONCLUSIONS: For CT of the paranasal sinus, SAFIRE algorithms are suitable for image-noise reduction. Because image quality decreases with dosage, careful choice of the appropriate iterative method is necessary to achieve an optimal balance between image noise and quality.

ABBREVIATIONS: CTDI_{vol} = volume CT dose index; FBP = filtered back-projection; IRIS = iterative reconstruction in image space; SAFIRE = sinogram-affirmed iterative reconstruction

CT is the imaging technique of choice for the evaluation of inflammatory disorders of the paranasal sinuses.^{1–3} CT imaging adds valuable information to the clinical diagnosis of rhinosinusitis regarding the extent and severity of inflammation and exquisitely demonstrates anatomy and surgically relevant anatomic variants. Due to a typically younger patient population and the proximity of radiosensitive organs such as the eye lenses and thyroid gland, increased concern is focused on radiation dosage.^{4,5} Given the relatively small diameter of the head in comparison with the trunk and the high intrinsic contrast of the evaluated

structures, CT can be performed with adapted dose parameters—depending on the indication.^{2,6} Reducing the tube current is eventually limited by increased noise leading to a decrease in image quality, however. Recently, iterative reconstruction techniques for CT have been introduced to decrease image noise as an alternative to the standard filtered back-projection method. By decreasing graininess, this technique will be able to reduce the necessary radiation dose 35%–76%, while maintaining equivalent image quality.^{7–9}

A second generation of iterative reconstruction processes, sinogram-affirmed iterative reconstruction, is now commercially available. In brief, SAFIRE estimates the noise content in raw data caused by fluctuations in neighboring voxels and subtracts the noise stepwise in several validation loops. The result of the first correction loop is compared with the “master data,” and an updated image is generated for the next iteration, leading to further noise reduction. In contrast to its predecessor, iterative reconstruction in image space, which performs a single correction loop,

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SAFIRE uses up to 5 repetitive correction loops aimed at further decreasing image noise.

The purpose of this phantom study was to evaluate the noise and image quality of FBP and iterative reconstruction techniques when performing facial CT at different dose levels.

MATERIALS AND METHODS

Data Acquisition and Image Reconstruction

Examinations were performed on a phantom head consisting of a human skull cast in gelatin. For this study, a 128-section CT device (Somatom Definition Flash; Siemens, Erlangen, Germany) was used to examine the phantom head. The scan was performed with a single-source spiral technique with parameters recommended by the manufacturer (collimation, 20×0.6 mm; rotation time, 1 second; pitch value, 1.0; tube current modulation deactivated). Six examinations were conducted with different settings of the tube voltage and current: 120 kV/100 mAs, 120 kV/50 mAs, 120 kV/25 mAs, 100 kV/100 mAs, 100 kV/50 mAs, and 100 kV/25 mAs. Dose measurements were derived from the study protocol as volume CT dose index and dose-length product. The effective dose was measured according to the European guidelines by using a conversion factor of $k = 0.0023$.¹⁰ Image sets were reconstructed in a transverse direction by using bone and soft-tissue reconstruction kernels ("hard kernel" versus "soft kernel") with each section having a thickness of 3 and 1 mm, respectively. SAFIRE software (syngo CT 2011A, VA40; Siemens) allows 5 different reconstruction strengths (I = weakest to V = strongest) controlling the amount of noise suppression. Each dataset was reconstructed in FBP, IRIS, and the 5 different SAFIRE levels, and the time duration for each reconstruction technique was measured.

Assessment of Image-Quality Parameters

Image quality was measured by placing a region of interest with a diameter of 10 mm in the left maxillary sinus of every image set. A mean SD in Hounsfield units of 3 repeated region-of-interest measurements was defined as image noise.

Subjective image quality was evaluated on a diagnostic monitor for 2 triplets of image sets (120 kV and 100 kV) acquired at 100 mAs, 50 mAs, and 25 mAs. The images selected for the triplets were equal in terms of image noise using SAFIRE. Seven radiologists, with experience ranging from 2 to 29 years (average, 13 years) who were blinded to the tube current and reconstruction technique evaluated the sharpness of relevant structures (frontal and maxillary sinus, ethmoidal sinus, sphenoidal roof, bony orbital boundaries, mastoid cells) within the images on a 5-point scale (1 = poor image quality, 2 = fair image quality, 3 = moderate image quality, 4 = good image quality, 5 = excellent image quality).

