RESEARCH ARTICLE

Reducing the dose of CT of the paranasal sinuses: potential of an iterative reconstruction algorithm

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Objective: To evaluate the feasibility and image quality of low-dose CT of the paranasal sinuses using iterative reconstruction with adaptive-iterative dose reduction in three dimensions (AIDR 3D) in comparison with conventional image protocols of older scanner generations.

Methods: Sinus CT scans of 136 patients were assessed retrospectively. Patients underwent CT either with low-dose settings (Protocol A: 80 kV, 30 mA s; Protocol B: 120 kV, 15 mA s or C: 80 kV, 90 mA s) reconstructed using AIDR 3D (Protocols A and B) or filtered back projection (FBP) (Protocol C) or with standard dose (Protocol D: 120 kV, 80 mA s) and FBP. Image quality was assessed in consensus by two blinded readers scoring the diagnostic image quality (from 1 = excellent to 5 = non-diagnostic) and conspicuity of important anatomic landmarks (from 0 = not visible to 2 = completely visible; maximum score of 16 points) as well as osseous structures (maximum score of 12 points). Dose-length product, effective dose (ED), CT dose index and scan length were retrieved for each scan and compared.

Results: Mean ED could be lowered by 82% when using Protocol A. The best image quality was found using Protocol B (mean score = 2.1 ± 0.51). Conspicuity of relevant anatomic landmarks was best with Protocol A (mean score = 11.97 ± 1.88). Protocol B provided the highest conspicuity of osseous structures (mean score = 8.27 ± 1.58). Image noise was highest in images obtained using Protocol A.

Conclusions: AIDR 3D allows a significant dose reduction while maintaining a good diagnostic image quality and conspicuity of relevant anatomic structures.

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Introduction

CT has evolved into the modality of choice for imaging the paranasal sinuses.^{1–3} It is one of the most commonly requested diagnostic imaging tests in clinical routine, and the radiation exposure is of special concern for several reasons. First, it is predominantly performed in younger patients. Second, eye lenses and the thyroid gland are radiosensitive and are exposed during CT examinations of the paranasal sinuses.⁴ Third, patients often require

numerous follow-up scans. Whereas it has long been known that radiation may cause thyroid cancer, discussion about a radiation threshold for cataractogenic effects has started only recently. It has been suggested that a cumulated dose of 100 mGy or above may be cataractogenic.⁵ Because of these radiation issues, many attempts have been made to reduce the radiation exposure of CT examinations of the paranasal sinuses.^{6–8} Most investigators focused on reducing dose by adjusting scan protocols, mostly by lowering tube voltage or more often the tube current–time product. While this has led to a distinct

dose reduction in many applications, image quality is often a limiting factor for further tube current reduction.^{6,7,9}

Drastic improvements in computing power have turned iterative reconstruction (IR) algorithms into a feasible alternative to the commonly used filtered back projection (FBP).¹⁰ IR algorithms are often provided in vendor-specific software packages, which complicates the comparison of different IR solutions.¹⁰ While “adaptive-iterative dose reduction in three dimensions” (AIDR 3D) has shown promising results with significant dose reductions of approximately 50–67% while maintaining sufficient image quality in several body regions, this algorithm has not yet been evaluated in paranasal sinus CT.^{11–13}

Unfortunately, IR is restricted to newer generation CT scanners or requires costly updates of hardware and software and many facilities hesitate to fully integrate IR into routine clinical practice. Therefore, a detailed evaluation of the possible benefits of vendor-specific IR algorithms is required. The aim of our study was to evaluate AIDR 3D regarding dose reduction and possible advantages in terms of image quality of paranasal sinus scans in comparison with a conventional protocol as well as with standard low-dose protocols of two different CT scanner generations used in daily routine.

Methods and materials

Patients

All CT scans of the paranasal sinuses obtained over a 10-month period were assessed for inclusion in this retrospective analysis, which was approved by the institutional review board. Inclusion criteria were as follows: age >18 years, suspected acute or chronic inflammation of the paranasal sinuses, complete sinus CT scan, no or minimal sinus changes and full set of reconstructions in coronal and sagittal views. Patients with fully obstructed sinuses were excluded to avoid confounding of noise measurement in the sinuses. Written consent was obtained from all patients or legal representatives.

