Received:
4 June 2014

Revised:
21 February 2015

Accepted:
31 March 2015

doi: 10.1259/bjr.20140404

Cite this article as:

Brodoefel H, Bender B, Schabel C, Fenchel M, Ernemann U, Korn A. Potential of combining iterative reconstruction with noise efficient detector design: aggressive dose reduction in head CT. *Br J Radiol* 2015;88:20140404.

FULL PAPER

Potential of combining iterative reconstruction with noise efficient detector design: aggressive dose reduction in head CT

¹H BRODOEFEL, MD, ²B BENDER, MD, ¹C SCHABEL, MD, ²M FENCHEL, MD, ²U ERNEMANN, MD and ²A KORN, MD

¹Department of Diagnostic and Interventional Radiology, University of Tübingen, Tübingen, Germany

²Department of Diagnostic and Interventional Neuroradiology, University of Tübingen, Tübingen, Germany

Address correspondence to: Dr Harald Brodoefel

E-mail: h.brodoefel@t-online.de

Objective: With further increase of CT numbers and their dominant contribution to medical exposure, there is a recent quest for more effective dose control. While reintroduction of iterative reconstruction (IR) has proved its potential in many applications, a novel focus is placed on more noise efficient detectors. Our purpose was to assess the potential of IR in combination with an integrated circuit detector (ICD) for aggressive dose reduction in head CT.

Methods: Non-contrast low-dose head CT [190 mAs; weighted volume CT dose index (CTDI_{vol}), 33.2 mGy] was performed in 50 consecutive patients, using a new noise efficient detector and IR. Images were assessed in terms of quantitative and qualitative image quality and compared with standard dose acquisitions (320 mAs; CTDI_{vol}, 59.7 mGy) using a conventional detector and filtered back projection.

Results: By combining ICD and IR in low-dose examinations, the signal to noise was improved by about 13% above the baseline level in the standard-dose control group. Both, contrast-to-noise ratio (2.02 ± 0.6 vs 1.88 ± 0.4 ; $p = 0.18$) and objective measurements of image sharpness (695 ± 84 vs 705 ± 151 change in Hounsfield units per pixel; $p = 0.79$) were fully preserved in the low-dose group. Likewise, there was no significant difference in the grading of several subjective image quality parameters when both noise-reducing strategies were used in low-dose examinations.

Conclusion: Combination of noise efficient detector with IR allows for meaningful dose reduction in head CT without compromise of standard image quality.

Advances in knowledge: Our study demonstrates the feasibility of almost 50% dose reduction in head CT dose (1.1 mSv per scan) through combination of novel dose-reducing strategies.

For more than a decade, major technical advances in CT have been motivated by the quest for increased speed, volume coverage and improvement of image quality. However, a lasting rise in overall study numbers and frequent serial CT examinations in individual patients has fed a heightened public awareness of radiation-associated cancer risks.¹ The latter may in fact account for up to 2% of all incident cancer cases and is likely to rise with further increase of CT installations.² While a single head CT is relatively low in dose, its high demand in the adult and paediatric population raises concerns regarding noticeable public health issues in the future.³ For example, in head CT, the number needed to harm in terms of a lifetime fatal cancer is only about 900 individuals in the 10-year age group.^{3,4} In younger children, there is the additional concern regarding repeated head scans as serial standard-dose examinations may also lead to adverse effects on intellectual development.⁵

Apart from the transition from xenon gas to solid scintillator material detectors, the relatively recent reintroduction of iterative reconstruction (IR) algorithms arguably represents the most important milestone in the quest for dose control. To a certain extent, IR allows decoupling of spatial resolution and image noise and—while still evolving—has by now been established as a powerful dose-reducing tool in many clinical CT applications.^{6–9}

The latest development in the field of dose efficiency is a new detector design that combines the photodiode and analogue-to-digital converter (ADC) device of conventional detectors in one integrated module. This integrated detector set-up aims at the decrease of system-inherent electronic noise and its added benefit is now suggested by a number of recent studies.^{10–13}

The aim of this study was to assess the feasibility of more aggressive dose reduction by combining a second-generation IR algorithm with a more noise efficient integrated circuit detector for routine head CT examinations.