Statistical Analysis

Image noise was transformed to percentile values, with FBP set at 100% image noise. The Student *t* test on paired samples was used to test for significances among the reconstruction techniques. Interobserver agreement between the raters was evaluated by using the weighted κ statistic to estimate consistency. A *P* value of $\alpha < .05$ was considered significant.

Table 1: Examination parameters and the corresponding calculated radiation doses

Tube Voltage (kV)	Tube Current (mAs)	CTDI _{vol} (mGy)	Dose-Length Product (mGy × cm)	Effective Dose (mSv)
120	100	9.45	228	0.52
120	50	4.79	115	0.26
120	25	2.44	59	0.14
100	100	5.93	144	0.33
100	50	3.02	73	0.17
100	25	1.54	37	0.09

Table 2: Mean image noise measured as an SD in Hounsfield units of images reconstructed at 3 and 1 mm

	120 kV 100 mAs	120 kV 50 mAs	120 kV 25 mAs	100 kV 100 mAs	100 kV 50 mAs	100 kV 25 mAs
3 mm						
Hard kernel						
FBP	60.3	101.0	115.7	78.2	130.1	181.3
SAFIRE I	48.2	80.7	91.1	60.1	105.2	146.4
SAFIRE II	40.0	53.8	69.8	52.9	88.3	121.0
SAFIRE III	30.9	37.7	55.5	41.5	70.2	101.7
SAFIRE IV	28.1	29.3	39.8	33.8	52.1	94.0
SAFIRE V	19.6	24.5	30.6	23.7	39.0	78.1
IRIS	34.4	48.3	59.9	36.2	62.7	86.5
Soft kernel						
FBP	7.2	8.2	14.1	8.3	11.7	16.7
SAFIRE I	5.9	6.7	11.0	7.1	11.2	12.8
SAFIRE II	5.4	5.3	9.3	7.3	10.8	12.1
SAFIRE III	3.4	4.7	10.2	8.1	10.3	15.4
SAFIRE IV	3.1	4.6	8.6	7.5	9.0	14.9
SAFIRE V	2.6	5.1	9.3	5.8	8.4	15.6
IRIS	4.3	5.4	10.2	7.8	10.9	15.6
1 mm						
Hard kernel						
FBP	87.8	162.7	178.5	153.0	202.2	318.5
SAFIRE I	75.0	134.4	123.9	103.7	175.1	182.9
SAFIRE II	57.1	102.8	110.0	74.8	146.0	134.7
SAFIRE III	44.2	81.0	99.1	62.6	112.5	169.7
SAFIRE IV	30.5	47.7	85.3	44.7	96.0	151.7
SAFIRE V	27.6	23.6	48.0	28.9	59.2	153.2
IRIS	60.9	80.8	85.9	57.6	97.2	179.2
Soft kernel						
FBP	13.7	15.6	18.1	12.3	22.0	29.8
SAFIRE I	9.4	9.2	11.6	9.1	21.3	23.6
SAFIRE II	4.6	7.5	11.0	8.9	17.7	20.6
SAFIRE III	4.8	6.3	10.6	7.7	15.9	22.6
SAFIRE IV	3.8	6.1	11.3	7.8	16.2	17.5
SAFIRE V	3.0	6.3	9.6	6.4	12.0	11.7
IRIS	8.3	11.4	9.7	8.7	10.8	25.2

RESULTS

Dosage

The average dose-length product of the different examination protocols ranged from 228 mGy × cm (120 kV/100 mAs) to 37 mGy × cm (100 kV/25 mAs), resulting in estimated effective doses from 0.52 to 0.09 mSv (Table 1).

Image Noise

The image noise of the FBP images was always greater compared with the iterative reconstruction algorithms IRIS and SAFIRE (Table 2). The greatest image-noise reduction, up to 85%, was achieved in the 1-mm image set (hard kernel) acquired at 120 kV/50 mAs by using the strongest iteration mode SAFIRE V (23.6-

Table 3: Average noise reduction of SAFIRE for soft tissue and bony kernel

	Hard Kernel (3 mm)	Hard Kernel (1 mm)	Soft Kernel (3 mm)	Soft Kernel (1 mm)
Mean noise reduction	47.5%	49.4%	24.8%	40.9%
Median noise reduction	48.5%	50.7%	24.2%	39.3%
SD	16.8%	17.6%	15.9%	16.9%

