

Image quality of iterative reconstruction in cranial CT imaging: comparison of model-based iterative reconstruction (MBIR) and adaptive statistical iterative reconstruction (ASiR)

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Abstract

Objectives The purpose of this study was to compare cranial CT (CCT) image quality (IQ) of the MBIR algorithm with standard iterative reconstruction (ASiR).

Methods In this institutional review board (IRB)-approved study, raw data sets of 100 unenhanced CCT examinations (120 kV, 50–260 mAs, 20 mm collimation, 0.984 pitch) were reconstructed with both ASiR and MBIR. Signal-to-noise (SNR) and contrast-to-noise (CNR) were calculated from attenuation values measured in caudate nucleus, frontal white matter, anterior ventricle horn, fourth ventricle, and pons. Two radiologists, who were blinded to the reconstruction algorithms, evaluated anonymized multiplanar reformations of 2.5 mm with respect to depiction of different parenchymal structures and impact of artefacts on IQ with a five-point scale (0: unacceptable, 1: less than average, 2: average, 3: above average, 4: excellent).

Results MBIR decreased artefacts more effectively than ASiR ($p < 0.01$). The median depiction score for MBIR was 3, whereas the median value for ASiR was 2 ($p < 0.01$). SNR and CNR were significantly higher in MBIR than ASiR ($p < 0.01$).

Conclusions MBIR showed significant improvement of IQ parameters compared to ASiR. As CCT is an examination that is frequently required, the use of MBIR may allow for substantial reduction of radiation exposure caused by medical diagnostics.

Key Points

- Model-Based iterative reconstruction (MBIR) effectively decreased artefacts in cranial CT.
- MBIR reconstructed images were rated with significantly higher scores for image quality.
- Model-Based iterative reconstruction may allow reduced-dose diagnostic examination protocols.

Keywords Iterative reconstruction · Cranial CT · Image quality enhancement · Depiction · Artefacts

Introduction

Computed tomography (CT) is an increasingly important tool in diagnostic imaging. Between 1995 and 2007, Larson et al. [1, 2] reported a 16 % annual increase in the number of CT examinations during visits to American and Canadian emergency departments (ED). Cranial CT (CCT), at approximately 40 %, was the most frequent CT examination [1, 2]. The most common and important indications for CCT were headache, head injury, vertigo, and convulsions [1, 2]. For the reporting radiologist, the evaluation of CCT images is a challenging task. Apart from the visualization of the whole cerebrum, cerebellum, and skull base, a critical aspect of CCT imaging is the visually sharp presentation of the grey and white matter of the basal ganglia, the intracranial vessels, the ventricular system, and the cerebrospinal fluid surrounding the mesencephalon and the brain [3]. Streaks and dark bands are common artefacts, especially in the posterior fossa, caused by beam hardening [4, 5]. On one hand, artefacts may superimpose small bleeding or ischemic areas, but on the other, artefacts themselves can be mistaken as pathological findings.

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Iterative reconstruction algorithms, which were introduced to improve image quality [6], have been shown to exhibit diagnostic image quality, while dose is reduced in CT examinations [7–10]. In contrast to the commonly used filtered back projection (FBP), adaptive statistical iterative reconstruction (ASiR; GE Healthcare, Waukesha, WI) is an image reconstruction technique that models system noise statistics, with gains in image quality compared to noise filtering techniques [8, 9]. ASiR has already been shown to improve image quality in CCT [11], and is valuable in retaining diagnostic image quality in dose-reduced CCT imaging [12, 13].

The model-based iterative reconstruction (MBIR, Veo (GE Healthcare, Waukesha, WI)) is a further development of the ASiR technology. The reconstruction process considers more information for data modelling (i.e., system optics such as X-ray physics and interactions with the human body) [9, 14]. With regard to the image quality and the potential for dose reduction, MBIR has outperformed ASiR in multiple studies using phantoms and investigating several body regions [15–22].

Although CCT is the examination most frequently required in emergency CT imaging, to date, very few phantom studies have investigated the value of MBIR in CCT imaging [23]. The aim of this prospective patient study was to compare image quality of the MBIR algorithm with standard iterative reconstruction (ASiR) of cranial CT.