METHODS AND MATERIALS

Patient groups

The study group consisted of 50 consecutive low-dose non-contrast adult head CT examinations, which were acquired between September and October 2012 using more noise efficient detector technology and reconstruction by both filtered back projection (FBP) and IR. Indications were manifold and included assessment for acute ischaemia, acute head injury, headache or tumour staging. The studies were compared with a control group of 50 consecutive regular-dose head CT scans, obtained on a similar scanner with standard detector during October and November 2012.

Institutional review board approval was obtained for the retrospective analysis of data sets, and Health Insurance Portability and Accountability Act-compliant practices were used throughout this study.

CT data acquisition

Low-dose CT examinations in the study group were obtained using a 128-slice CT scanner equipped with the more noise efficient integrated circuit detector (SOMATOM® Definition Edge; Siemens AG Healthcare, Forchheim, Germany). Image acquisition parameters of the low-dose protocol included a collimation of 40.00×0.6 mm, pitch of 0.55, rotation time of 1.0 s, tube voltage of 120 kV and tube current of 190 mAs. The routine dose control group examinations were acquired by a similar 128-slice CT scanner, equipped with a conventional discrete circuit detector (SOMATOM Definition Flash, Siemens AG Healthcare). Scan parameters in the control group were identical except for a tube current of 320 mAs. The choice of tube current reduction to 190 mAs in the low-dose group was based on previous experience with IR and the integrated electronics detector.^{14,15}

CT data reconstruction

Raw data of low-dose CT examinations in the study group were reconstructed using both FBP and IR [sinogram affirmed iterative reconstruction (SAFIRE); Siemens AG Healthcare]. Standard dose CT studies in our control group were reconstructed by FBP only.

The IR algorithm used in our study offers the option to select five preset strength levels associated with different levels of noise reduction and overall image quality impression. As per recommendation by the vendor, an intermediate level of 3 was selected for all reconstructions in our study.

Reconstruction parameters included an H30 medium smooth convolution kernel for FBP and the equivalent J30 medium smooth kernel for IR, a slice thickness of 4.5 mm with 4.5-mm increment and a field-of-view appropriate to the head size.

For a subset analysis of image sharpness, additional reconstructions were performed in the first 25 patients of each group

with bone window kernels, notably the H70 for FBP and the equivalent J70 for IR. Slice thickness and increment in these reconstructions were 0.75 mm.

Dose measurements

The weighted volume CT dose index (CTDI_{vol}) and dose-length product (DLP) were recorded for each CT examination. Effective dose (mSv) was estimated by multiplying DLP with a constant region-specific conversion coefficient of 0.0023 mSv (mGy cm)⁻¹.¹⁶

Quantitative image analysis

Assessment of quantitative image parameters was carried out by board-certified, subspecialty-certified Reader 1. For both protocols and reconstruction algorithms, 0.4-cm² regions of interest (ROIs) were placed in corresponding supratentorial white matter (WM) and grey matter (GM) locations (at the level of the centrum semiovale), in the lateral ventricles as well as in the white matter of the middle cerebellar peduncle. Thereby, signal and image noise were assessed in terms of CT density in Hounsfield units (HU) and standard deviation (SD) of attenuation within a region of interest. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated according to the following standard equations:

$$\text{SNR} = \text{Mean HU of tissue in ROI} / \text{SD of HU in ROI} \quad (1)$$

$$\text{CNR} = \frac{(\text{Mean GM HU} - \text{mean WM HU})}{[(\text{SD GM HU})^2 + (\text{SD WM HU})^2]^{1/2}} \quad (2)$$

For a subset analysis of image sharpness, thin-slice bone window reconstructions of the first 25 patients in each group were assessed by a MATLAB® tool (MathWorks®, Natick, MA) on a separate workstation. The program measures CT density values in HU across pixels that are lined perpendicular to the skull circumference. The mean of three measurements per patient was used for further analysis and sharpness quantified in terms of gradient or maximal slope (change in HU per pixel).^{17,18}

Qualitative image analysis

Qualitative analysis of images was independently performed by two board-certified, subspecialty-certified Readers 2 and 3. Randomized and anonymous assessment of studies was ensured through random selection of subjects or reconstructions by one of the authors and their presentation to the readers in a blinded fashion. Studies were reviewed at a picture archiving and communication system workstation (Centricity; GE Healthcare, Milwaukee, WI) using standard display settings (window level 36, width 80). Prior to the analysis of actual study images, our reading radiologists performed a training session on 10 routine head CT examinations to achieve consensus regarding our image quality scoring system.