Table 4: Time efficiency of FBP and iterative image reconstruction techniques^a

	No. of Images	FBP	SAFIRE	IRIS
Soft kernel 3 mm	36	12.3 seconds (2.9 img/s)	38.5 seconds (0.9 img/s)	48 seconds (0.8 img/s)
Hard kernel 3 mm	36	9.3 seconds (3.9 img/s)	39.3 seconds (0.9 img/s)	63.6 seconds (0.6 img/s)
Soft kernel 1 mm	110	20.6 seconds (5.3 img/s)	71.1 seconds (1.5 img/s)	105.6 seconds (1.0 img/s)
Hard kernel 1 mm	110	16.6 seconds (6.6 img/s)	70.5 seconds (1.6 img/s)	85.8 seconds (1.3 img/s)

Note:—img indicates images.

^a Calculations were done with a section thickness of either 3 mm (3-mm increments) or 1 mm (1-mm increment) in transverse reformation.

versus 167.7-HU FBP). For the examination protocol with the smallest radiation dosage (100 kV/25 mAs), the average image-noise reductions of the iterative techniques were 42.3% (3 mm, hard kernel), 49.2% (1 mm, hard kernel), 13.8% (3 mm, soft kernel), and 32.2% (1 mm, soft kernel).

The mean image-noise reductions of all examination protocols were 47.5% for 3-mm images and 49.4% for 1-mm images rendered with hard kernel (Table 3). With the soft kernel, mean overall image-noise reduction was less, only 24.8% (3-mm images) and 40.9% (1-mm images). The differences in image-noise reduction between the hard versus soft kernel were statistically significant (hard versus soft kernel on 3-mm images, $P < .01$; hard versus soft kernel on 1-mm images, $P = .006$).

Apart from a few exceptions, SAFIRE V performed the best in image-noise reduction, while SAFIRE I diminished noise the least. On average, IRIS performed noise reduction at an equal noise level either to SAFIRE III (1 mm and 3 mm, hard kernel) or to SAFIRE I (3 mm, soft kernel) and SAFIRE II (1 mm, soft kernel).

Time Performance Calculations

As shown in Table 4, the FBP method required 12.3 seconds for reconstruction of 36 images with the soft kernel at a thickness of 3 mm (IRIS, 48 seconds; SAFIRE, 38.5 seconds). The new SAFIRE reconstruction method was 20%–67% faster than IRIS. When we took into account all image thicknesses and kernels in this study, the average time needed for reconstruction of a SAFIRE image set was higher by an average factor of 3.7 compared with standard FBP.

Subjective Image Quality of Noise-Adapted Image Sets

Regarding the 4 image triplet series (120 kV/100 kV in 3- and 1-mm thicknesses), the 7 readers voted every time in favor of the datasets with the highest tube current, which were calculated in the FBP technique (5-point scale, 4.71–5.0). Figure 1 illustrates the image sets that were graded by the readers. The 50% tube current images were evaluated worse than the 100% ones, from

3.4 to 4.4, while the images using a quarter of the maximum tube current scored worst, 2–3.1 points. Most of the differences reached statistical significance, as noted in Fig 1. Overall interobserver agreement among the 7 raters was good, with a mean weighted κ value of $\kappa = 0.711$ (median, $\kappa = 0.729$; SD, 0.130; minimum, $\kappa = 0.400$; maximum, $\kappa = 0.933$).

DISCUSSION

The main focus of our study was to investigate the performance and image quality of the latest generation of iterative reconstruction methods for CT of the paranasal sinus region. Because examination protocols vary between different hospitals, we analyzed image noise at various dose preferences.

In comparison with standard FBP, all iterative reconstruction techniques reduced image noise by 15%–85%, depending on the algorithm strength and type of image. Bone kernel images were significantly more susceptible to iterative-based noise reduction than soft-tissue images, potentially due to the generally increased ambient noise level caused by the sharp edge-enhancing quality of the hard kernel algorithm. In our study, iterative reconstruction techniques with a soft-tissue kernel were more efficient at 120 kV than the 100-kV image series; at the lowest dosage settings, the soft-tissue kernel algorithm showed the least benefit by using IRIS or SAFIRE.