Materials and methods

Patient population

The study was approved by the local ethics review board. All patients provided written informed consent before examination. Patients under the age of 18 years and patients suffering multiple severe trauma injuries were excluded from the study. A minimum of 92 cases aimed to acquire statistical significance at $p=0.05$. A total of 108 patients were prospectively included, and were examined with clinical indication for cranial CT between January and March 2013. Due to severe motion artefacts, eight cases were excluded from evaluation, leaving 100 patients (52 male, 48 female) who were included in the study.

The underlying cause of accidents were fall ($n=53$), beating/assault ($n=14$), traffic accident ($n=8$), non-defined trauma ($n=11$), stroke ($n=5$), tumour ($n=3$), collapse ($n=2$), and other ($n=4$). Findings were intracranial bleeding ($n=14$), extracranial hematoma ($n=14$), fracture ($n=14$), infarction ($n=5$), and other ($n=4$), and 60 patients had no pathological findings. The age of patients ranged from 20 to 91 years, with an average of 54 years. Patient demographics are included in Table 1.

Table 1 Patient Demographics

| | |
|---|--------------------------|
| Number of patients | |
| 100 patients included; 52 male, 48 female | |
| Age of patients | |
| Range from 20 to 91 years, 54 years average | |
| Indications for CCT | |
| 53 | fall |
| 14 | beating/assault |
| 8 | traffic accident |
| 11 | non-defined trauma |
| 5 | stroke |
| 3 | tumour |
| 2 | collapse |
| 4 | other |
| Findings in CCT | |
| 14 | intracranial bleeding |
| 14 | extracranial hematoma |
| 14 | fracture |
| 8 | infarction |
| 4 | other |
| 60 | no pathological findings |

Acquisition of images

All included patients received an unenhanced cranial CT performed on a Discovery CT750 HD unit (GE Healthcare, Waukesha, WI). The patients were examined in the supine position, and examined in sequential pitch in craniocaudal direction with tilted gantry to achieve a beam projection parallel to the skull base. The institutional standard protocol included examination parameters of 120 kV peak tube voltage, 50–260 mAs tube current, 20 mm detector collimation, and 0.984 pitch factor, based on recommendations of the European Guidelines on Quality Criteria for Computed Tomography [3, 11]. Patient-specific attenuation values in the CT planning scout(s) were matched with tube current values using the standard lookup table provided by the vendor. Additionally, the tube modulation was driven and limited by a so-called noise index (NI), which was set to 50. NI represents the measurement for an image noise threshold and is based on the maximum allowed standard deviation of Hounsfield units in a water phantom [3, 24–26]. Raw data sets with a slice thickness of 0.625 mm were reconstructed using two types of iterative reconstruction algorithms: MBIR and 60 %-weighted ASiR. The ASiR weighting of 60 % indicates a blend of 60 % ASiR and 40 % FBP images. A higher percentage of ASiR weighting results in increased noise reduction but also blurring [11, 12], and the 60 % weighting was chosen to achieve a good balance of noise reduction and image sharpness. MBIR is an iterative reconstruction

technique with no blending of FBP images. Multiplanar reformations (MPRs) were performed with an identical slice thickness of 2.5 mm [3, 27, 28]. ASiR reconstructed images were released to the clinical routine. The elapsed time for reconstruction was recorded by the technician. Prior to evaluation, information with respect to the patient or to the reconstruction algorithms used was removed to allow blinded reading.

Evaluation of radiation dose

Dose parameters were recorded in dose-length-product (DLP [mGy × cm]) and volume-weighted computed tomography dose index (CTDIvol, [mGy]). Effective dose [mSv] was calculated from DLP multiplied by a conversion factor (0.0019 mSv/(mGy × cm) as published by Deak et al. [29], and evaluated using ICRP Publication 103 [30]).