Assessment of subjective image quality was performed on axial data sets in terms of noise, grey-white matter differentiation, sharpness of subarachnoid space margins, distinctness of posterior fossa contents and overall diagnostic acceptability.

Thereby, grades for noise included (1) very low, (2) low, (3) considerable with preserved diagnostic image quality, (4) high and causative to non-diagnostic image quality. All other parameters were graded as (1) excellent, (2) good, (3) suboptimal but still diagnostic, (4) unacceptable and non-diagnostic. All scores for image quality were averaged across both readers for further analysis.

Statistical analysis

Statistical analysis was performed with software (JMP v. 6; SAS® Institute, Cary, NC and Prism v. 4.00; GraphPad Software Inc., San Diego, CA). A p -value of <0.05 was considered statistically significant. Continuous and proportional patient characteristics between subgroups were compared by unpaired t -test and χ^2 test.

Comparison between quantitative image quality parameters in low-dose FBP and IR and standard dose FBP was performed by unpaired t -test. Subjective image quality scores were compared by Mann–Whitney U test.

Interrater agreement in the assessment of image quality was quantified by weighted kappa statistics.

RESULTS

Patient demographics, exposure parameters and associated radiation doses are evident from Table 1. Differences in age and sex between the study and control groups were insignificant. All protocol parameters except tube current were kept identical in both series and the apparent mismatch between 41% reduction of current and 44% reduction of CTDI or DLP is explained by improvement in z -overscanning with the more advanced CT generation.

Quantitative analysis

Despite data acquisition by the more noise efficient integrated circuit detector, reduction of tube current in our low-dose protocol was associated with a significant decline of SNR in various cerebral tissues when images were reconstructed by FBP (Table 2). However, this effect was more than compensated when data were reconstructed by IR, resulting in an average 13% increase of SNR above baseline level (Table 2). Similarly, CNR was reduced by 24% when low-dose acquisitions were reconstructed by FBP (1.43 ± 0.40 vs 1.88 ± 0.40 ; $p < 0.0001$). When IR was used in addition to the integrated circuit detector, CNR

was not significantly different from findings in our standard-dose control group (2.02 ± 0.6 vs 1.88 ± 0.40 ; $p = 0.18$; Figure 1).

A 25 patient subset analysis of image sharpness on thin-slice bone window kernel reconstructions demonstrated a 10% decrease in low-dose scans with FBP reconstruction (634 ± 75 vs 705.4 ± 151.0 change in HU per pixel; $p = 0.06$; Figure 2). Again, the combination of improved detector technology with IR of the data resulted in restoration of the baseline level (695 ± 84 vs 705.4 ± 151.0 change in HU per pixel; $p = 0.79$; Figure 2).

Qualitative analysis

The interobserver agreement in the assessment of image quality parameters was good (weighted kappa, 0.73). Despite data acquisition by integrated circuit detector, reduction of tube current resulted in lower subjective scores for noise, grey–white matter differentiation, sharpness of subarachnoid space and overall diagnostic acceptability (Table 3). However, the additional use of IR in low-dose examinations was associated with substantial improvement of subjective image quality in all categories, notably without a meaningful difference in comparison to quality standards in our control group (Table 3). Imaging examples are provided in Figures 3–5.

DISCUSSION

The more widespread use of multidetector CT has sparked off a growing concern regarding potential hazards and has shifted the focus of technical innovation from volume coverage and image quality towards minimization of radiation exposure. Recent reintroduction of IR represents a breakthrough in this quest for dose control. The hallmark of the specific iterative post-processing algorithm used in this study is a correction loop that is introduced in the image reconstruction process. This loop is continued until the deviation between measured and calculated projections is smaller than a pre-defined limit. Each time the original image is updated, non-linear image processing algorithms, so called edge-preserving algorithms, are used to stabilize the resolution. Within certain limits, image noise can thereby be lowered without the loss of detail resolution, thus enabling reduction of radiation exposure to the patient.^{19,20} Sinogram-affirmed IR is a second-generation variant of IR, which combines raw data-based iterations for artefact reduction with image-based iterations using a refined