Regarding the subjective image quality, the readers, unaware of tube current and type of reconstruction, independently voted in favor of the image sets acquired at the highest tube current (FBP images), though the images were aligned in terms of image noise. This result held true for both 120 and 100 kV image triplets. The reason may be an overall increased softening of cortical structures and bone edges caused by the iterative process. Increased image blurring has been discussed in several publications that investigated iterative reconstruction techniques.^{11–13} Silva et al¹² suggested that the diminished noise manifests as an oversmoothing of the images. We have read with interest the results of Bulla et al,⁸ who examined IRIS and concluded that iterative reconstructed paranasal sinus CT images did not lose image quality even though the tube current was reduced by >50%. However, their work-group subjectively evaluated image noise and diagnostic conclusiveness on a common 5-point scale, which might be too imprecise for evaluating the image quality of a CT dataset.

Because the images rated in our study were aligned in terms of image noise, 1 conclusion would be that the lack of sufficient photons cannot be compensated for by simply increasing iterative reconstruction strength. Mitsumori et al,¹³ who examined adaptive statistical iterative reconstruction on liver CT, recommended the use of balanced reconstruction preferences with a mild iterative influence to prevent a “waxy” image impression that may constrain diagnostic validity. Although we are aware that decreased image noise can lead to increased image quality, this field requires more and precise scientific evaluation. Especially when one designs new examination protocols with reduced dosage parameters based on iterative reconstruction techniques, the appearance of an increased blurriness or artificial image impression should be considered. Furthermore, regarding the heterogeneous reduction in image noise for the different datasets rendered with