Statistical evaluation of image quality

For the evaluation of image quality, mean attenuation values (MAVs) and standard deviation (SD) were measured. Measurements were performed using the Advantage Workstation AW VolumeShare 5 (GE Healthcare, Waukesha, WI). Spherical volumes of interest (VOIs) of 5 mm diameter were placed in the images in identical positions in both ASiR and MBIR: in the cerebrospinal fluid of the left anterior horn of the lateral ventricle and in the fourth ventricle, in the grey matter of the left caudate nucleus, in the white matter of the frontal lobe and in the pons, and in the air anterior of the forehead (Fig. 1). If necessary, the VOI diameter was scaled down, with a minimum diameter of 3 mm to avoid partial volume effects. The minimum number of voxels was always above 10. Downscaling of VOI was necessary in 56 of 100 cases. Signal-to-noise ratio (SNR) was calculated from the quotient of mean attenuation value and corresponding standard deviation measured in the VOI [13]. Contrast-to-noise ratio (CNR) is an indicator for the depiction of different anatomical structures related to differences in signal intensity of an interesting tissue compared to the signal of a reference tissue/structure related to pure image noise [31, 32]. We calculated CNR for the differentiation of grey to white matter and cerebrospinal fluid to white matter, in relation to the measured SD of air [31, 32]. The acquired values of ASiR and MBIR reconstructed image sets were visualized with bar charts and compared with ANOVA to assess statistical significance. Level of significance (α) was set at 0.05.

Evaluation of depiction and impact of artefacts on image quality

Two radiologists (with two and four years of experience in CT imaging), blinded to the reconstruction algorithms,

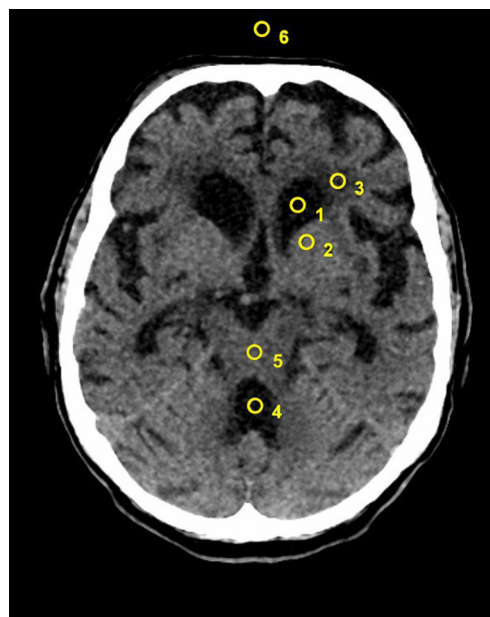


Fig. 1 Example placement of volume of interest (VOI) Example placement of volumes of interest with 5 mm diameter in left lateral ventricle (1), caudate nucleus (2), frontal white matter (3), fourth ventricle (4), pons (5) and anterior air (6). The centre of VOI did not need to be placed in the same image slice. Signal-to-noise and contrast-to-noise ratios were calculated from measured mean attenuation values and standard deviation

independently evaluated the depiction of anatomical structures and the impact of artefacts on image quality. The anatomical structures were assigned to four groups, as shown in Table 2. The evaluators' attention was especially focused on the depiction of the subarachnoid space, the grey and white matter differentiation, the basal ganglia, and lobulation of the cerebellum, according to the European Guidelines on Quality Criteria for Computed Tomography [3].

The depiction of anatomical structures was graded on a five-point scale, as shown in Table 3a [11]. The same five-point-scale was used for the evaluation of image quality in general, as shown in Table 3b. The results were visualized with bar charts. Statistical significance was assessed with the Mann–Whitney U test. The intraclass correlation coefficient (ICC) was calculated to analyze the variability of given scores within ASiR and MBIR reconstruction groups, the subgroups of evaluated anatomical structures, and between the evaluators.

Results

The average effective dose of CCT was 0.93 ± 0.13 mSv, according to ICRP 103 [29], with an average DLP of 491.1 mGy × cm. The average reconstruction time was 48.5 ± 5.0 seconds for ASiR and $1,920.2 \pm 112.8$ seconds (32 ± 1.88 minutes) for MBIR, 39.6-fold longer than ASiR.