Table 1. Patient characteristics and radiation dose in standard- and low-dose CT head protocols

Characteristic	Control group	Low-dose study group	p -value
Age (years)	64 ± 15	62 ± 23	0.66
Sex (male/female)	31/19	26/24	0.41
Tube current (mAs)	320	190	–
CTDIvol (mGy)	59.7	33.2	–
Dose–length product (mGy cm)	1033 ± 55	530 ± 21	<0.0001
Effective dose (mSv)	2.2 ± 0.1	1.1 ± 0.04	<0.0001

CTDIvol, weighted volume CT dose index.

Table 2. Signal-to-noise ratios in control and low-dose groups

Anatomic compartment	Control group Conventional distributed detector	Low-dose group Integrated circuit detector	
	FBP	FBP	Iterative reconstruction
ST-WM	8.1 ± 1.1	6.6 ± 0.9 ; $p < 0.0001$	9.1 ± 1.9 ; $p = 0.0006$
ST-grey matter	9.8 ± 2.0	8.1 ± 1.3 ; $p < 0.0001$	11.1 ± 2.3 ; $p = 0.0062$
Infratentorial compartment-WM	7.6 ± 1.2	6.3 ± 0.9 ; $p < 0.0001$	8.5 ± 1.9 ; $p = 0.0055$
Cerebrospinal fluid	1.2 ± 0.5	1.0 ± 0.4 ; $p = 0.0042$	1.4 ± 0.5 ; $p = 0.17$

FBP, filtered back projection; ST, supra tentorial compartment; WM, white matter.

Mean and standard deviation of signal-to-noise ratios in standard-dose acquisitions with conventional distributed detector and low-dose examinations using an integrated circuit detector and iterative reconstruction in addition to FBP.

p -values refer to comparisons with the standard-dose control group.

regularization algorithm. The latter estimates the variance of the image noise in different directions in each image pixel and adjusts the space-variant regularization function correspondingly.²¹ At this point, a number of studies have assessed the benefit of IR in head CT and the published dose-saving potential varies from 20% to 40%.^{7,15,18,22–26} In our own experience, use of sinogram-affirmed IR may increase SNR of grey and white matter by >40% but has only a relatively small effect on image sharpness.²⁷

While the iterative algorithms are currently subject to constant refinement, vendors are also aiming at decreasing scanner-related system-inherent noise by designing more noise efficient detectors. A conventional solid-state detector consists of a radiation-sensitive solid-state material, converting the absorbed X-rays into visible light. The latter is then detected by an attached silicon photodiode and converted into an electrical current. In a third step, the analogue current is amplified and converted into a digital signal. The amplification and analogue-to-digital conversion process are thereby performed on an external board, requiring analogue

connections between detector cells and the electronic circuit components of this board. On its way through the analogue cables, the signal is affected by ohmic resistance and capacitive loss through capacitive coupling. In contrast to the conventional detector type, the version assessed in our study integrates photodiode, pre-amplifiers and analogue-to-digital converters in one silicon chip. The shortening of the conducting pathways allows transportation of the digitized signal without losses, resulting in 70% reduction of power consumption, reduced heat dissipation and, most importantly, significant reduction of electronic noise. In the literature, the effect of this new detector type varies with scan protocol and CT application from 6% to 14% noise reduction.^{11–13} According to our own experience, the transition from a conventional discrete circuit detector to the integrated circuit detector is associated with >10% reduction of noise and almost 50% increase of image sharpness in neuro-CT applications.¹⁴ Interestingly, there is a significant correlation between tube current or patient size and the relative reduction in noise with the integrated circuit detectors.^{10,12,13} This is explained by the greater relative contribution of electronic noise in situations

Figure 1. Contrast-to-noise ratio (CNR) in standard-dose acquisitions with conventional distributed detector (CDD) vs low-dose examinations using integrated circuit detector (ICD) and iterative reconstruction (IR) in addition to filtered back projection (FBP). In the box plot diagrams, the line across the middle of the box identifies the median sample value; boxes extend from the 25th to the 75th quartile and whiskers down to the lowest and highest values.