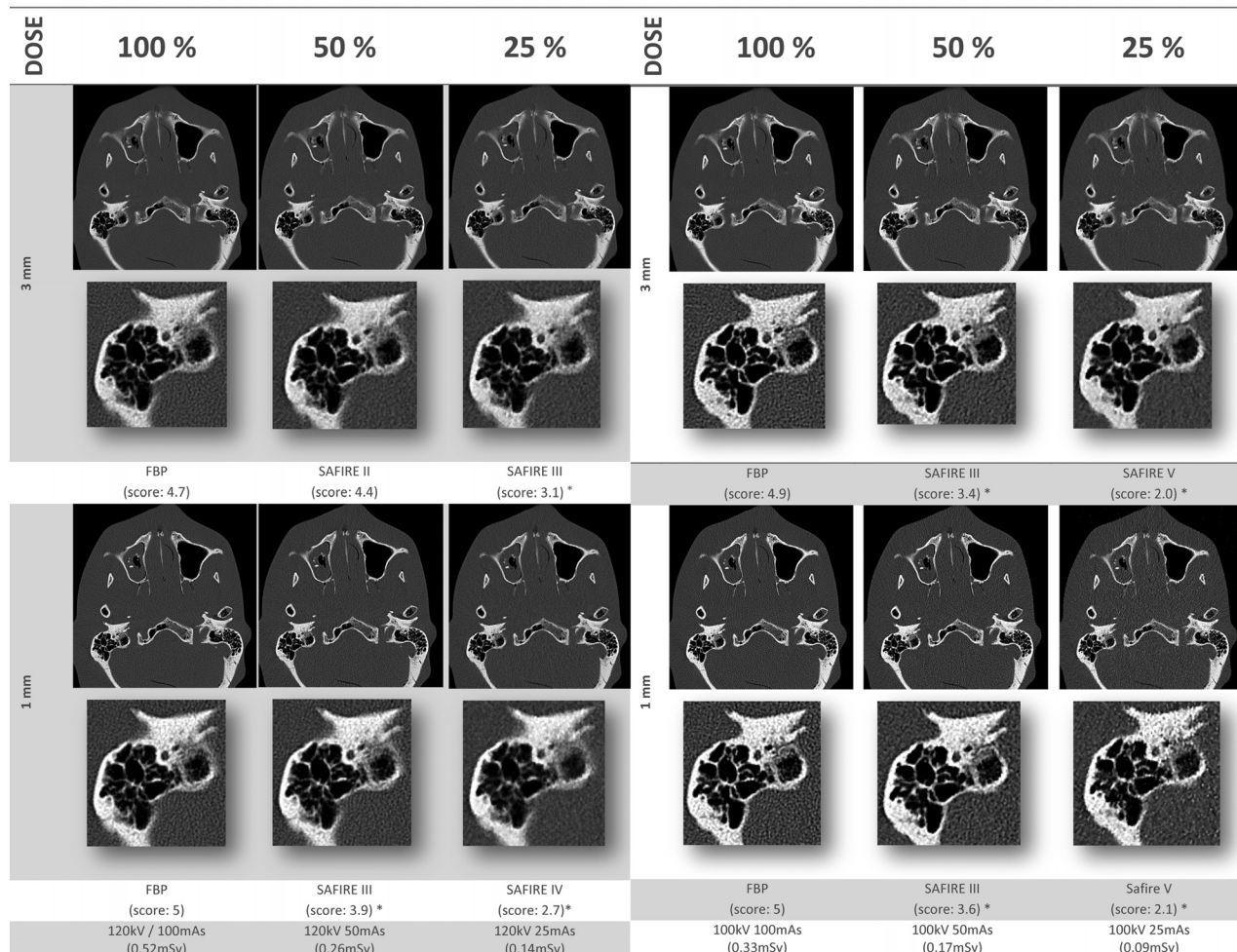


FIG1. Noise-adapted image triplets (120 kV versus 100 kV: 3- versus 1-mm thickness) at tube-current-adjusted dose levels of 100%, 50%, and 25%, which were evaluated by 7 readers regarding the subjective image quality. The right mastoid region of each image is amplified to emphasize the differences in detail. Beneath each reconstruction algorithm, the average rating score is noted (the asterisk indicates significant differences of $\alpha < .05$ in comparison with the corresponding FBP of the image triplet). For each examination type, the effective dose was calculated according to the European guidelines.¹⁰

soft and hard kernel preferences, it seems mandatory to choose an individual reconstruction method for a particular image type.

Regarding the time frame for image calculation, the iterative techniques require a time increase by a factor of 3.7 (SAFIRE) to 5.2 (IRIS), compared with corresponding FBP reconstructions. This has to be considered, especially when generating large datasets with thin images, small increments, or multiple multiplanar reconstructions, all of which can lead to a dataset of thousands of images. During a typical daily task, calculating complete datasets by using iterative reconstruction techniques would lead to a considerable queue of images and could cause delays in interpreting the CT studies. However, with the increased computing power of modern workstations, this disadvantage may be negligible in the near future.

As deduced from the results of our phantom study, we consider 2 interesting application areas that might be suitable for iterative reconstruction techniques: One may be the evaluation of bony structures with decreased dose parameters, because these structures are usually evaluated by using a sharp-edged rendered dataset (eg, hard kernel). However, the clinical value is still mixed in this research field: While Pontana et al⁹ did not notice any loss

of image quality with iteratively reconstructed CT, Yanagawa et al¹⁴ noticed an increase in false-positive pathologic findings when using the adaptive statistical iterative reconstruction technique. Again, these results oppose the findings of the workgroup of Hu et al,¹⁵ who concluded that using 40% dose-reduction IRIS images produced a dataset with quality equal to or even superior to that of the 100% dose using FBP.

Another field for application could be standard-dose CT examinations that are evaluated by using a soft-tissue kernel and undergo marginal iterative enhancement, because significant image-noise reduction can be achieved with even slight iterative alterations at higher dose levels. This hypothesis is underlined by a recent phantom study that researched image-noise suppression of an adaptive iterative dose-reduction method and concluded that the 40% decrease in image noise has the potential to reduce radiation dosage in future clinical applications.¹⁶

A limitation of our study is the artificial nature of the methods used to assess a phantom head for image quality. Because the gelatin material of the phantom head has an average attenuation of 130 HU, denser than that of human soft tissue, the results of iterative noise reduction and even the base level of image noise

itself might be exaggerated. Furthermore, the noise results regarding the soft-tissue kernel have to be interpreted critically because the absolute values are quite contiguous with a dispersion of only 4–10 HU. Dedicated analyses of live CT studies are necessary for actual analysis of the clinical value of iterative reconstructions for images rendered with a soft-tissue kernel. In addition, the influence of artifacts caused by patient movement on iterative techniques cannot be estimated by a phantom model. Another limitation of the study is the restriction of the analyzed iterative technique itself to 1 specific algorithm (SAFIRE, Siemens), though the overall conclusion is likely still generalizable to other vendors and methodologies.

CONCLUSIONS

Sinogram-affirmed iterative reconstruction (SAFIRE) algorithms are suitable for image-noise reduction for CT of the paranasal sinus region. Because image quality decreases with dosage, careful choice of the appropriate iterative method is necessary to achieve an optimal balance between image noise and quality.

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