Table 2 Anatomical Regions

| CSF group | GWD group | BC group | CB group |
|--|--|---|---|
| <ul style="list-style-type: none"> • subarachnoid space • ventricular system | <ul style="list-style-type: none"> • basal ganglia • grey and white matter differentiation | <ul style="list-style-type: none"> • basal cistem • cavernous sinus • medial cerebral arteries | <ul style="list-style-type: none"> • cerebellum • pons • medulla oblongata • basilar artery |

*Abbreviations: CSF = cerebrospinal fluid; GWD = grey and white matter differentiation; BC = basal cistem; CB - cerebellum

Average signal-to-noise ratios calculated for the parenchymal brain tissues were 28.9 % higher ($p < 0.01$) in MBIR than in ASiR reconstructed images (Table 4 and Fig. 2a). However, the signal-to-noise ratios calculated for the ventricular system showed no significant difference (ASiR, 1.18; MBIR, 1.10; $p = 0.2$) between the image reconstructions.

Contrast-to-noise ratio was significantly higher (37.29 % average difference, $p < 0.01$) in MBIR than in ASiR reconstructed images (Table 5 and Fig. 2b).

In the qualitative assessment of the depiction of anatomical structures, MBIR was evaluated with significantly better scores than ASiR (median score for MBIR, 3; median score for ASiR, 2; $p < 0.01$; Table 6 and Fig. 3a). In terms of the general image quality, MBIR showed significantly higher scores than ASiR (median score for MBIR, 2; median score for ASiR, 1; $p < 0.01$; Table 7 and Fig. 3b).

An intraclass correlation coefficient (ICC) of 0.973 revealed a very high concordance between the two observers. ICC for all subgroups, CSF group, GWD group, BC group, and CB group were 0.50, 0.48, 0.37, 0.51, and 0.54, respectively, revealing a fair to moderate agreement among the groups.

Discussion

Reliable diagnosis is important for the clinical management of diseases and injuries of the central nervous system. Diagnostic image quality, including the sharp visual reproduction of anatomical structures, plays a major role in cranial CT imaging [3].

This prospective study compared the image quality of CCT reconstructed with ASiR and the new MBIR algorithm, and revealed a high potential for MBIR in the improvement of image quality.

Significantly higher scores for the depiction of anatomical structures (median 3.0, indicating “above average”) and significantly higher values for contrast-to-noise ratio for MBIR suggest that MBIR is superior to ASiR in terms of depiction and sharp reproduction of anatomical structures. The better quality of reconstructed images associated with MBIR versus ASiR was confirmed by significantly higher signal-to-noise ratios calculated for parenchymal structures. Low and equal signal-to-noise ratios calculated for the cerebrospinal fluid in both ASiR and MBIR may be explained by higher values for standard deviation caused by smaller VOIs, adjusted to

Table 3 Five-Point Scale for Qualitative Assessment

| Score | Grade | Statement | Example |
|-------|---------------|---|--|
| a) | | | |
| 0 | Unacceptable | Non-diagnostic image quality | Distorted or blurry depiction of the anatomical structures |
| 1 | Below average | Relevant diagnostics hampered | Anatomical structures are definable but superimposed by more noise than usual |
| 2 | Average | Relevant diagnostics possible | Anatomical structures are definable with a common noise level |
| 3 | Above average | More than relevant diagnostics possible | Visually sharp and homogenous depiction of the anatomical structures with a noise level clearly below the common noise level |
| 4 | Excellent | Optimal images without recognizable limitations according to image processing | Structures are visualized in rich detail |
| b) | | | |
| 0 | Unacceptable | Non-diagnostic image quality | Distorted depiction or complete superimposition of anatomic structures due to artefacts |
| 1 | Below average | Relevant diagnostics hampered | Substantial superimposition of anatomical structures due to artefacts |
| 2 | Average | Relevant diagnostics possible | Partial superimposition of anatomical structures due to artefacts |
| 3 | Above average | More than relevant diagnostics possible | Negligible artefacts and noise |
| 4 | Excellent | Optimal images without recognizable limitations according to image processing | No artefacts |