Scan protocols

All data sets included in the analysis were acquired using a total of four scan protocols on one of three CT scanners: Toshiba Aquilion Prime (Toshiba Medical Systems, Otawara, Japan), Siemens Somatom Definition (Siemens Healthcare AG, Erlangen, Germany) and Siemens Somatom Sensation (Siemens Healthcare AG, Erlangen, Germany). Tube voltage and tube current parameters differed for the three CT scanners. The parameters of the four scan protocols (Protocols A–D) are summarized in Table 1. Since all scans were performed in the routine clinical setting, patients were randomly assigned to a scanner according to availability. For each CT scanner, a dedicated protocol with thoroughly optimized parameters was used. All scan protocols were optimized to obtain a radiation dose as low as reasonably achievable. CT scans acquired on both Siemens CT were generated using FBP. The images

acquired on the Toshiba CT scanner were generated by using the AIDR 3D algorithm (Toshiba Medical Systems, Otawara, Japan). All data sets were reconstructed with separate kernels for the bone and soft tissue in the axial, coronal and sagittal planes. Coronal and sagittal views were reformatted with 1.0-mm slice thickness. Identical bismuth eye shields were used in all patients.

Image review

Two blinded experienced readers (LAS, SMN) graded the image quality in consensus by assessing three categories. First, diagnostic image quality was assessed using a 5-point scale from 1 (excellent) to 5 (non-diagnostic). Second, the conspicuity of important osseous structures and relevant anatomic landmarks was assigned a score of 0, 1 or 2 (not visualized, partially visualized or fully visualized). The following anatomic landmarks and osseous structures were assessed for each side: uncinate process of the ethmoid bone, ostium of maxillary sinus, ethmoidal infundibulum, nasolacrimal duct, cribriform plate, fovea ethmoidalis and lamina papyracea. Maximum scores were 16 for anatomic landmarks and 12 for osseous structures. All graded structures are shown in Figure 1. Lastly, noise was measured by placing three regions of interest (ROIs) of 10 mm² in the left maxillary sinus, left masseter muscle and left bulbus oculi to obtain different values for air, soft tissue and aqueous tissue. Noise was defined as the mean standard deviation (SD) of attenuation measured in Hounsfield units. All images were assessed in two preset windows with a focus on either bone (window centre: 700 HU, window width: 2700 HU) or soft tissue (window centre: 50 HU, window width: 400 HU).

Dose

Besides tube current (in milliamperere second) and tube voltage (in kilovoltage), each scan was characterized in terms of CT dose index, scan length and dose-length product (DLP). The effective dose (ED) was calculated by multiplying DLP with the conversion coefficient for the facial skull [0.0023 mSV/(mGy cm)] as proposed by the European Working Group for Guidelines on Quality Criteria in CT.

Statistical analysis

Statistical analysis was performed using SPSS 23 for Macintosh (IBM, Armonk, USA). Means and SDs of all acquired continuous and ordinal variables were calculated. The Kolmogorov–Smirnov test was used to test all variables for normal distribution. Afterwards, the Mann–Whitney test was used to test for differences between non-normally distributed variables. *p*-values <0.01 were considered statistically significant.

Results

We initially identified 145 paranasal sinus CT scans. Nine scans were excluded owing to completely obstructed maxillary sinuses, which precluded noise measurement.

Table 1 Overview of scan protocols compared in this study

Protocol	CT	Tube voltage (kV)	Tube current–time product (mAs)	Collimation (mm)	Reconstruction
A	Toshiba Aquillon Prime (Toshiba Medical Systems, Otawara, Japan)	80	30	0.5	AIDR 3D
B	Toshiba Aquillon Prime	120	15	0.5	AIDR 3D
C	Siemens Definition (Siemens Healthcare AG, Erlangen, Germany)	80	90	0.75	FBP
D	Siemens Sensation (Siemens Healthcare AG, Erlangen, Germany)	120	100	0.75	FBP

AIDR 3D, adaptive-iterative dose reduction in three dimensions; FBP, filtered back projection.

As a result, a total of 136 scans were included in our analysis. 63 (46%) patients included were females. The distribution of patients among the scan protocols was as follows: Protocol A (80 kV, 30 mA s, AIDR 3D): 66 patients; Protocol B (120 kV, 15 mA s, AIDR 3D): 15 patients; Protocol C (80 kV, 90 mA s, FBP): 31 patients; and Protocol D (120 kV, 100 mA s, FBP): 24 patients. Mean age was 41.7 ± 17.3 years with no significant differences between the four protocols (p -values 0.338–0.836). All CT data sets had at least a sufficient diagnostic quality.

Means and SDs of dose-related parameters are given in Table 2. The mean scan length was 11.06 ± 2.0 cm and it did not differ significantly between scan protocols (p -values 0.08–0.545). The DLP and ED of Protocol A were lowest throughout our study, with mean values of 33.12 ± 4.53 mGy cm and 0.08 ± 0.07 mSv, respectively, and were significantly lower than the values of Protocols B–D ($p < 0.001$). Protocol B utilized a higher kilovoltage but lower milliamperere second, leading to a higher mean DLP and ED than those of Protocols A and C ($p < 0.001$). Still, dose-related parameters were well below those of the standard-dose Protocol D ($p < 0.001$).