Figure 2. Objectively measured image sharpness in standard-dose acquisitions with conventional distributed detector (CDD) vs low-dose examinations using integrated circuit detector (ICD) and iterative reconstruction (IR) in addition to filtered back projection (FBP). In the box plot diagrams, the line across the middle of the box identifies the median sample value; boxes extend from the 25th to the 75th quartile and whiskers down to the lowest and highest values. HU, Hounsfield unit.

of photon starvation and explicitly qualifies this detector for low-dose examinations.

In this study, we combined the noise-reducing qualities of advanced detector and reconstruction technique for aggressive adjustment of our head CT protocol. While the choice of tube current or CTDI level was based on our previous experience with IR and the integrated electronics detector, we demonstrate that good image quality can be preserved at only 60% of our standard dose. In fact, SNR values in supra- and infra-tentorial tissues were slightly higher in our low-dose protocol, although this did not translate into higher CNR or superior subjective image quality.

Our results are in line with recently published findings by Ozdoba et al²⁵ who assessed IR and a high-yield detector in a 34.9-mGy CTDI head CT protocol. Of note, in their study, a comparable degree of dose reduction was achieved by concomitant adjustment of tube current and voltage. From our own experience, however, reduction of tube voltage may be associated with significant increase of streak artefacts along the bony coverage of the posterior fossa. For this reason, we prefer exclusive

adjustment of current except for paediatric applications. Preservation of diagnostic image quality has also been reported by Wu et al¹⁸ for 36.7- and 33.6-mGy CTDI protocols and the use of a different IR algorithm. However, in that study, data were acquired by conventional detector, and the obtained CNR values were significantly lower.

In all assessment of dose-reducing strategies, quantification of image sharpness is vitally important. This is because sharpness and noise are essentially interdependent image-defining parameters, which can easily be traded by using different reconstruction algorithms or kernels. In our study, sharpness was assessed in terms of HU gradient along perpendicular lines across the skull and was quantified as change in HU per pixel. The reduction of sharpness with lower tube current was found to be relatively small and statistically insignificant, likely because of partial compensation by use of the high-yield detector alone. When IR reconstruction and integrated detector electronics are combined, restoration of noise level is accompanied by full improvement of sharpness to baseline range. This confirms genuine reduction of noise by the above techniques rather than mere trade-off for image sharpness.

Table 3. Subjective image quality scores in control and low-dose groups

Subjective image quality criteria	Control group Conventional distributed detector	Low-dose group Integrated circuit detector	
	FBP	FBP	Iterative reconstruction
Noise	1.6 (1.5)	2.5 (2.5); $p < 0.0001$	1.5 (1.5); $p = 0.40$
Grey matter/white matter	1.8 (2)	2.8 (3); $p < 0.0001$	1.7 (1.5); $p = 0.48$
Subarachnoid space	1.8 (2)	2.7 (3); $p < 0.0001$	1.8 (2); $p = 0.83$
Posterior fossa	2.1 (2)	3.2 (3); $p < 0.0001$	2.2 (2); $p = 0.20$
Diagnostic acceptability	1.7 (2)	2.7 (3); $p < 0.0001$	1.8 (2); $p = 0.51$

FBP, filtered back projection.

Mean and median (brackets) image quality scores in standard-dose acquisitions with conventional distributed detector and low-dose examinations using an integrated circuit detector and iterative reconstruction in addition to FBP. Image quality grading is provided for noise, grey-white matter differentiation, posterior fossa delineation and overall diagnostic acceptability. p -values refer to comparisons with the standard-dose control group.

Figure 3. Intra-individual comparison of techniques in a patient with serial CT scans. Image quality of 320 mAs full dose exam acquired by conventional detector and reconstructed by filtered back projection (FBP) (a) is compared with a low-dose 190 mAs scan using a more noise efficient detector, reconstructed by FBP (b) and iterative reconstruction (c).