Table 4 Quantitative Assessment

| Signal-to-Noise Ratio (SNR) | | | | | |
|-----------------------------|-----------|-----------|-----------|-----------|-----------|
| | CN | LV | WM | PN | 4V |
| ASiR | 5.29±0.75 | 0.95±0.32 | 4.57±0.69 | 4.98±0.84 | 1.28±0.34 |
| MBiR | 6.15±0.9 | 0.86±0.35 | 5.15±0.8 | 6.11±1.05 | 1.29±0.41 |

*Abbreviations: SNR = signal-to-noise ratio; ASiR = adaptive statistical iterative reconstruction; MBiR = model-based iterative reconstruction; CN = caudate nucleus; LV = lateral ventricle; WM = white matter; PN = pons, 4V = fourth ventricle

narrow ventricles in 53 of 100 cases, and low mean attenuation values for fluid near 0 (MAV [HU]: ASiR 2.37, MBiR 3.11) and equal standard deviation (SD: ASiR 0.74, MBiR 0.69), resulting in low values for SNR.

The results of this patient study were concordant with those of prior studies, in which MBiR showed more efficient reduction of artefacts in phantom models [33, 34]. In MBiR reconstructed images where the evaluators assigned lower artefact scores, streaks and dark bands were diminished (Figs. 3b and 4b). The reason diminished beam hardening effects with MBiR may be explained by the consideration of the X-ray behaviour in human models [33, 35, 36]. False absorption values are eliminated during the iterative calculations of the

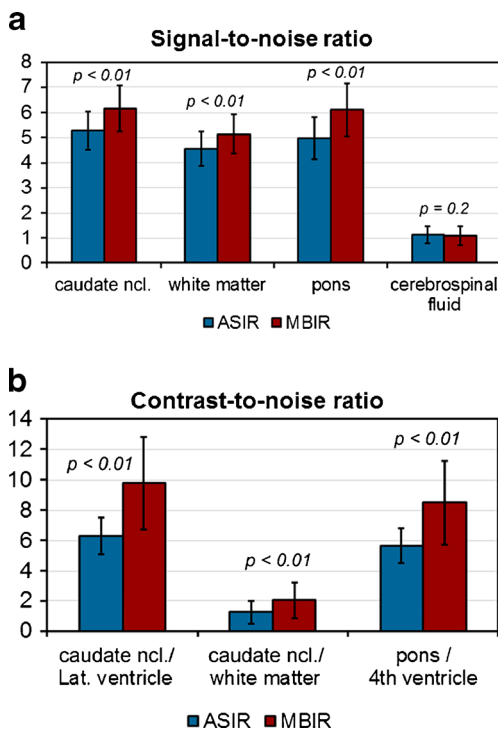


Fig. 2 Quantitative Assessment **a)** The average signal-to-noise ratios (SNR) of caudate nucleus, white matter, and pons were significantly higher in MBiR than ASiR. In cerebrospinal fluid, SNR was equal in MBiR and ASiR. **b)** Average contrast-to-noise ratios were calculated for caudate nucleus to lateral ventricle, grey/white matter differentiation, and pons to fourth ventricle. Contrast-to-noise ratio was significantly higher in MBiR than in ASiR

Table 5 Quantitative Assessment

| Contrast-to-Noise Ratio (CNR) | | | |
|-------------------------------|-----------|-----------|-----------|
| | CN/LV | CN/WM | PN/4V |
| ASiR | 6.28±1.2 | 1.25±0.78 | 5.63±1.16 |
| MBiR | 9.78±3.03 | 2.04±1.19 | 8.49±2.77 |

*Abbreviations: CNR = contrast-to-noise ratio; ASiR = adaptive statistical iterative reconstruction; MBiR = model-based iterative reconstruction; CN = caudate nucleus; LV = lateral ventricle; WM = white matter; PN = pons, 4V = fourth ventricle

MBiR algorithm, which accounts for X-ray physics compared to ASiR [30, 36, 37].