Scores of the diagnostic image quality and conspicuity of structures and noise measurements for each of the four protocols are shown in Table 3. Image quality was best for Protocol B and was significantly better than that for the conventional low-dose protocol C ($p < 0.001$). There were no differences in image quality between Protocols A and B with AIDR 3D compared with

standard-dose protocol D ($p = 0.722$ and 0.155 , respectively). Conspicuity of anatomic landmarks was best for Protocol A, followed by Protocol B, but there were no significant differences between all scan protocols (p -values 0.016–0.985). In contrast, we found differences in the visualization of osseous structures, which were most conspicuous for Protocol B and significantly less conspicuous for low-dose protocol C ($p < 0.001$ for all comparisons) (Figure 2).

Discussion

Our results for the conventional low-dose CT protocol C show that dose reduction requires a compromise and is limited by the need to maintain diagnostic image quality. By using a low-dose protocol in conjunction with IR, we were able to achieve a significant reduction of ED of 82% compared with a non-dose-reduced protocol and 20% compared with a conventional low-dose protocol. Furthermore, our results show that the combination of dose reduction and IR significantly improves the image quality and conspicuity of anatomic landmarks compared with low-dose CT using FBP.

Our results are mostly congruent with studies which have evaluated different IR algorithms in paranasal sinus CT. However, it must be noted that owing to substantial differences regarding data processing and especially computing time, vendor-specific IR algorithms remain difficult to compare.^{8,14,15} Contrary to Hoxworth *et al*,¹⁴ who evaluated the IR algorithm VEO from

Figure 1 Structures used for scoring conspicuity: 1 = uncinat process of the ethmoid bone, 2 = ostium of maxillary sinus, 3 = ethmoidal infundibulum, 4 = nasolacrimal duct, 5 = cribriform plate, 6 = fovea ethmoidalis and 7 = lamina papyracea. Scores were given for each side.

Table 2 Overview of dose-related parameters

Protocol	Number of patients	DLP (mGy cm)	ED (mSv)	CTDI _{vol} (mGy)	Scan length
A	66	33.12 ± 4.53 ^a	0.08 ± 0.07 ^a	2.16 ± 0.26 ^a	10.8 ± 1.48 ^a
B	15	67.93 ± 9.51 ^a	0.14 ± 0.02 ^a	4.52 ± 0.17 ^a	10.72 ± 2.30 ^a
C	31	46.78 ± 8.86 ^b	0.10 ± 0.02 ^b	3.37 ± 0.42 ^b	10.96 ± 1.81 ^b
D	24	208.17 ± 124.92	0.44 ± 0.26	14.55 ± 7.49	12.14 ± 2.89

CTDI_{vol}, CT dose index; DLP, dose-length product; ED, effective dose.

All values are given as mean and standard deviation.

^aStatistically significant difference ($p < 0.01$) compared with Protocols C and D.

^bStatistically significant difference ($p < 0.01$) compared with Protocol D.

General Electric Medical Systems Ltd (Chalfont St Giles, UK), we found no significant differences in the depiction of osseous structures in comparison with 120 kV with FBP. Hoxworth *et al*¹⁴ attributed the poorer conspicuity to increased image smoothing of the IR algorithm. This was not the case for images acquired with filtered back projection at 120 kV. Nevertheless, further evaluation with direct comparison of both algorithms is necessary before definitive conclusions can be drawn. Diagnostic image quality and conspicuity of relevant structures were best at 120 kV with IR (Protocol B), corroborating our finding of IR being superior to FBP regarding optimal depiction of the paranasal sinus region. Nevertheless, Protocol B was an interim stage during the implementation of AIDR 3D in our department, and Protocol A was found to be superior in terms of dose reduction and maintaining diagnostic image quality.

Contrary to other studies investigating IR, we found significantly more image noise in the images acquired with protocols using IR, with Protocol A showing the most severe noise.^{8,14,16} This can be partially explained by the lower radiation dose in our study with a mean DLP of 33.1 mGy cm compared with 37–49.6 mGy cm in the aforementioned studies. However, AIDR 3D produces less noise at 120 kV than at 80 kV, suggesting that there is still a physical limit for dose reduction even when using an IR, since not even this algorithm can compensate for an insufficient number of photons arriving at the detector. These findings are comparable with those reported by Schulze *et al*,¹⁶ who found IR algorithms from Siemens Healthcare AG, Erlangen, Germany [sinogram affirmed iterative reconstruction (SAFIRE) and iterative reconstruction in image space (IRIS)] to be more effective at 120 kV than at a lower tube voltage. However, additional noise in images reconstructed with AIDR 3D did