Notably, the percentage dose reduction we claim for our low dose protocol is arbitrarily related to the institutional standard protocol that we previously used at our 128-slice scanner. However, protocols vary considerably with different CT scanners and image quality preferences. Therefore, all dose reduction efforts should ultimately be measured against the current reference levels. The latter range from a CTDI of 60 mGy according to a guideline of the American College of Radiology to a CTDI of 75 mGy according to the European Guidelines for Multislice CT.^{28,29} A CTDI of 33.2 mGy as used in our study hence represents a dose reduction of about 50% of the reference standard. This is a meaningful improvement in terms of collective dose and public health issues as well as individual risk, especially in patients in need for serial follow-up examinations.

Our study has a number of limitations. First, it focuses on image quality; a potential impact of technical changes on diagnostic accuracy has not been assessed. Second, the comparison was not intraindividual but rather based on different patient groups. However, as our cohorts were relatively large, we believe that

differences in head habitus should not have impacted our results. Third, the choice of our low-dose level was based on an intelligent guess from prior experience with both dose-reducing strategies. We did not perform a systematic titration of dose levels, and although our results suggest a CTDI of 33 mGy to be close to the currently achievable cut-off for non-inferior image quality, we cannot exclude a potential for even more ambitious dose reduction with the given techniques. In our study, the evaluation of image sharpness was not performed by measurement of modulation transfer functions. Our assessment of sharpness in terms of change of HU values between adjacent pixels across the skull interface is susceptible to partial volume effects and the particular anatomy, although we tried to limit such effects by performing the measurements on thin-section bone window kernel reconstructions. Finally, our findings are based on the techniques from one single vendor, and it is not clear how far our results may be generalized.

In summary, we demonstrate that combination of recent dose-reducing strategies such as more noise efficient detectors and IR

Figure 4. Intraindividual comparison of image quality in a patient with serial head CT scans. (a) A 320-mAs full-dose examination acquired by conventional detector and reconstructed by filtered back projection; (b) the corresponding low-dose 190-mAs scan using a noise efficient detector and iterative reconstruction (b). A small post-ischaemic lesion is noted in the head of the left caudate nucleus.

Figure 5. Example of image quality in the posterior fossa. A pontine lacunar infarct is visualized by low-dose 190-mAs CT, using integrated circuit detector and iterative reconstruction (a) as well as by T_1 spin echo sequence in MRI (b).

allows for meaningful dose reduction without compromise of standard image quality. With regard to a continued industrial focus on dose efficiency, further improvements are expected and

a more widespread implementation of such techniques may result in measurable reduction of population exposure in the near future.