A reconstruction time of 32 minutes for MBiR (39.6-fold longer than for ASiR) indicates that MBiR is not yet an appropriate algorithm in emergency settings, and therefore developers should focus on speeding up the reconstruction process.

The diagnostic accuracy for the detection of pathological findings such as bleeding, infarction, or fractures could not be evaluated in this study. Further studies to assess the diagnostic accuracy of iterative reconstructed CCT imaging will be needed, including a higher number of cases and comparison with a gold standard such as magnetic resonance imaging of the head.

This study was limited to iterative reconstruction algorithms specific for CT machines manufactured by General Electric (GE Healthcare, Waukesha, WI). However, the

Table 6 Qualitative Assessment

| Visual Assessment of Depiction | | | |
|--------------------------------|-----|-----------|-----------|
| | | ASiR | MBiR |
| Axial | CSF | 2.37±0.74 | 3.11±0.69 |
| | GWD | 2.27±0.62 | 2.93±0.67 |
| | BC | 2.17±0.75 | 3.1±0.9 |
| | CB | 1.91±0.79 | 2.95±0.9 |
| Sagittal | CSF | 2.3±0.78 | 2.9±0.58 |
| | GWD | 2.2±0.66 | 2.77±0.54 |
| | BC | 2.18±0.8 | 2.72±0.8 |
| Coronal | CB | 1.83±0.89 | 2.29±1.04 |
| | CSF | 2.07±0.79 | 2.77±0.64 |
| | GWD | 2.03±0.58 | 2.64±0.56 |
| | BC | 1.76±0.79 | 2.45±0.89 |
| | CB | 1.71±0.83 | 2.34±0.91 |

Scores: 0: non-diagnostic; 1: less than average; 2: average; 3: above average; 4: excellent

*Abbreviations: ASiR = adaptive statistical iterative reconstruction; MBiR = model-based iterative reconstruction; CSF = cerebrospinal fluid; GWD = grey and white matter differentiation; BC = basal cistern; CB = cerebellum

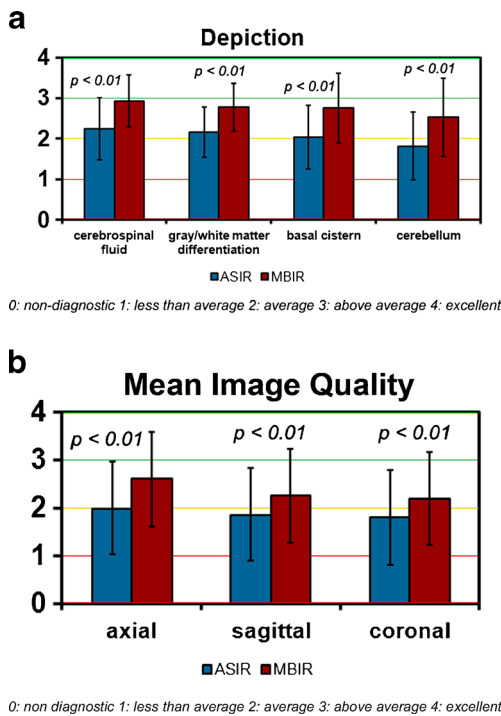


Fig. 3 Qualitative Assessment **a**) Average scores given for the depiction of anatomical structures were significantly higher in MBiR than in ASiR. Median score was 3 for MBiR and 2 for ASiR. **b**) Average scores for the general image quality were significantly higher in MBiR than in ASiR. Median scores were 2 for MBiR and 1 for ASiR

iterative reconstruction technique is available for other CT machines and from other vendors. Six different iterative reconstruction algorithms have already been quantitatively evaluated in a phantom model by Löve et al. [23]. To investigate whether those results are transferable to humans and to compare the impact of iterative reconstruction algorithms of different vendors on image quality in cranial CT, further studies, including patient trials and qualitative assessment, are needed.