not negatively affect the subjective image quality or visibility of relevant structures. This is consistent with the results of Schulz *et al*,¹⁶ who observed that more image noise did not necessarily degrade the subjective image quality, as perceived by readers blinded to tube settings.¹⁶ Furthermore, Hojreh *et al*¹⁷ proposed a grading of image quality of sinus CT by noise in the soft tissue (*i.e.* masseter muscle) and found that diagnostic quality was still adequate for noise of up to 70–90 HU. With mean noises of 29.6 HU (Protocol A) and 15.1 HU (Protocol B), images reconstructed with AIDR 3D in our study are well below these thresholds.

IR software packages provided by major CT vendors are often considered “black boxes”, since there is little information about the implemented reconstruction algorithms. Therefore, investigators have demanded an independent evaluation of commercially available IR packages in different body regions.¹⁰ We aimed to investigate the performance of AIDR 3D in CT of the paranasal sinuses, as to our knowledge, this has not been previously examined. Our results show that AIDR 3D is feasible for this purpose and is equally effective as other IR algorithms, since our findings are mostly consistent with those of studies obtained with packages from other CT vendors.

Still, our study has some limitations: first, like investigators conducting similar studies, we were not able to compare different vendor-specific IR algorithms, since only one of our CT scanners had IR capabilities during the study period and raw data of a scan are not interchangeable between platforms of different manufacturers. Furthermore, comparison of FBP and AIDR 3D was conducted by analyzing the sinus scans of different CT scanners. While comparability of those protocols is biased by influencing factors such as different

Table 3 Image quality, conspicuity of structures and noise measurement

Protocol	Image quality	Anatomic landmarks	Osseous structures	Noise (HU) air	Noise (HU) masseter muscle	Noise (HU) bulbus oculi
A	2.4 ± 0.58 ^c	11.97 ± 1.88	7.53 ± 1.45 ^c	53.31 ± 17.91 ^a	29.64 ± 7.21 ^a	33.56 ± 6.90 ^a
B	2.1 ± 0.51 ^c	11.53 ± 3.04	8.27 ± 1.58 ^c	13.56 ± 4.21 ^a	15.11 ± 2.54 ^a	13.98 ± 2.44 ^a
C	2.9 ± 0.54	10.42 ± 2.73	5.54 ± 1.46 ^b	10.84 ± 3.12 ^b	16.92 ± 7.81 ^b	31.79 ± 28.32 ^b
D	2.5 ± 0.72	11.25 ± 3.41	7.71 ± 1.68	7.99 ± 6.91	10.67 ± 5.84	10.36 ± 4.52

Scores for subjective image quality and for conspicuity anatomic landmarks [maximum (max) 16 points] and osseous structures (max 12 points) are given as mean and standard deviation (SD).

Image noise is defined as mean SD of measured Hounsfield units and is given as mean and SD.

^aStatistically significant difference ($p < 0.01$) compared with Protocols C and D.

^bStatistically significant difference ($p < 0.01$) compared with Protocol D.

^cStatistically significant difference ($p < 0.01$) compared with Protocol C.

Figure 2 Comparison of image quality of Protocols A–D. Sagittal views were reconstructed with 1.0-mm slice thickness in the bone window (window centre: 700 HU, window width: 2700 HU).

properties of the CT scanners, the authors believe that this study design may reflect the situation in many facilities where new CT scanners with IR are operated alongside a broad range of older generation scanners without IR. Second, we did not compare the image quality of IR and FBP intraindividually, since we assumed that the anatomy of the paranasal sinus is rather similar throughout adult patients and an intraindividual comparison would have meant at least one more scan per patient and therefore significantly a higher radiation dose per patient. Third, the sample size per scan protocol varies, since one CT scanner was dismantled and one scan protocol was updated during the study period. Furthermore, based on our initial results, we abandoned Protocol D in favour of other protocols affording better dose reduction. Still, we think we were able to provide a balance between comparison of various scan protocols and sufficient statistical power. Lastly, since consistent noise measurement across all subjects is dependent on proper ROI placement, manual ROI placement, as in our study, might bias the results even when performed by highly trained readers. Despite these drawbacks, the strength of our study lies in the comparatively large number of patients as well as in a complex evaluation of image quality.

Conclusions

Combining a low-dose scan protocol with AIDR 3D reconstruction significantly lowers the ED by up to 82%, thus reducing the risk of deterministic radiation

damages while maintaining or even improving the image quality and conspicuity of relevant structures. However, it is still desirable to intraindividually compare different IR algorithms.

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