REFERENCES

- Brenner DJ. Slowing the increase in the population dose resulting from CT scans. *Radiat Res* 2010; **174**: 809–15. doi: [10.1667/RR1859.1](https://doi.org/10.1667/RR1859.1)
- Berrington de González A, Darby S. Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries. *Lancet* 2004; **363**: 345–51.
- Brenner DJ, Hall EJ. Computed tomography—an increasing source of radiation exposure. *N Engl J Med* 2007; **357**: 2277–84. doi: [10.1056/NEJMr072149](https://doi.org/10.1056/NEJMr072149)
- Task Group on Control of Radiation Dose in Computed Tomography. Managing patient dose in computed tomography. A report of the International Commission on Radiological Protection. *Ann ICRP* 2000; **30**: 7–45. doi: [10.1016/S0146-6453\(01\)00049-5](https://doi.org/10.1016/S0146-6453(01)00049-5)
- Hall P, Adami HO, Trichopoulos D, Pedersen NL, Lagiou P, Ekblom A, et al. Effect of low doses of ionising radiation in infancy on cognitive function in adulthood: Swedish population based cohort study. *BMJ* 2004; **328**: 19. doi: [10.1136/bmj.328.7430.19](https://doi.org/10.1136/bmj.328.7430.19)
- Baummueller S, Winklehner A, Karlo C, Goetti R, Flohr T, Russi EW, et al. Low-dose CT of the lung: potential value of iterative reconstructions. *Eur Radiol* 2012; **22**: 2597–606. doi: [10.1007/s00330-012-2524-0](https://doi.org/10.1007/s00330-012-2524-0)
- Rapalino O, Kamalian S, Kamalian S, Payabvash S, Souza LC, Zhang D, et al. Cranial CT with adaptive statistical iterative reconstruction: improved image quality with concomitant radiation dose reduction. *AJNR Am J Neuroradiol* 2012; **33**: 609–15. doi: [10.3174/ajnr.A2826](https://doi.org/10.3174/ajnr.A2826)
- Vardhanabhuti V, Riordan RD, Mitchell GR, Hyde C, Roobottom CA. Image comparative assessment using iterative reconstructions: clinical comparison of low-dose abdominal/pelvic computed tomography between adaptive statistical, model-based iterative reconstructions and traditional filtered back projection in 65 patients. *Invest Radiol* 2014; **49**: 209–16. doi: [10.1097/RLL.0000000000000017](https://doi.org/10.1097/RLL.0000000000000017)
- Yin WH, Lu B, Li N, Han L, Hou ZH, Wu RZ, et al. Iterative reconstruction to preserve image quality and diagnostic accuracy at reduced radiation dose in coronary CT angiography: an intraindividual comparison. *JACC Cardiovasc Imaging* 2013; **6**: 1239–49. doi: [10.1016/j.jcmg.2013.08.008](https://doi.org/10.1016/j.jcmg.2013.08.008)
- Duan X, Wang J, Leng S, Schmidt B, Allmendinger T, Grant K, et al. Electronic noise in CT detectors: impact on image noise and artifacts. *AJR Am J Roentgenol* 2013; **201**: W626–32. doi: [10.2214/AJR.12.10234](https://doi.org/10.2214/AJR.12.10234)
- Liu Y, Leng S, Michalak GJ, Vrieze TJ, Duan X, Qu M, et al. Reducing image noise in computed tomography (CT) colonography: effect of an integrated circuit CT detector. *J Comput Assist Tomogr* 2014; **38**: 398–403. doi: [10.1097/RCT.0000000000000081](https://doi.org/10.1097/RCT.0000000000000081)
- Morsbach F, Bickelhaupt S, Rätzer S, Schmidt B, Alkadhi H. Integrated circuit detector technology in abdominal CT: added value in obese patients. *AJR Am J Roentgenol* 2014; **202**: 368–74. doi: [10.2214/AJR.13.10839](https://doi.org/10.2214/AJR.13.10839)
- Morsbach F, Desbiolles L, Plass A, Leschka S, Schmidt B, Falk V, et al. Stenosis quantification in coronary CT angiography: impact of an integrated circuit detector with iterative reconstruction. *Invest Radiol* 2013; **48**: 32–40. doi: [10.1097/RLL.0b013e318274cf82](https://doi.org/10.1097/RLL.0b013e318274cf82)
- Korn A, Bender B, Spira D, Schabel C, Bhadelia R, Claussen C, et al. Added value of integrated circuit detector in head CT: objective and subjective image quality in comparison to conventional detector design. *Acad Radiol* 2014; **21**: 1506–11. doi: [10.1016/j.acra.2014.07.012](https://doi.org/10.1016/j.acra.2014.07.012)
- Korn A, Fenchel M, Bender B, Danz S, Hauser TK, Ketelsen D, et al. Iterative reconstruction in head CT: image quality of routine and low-dose protocols in comparison with standard filtered back-projection. *AJNR Am J Neuroradiol* 2012; **33**: 218–24. doi: [10.3174/ajnr.A2749](https://doi.org/10.3174/ajnr.A2749)
- Shrimpton PC, Hillier MC, Lewis MA, Dunn M. National survey of doses from CT in the UK: 2003. *Br J Radiol* 2006; **79**: 968–80. doi: [10.1259/bjr/93277434](https://doi.org/10.1259/bjr/93277434)
- Schabel C, Fenchel M, Schmidt B, Flohr TG, Wuerslin C, Thomas C, et al. Clinical evaluation and potential radiation dose