In summary, MBiR was shown to be superior to ASiR in terms of reduction of artefacts and consistent diagnostic image quality. The effective reduction of artefacts with MBiR may be particularly helpful for radiologists in order to avoid missing small lesions close to streaks and dark bands or mistaking

Table 7 Qualitative Assessment

| Visual Assessment of Image Quality | | |
|------------------------------------|-----------|-----------|
| | ASiR | MBiR |
| Axial | 1.98±0.97 | 2.6±1.0 |
| Sagittal | 1.85±0.96 | 2.25±0.98 |
| Coronal | 1.79±0.99 | 2.19±0.96 |

Scores: 0: no artefacts; 1: less than average; 2: average; 3: above average; 4: excellent

*Abbreviations: ASiR = adaptive statistical iterative reconstruction; MBiR = model-based iterative reconstruction

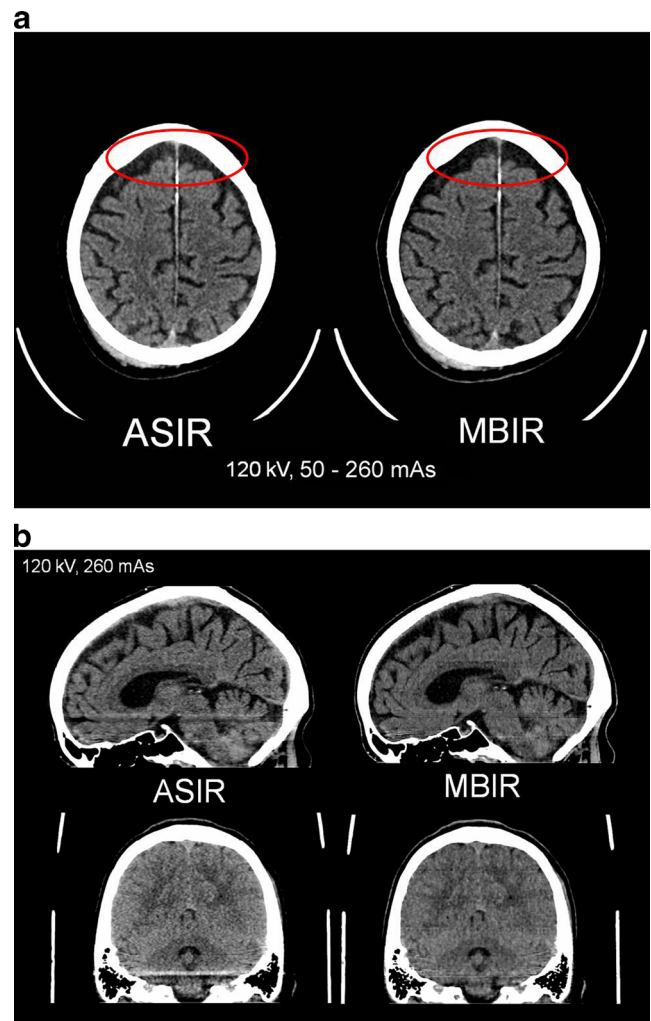


Fig. 4 Exemplary comparison of ASiR and MBiR multiplanar reformations **a**) Noise in the subarachnoid space in ASiR compared to corresponding MBiR. **b**) Example of ASiR and MBiR MPRs, showing the more effective reduction of streak artefacts in MBiR than in corresponding ASiR images

artefacts for lesions. Furthermore, the improvement of the image quality may allow reduced-dose diagnostic examination protocols. As CCT is the method most often utilized in CT imaging, this may contribute to greater protection of the population from increasing radiation risk associated with medical applications [38, 39]. To achieve faster workflow with the implementation of these protocols, manufacturers must develop faster processing of the iterative calculations and increased computer performance. With these technical improvements, MBiR would appear to be a promising technique to for replace both ASiR and FBP in clinical routine and to allow for reduced-dose examination protocols.

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related to the subject matter of the article. One of the authors has significant statistical expertise. Institutional Review Board approval was obtained. Written informed consent was obtained from all subjects (patients) in this study. Study subjects or cohorts have not been previously reported. Methodology: prospective non-randomised controlled trial, performed at one institution.

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