- reduction of the novel sinogram-affirmed iterative reconstruction technique (SAFIRE) in abdominal computed tomography angiography. *Acad Radiol* 2013; **20**: 165–72. doi: [10.1016/j.acra.2012.08.015](https://doi.org/10.1016/j.acra.2012.08.015)
18. Wu TH, Hung SC, Sun JY, Lin CJ, Lin CH, Chiu CF, et al. How far can the radiation dose be lowered in head CT with iterative reconstruction? Analysis of imaging quality and diagnostic accuracy. *Eur Radiol* 2013; **23**: 2612–21. doi: [10.1007/s00330-013-2846-6](https://doi.org/10.1007/s00330-013-2846-6)
 19. Nuyts J, De Man B, Dupont P, Defrise M, Suetens P, Mortelmans L. Iterative reconstruction for helical CT: a simulation study. *Phys Med Biol* 1998; **43**: 729–37. doi: [10.1088/0031-9155/43/4/003](https://doi.org/10.1088/0031-9155/43/4/003)
 20. Thibault JB, Sauer KD, Bouman CA, Hsieh J. A three-dimensional statistical approach to improved image quality for multislice helical CT. *Med Phys* 2007; **34**: 4526–44. doi: [10.1118/1.2789499](https://doi.org/10.1118/1.2789499)
 21. Ghetti C, Palleri F, Serreli G, Ortenzia O, Ruffini L. Physical characterization of a new CT iterative reconstruction method operating in sinogram space. *J Appl Clin Med Phys* 2013; **14**: 4347. doi: [10.1120/jacmp.v14i4.4347](https://doi.org/10.1120/jacmp.v14i4.4347)
 22. Becker HC, Augart D, Karpitschka M, Ulzheimer S, Bamberg F, Morhard D, et al. Radiation exposure and image quality of normal computed tomography brain images acquired with automated and organ-based tube current modulation multiband filtering and iterative reconstruction. *Invest Radiol* 2012; **47**: 202–7. doi: [10.1097/rli.0b013e31823a86d5](https://doi.org/10.1097/rli.0b013e31823a86d5)
 23. Kilic K, Erbas G, Guryildirim M, Arac M, Ilgit E, Coskun B. Lowering the dose in head CT using adaptive statistical iterative reconstruction. *AJNR Am J Neuroradiol* 2011; **32**: 1578–82. doi: [10.3174/ajnr.A2585](https://doi.org/10.3174/ajnr.A2585)
 24. Komlosi P, Zhang Y, Leiva-Salinas C, Ornan D, Patrie JT, Xin W, et al. Adaptive statistical iterative reconstruction reduces patient radiation dose in neuroradiology CT studies. *Neuroradiology* 2014; **56**: 187–93. doi: [10.1007/s00234-013-1313-z](https://doi.org/10.1007/s00234-013-1313-z)
 25. Ozdoba C, Slotboom J, Schroth G, Ulzheimer S, Kottke R, Watzal H, et al. Dose reduction in standard head CT: first results from a new scanner using iterative reconstruction and a new detector type in comparison with two previous generations of multi-slice CT. *Clin Neuroradiol* 2014; **24**: 23–8. doi: [10.1007/s00062-013-0263-5](https://doi.org/10.1007/s00062-013-0263-5)
 26. Vorona GA, Zuccoli G, Sutcliffe T, Clayton BL, Ceschin RC, Panigrahy A. The use of adaptive statistical iterative reconstruction in pediatric head CT: a feasibility study. *AJNR Am J Neuroradiol* 2013; **34**: 205–11. doi: [10.3174/ajnr.A3122](https://doi.org/10.3174/ajnr.A3122)
 27. Korn A, Bender B, Fenchel M, Spira D, Schabel C, Thomas C, et al. Sinogram affirmed iterative reconstruction in head CT: improvement of objective and subjective image quality with concomitant radiation dose reduction. *Eur J Radiol* 2013; **82**: 1431–5. doi: [10.1016/j.ejrad.2013.03.011](https://doi.org/10.1016/j.ejrad.2013.03.011)
 28. Lieto RP, Gray JE, Ruckdeschel TG, Martin MC, Brink JA, Strauss KJ, et al. ACR-AAPM practice parameter for diagnostic reference levels and achievable doses in medical X-ray imaging. Practice Guideline Amended 2014. Available from: http://www.acr.org/~media/ACR/Documents/PGTS/guidelines/Reference_Levels.pdf
 29. Bongartz GZ, Golding SJ, Jurik AG, Leonardi M, van Persijn van Meerten E, Rodríguez R, et al. European guidelines for multislice computed tomography. 2004. Available from: <http://www.drs.dk/guidelines/ct/quality/index.htm>