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ORIGINAL ARTICLE

Comparison of image quality between filtered back-projection and the adaptive statistical and novel model-based iterative reconstruction techniques in abdominal CT for renal calculi

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Abstract
Objectives To compare image quality on computed tomographic (CT) images acquired with filtered back-projection (FBP), adaptive statistical iterative reconstruction (ASIR) and model-based iterative reconstruction (MBIR) techniques in CT kidney/ureter/bladder (KUB) examination.
Methods Eighteen patients underwent standard protocol CT KUB at our institution. The same raw data were reconstructed using FBP, ASIR and MBIR. Objective [mean image noise, contrast-to-noise ratio (CNR) for kidney and mean attenuation values of subcutaneous fat] and subjective image parameters (image noise, image contrast, overall visibility of kidneys/ureters/bladder, visibility of small structures, and overall diagnostic confidence) were assessed using a scoring system from 1 (best) to 5 (worst).
Results Objective image measurements revealed significantly less image noise and higher CNR and the same fat attenuation values for the MBIR technique ($P<0.05$). MBIR scored best in all the subjective image parameters ($P<0.001$) with averages ranging between 2.05–2.73 for MBIR, 2.95–3.10 for ASIR and 3.08–3.31 for FBP. No significant difference was observed between FBP and ASIR ($P>0.05$), while there was a significant difference between ASIR vs. MBIR ($P<0.05$). The mean effective dose was 3 mSv.
Conclusion MBIR shows superior reduction in noise and improved image quality (both objective and subjective analysis) compared with ASIR and FBP CT KUB examinations.
Main Messages
- *There are many reconstruction options in CT.*
- *Novel model-based iterative reconstruction (MBIR) showed the least noise and optimal image quality.*
- *For CT of the kidneys/ureters/bladder, MBIR should be utilised, if available.*
- *Further studies to reduce the dose while maintaining image quality should be pursued.*

Keywords Computed tomography · Image processing · Urolithiasis · Image enhancement

Introduction

The CT KUB is now regarded as the imaging investigation of choice for most patients with suspected renal stone disease because of its unrivalled stone detection capacity, speed and non-dependence on intravenous contrast medium administration [1, 2]. There are well-established practices of using low-dose CT in the detection of renal stone disease resulting in inherently 'noiser' images than in conventional CT examinations but without compromising diagnostic confidence for this clinical entity [3, 4]. In this article, we focus on the emergence of new iterative reconstruction techniques that have developed over the past few years. Traditional filtered back-projection (FBP) has given way to novel iterative reconstruction algorithms, and its use has increasingly been employed. For example, General Electric (GE, Milwaukee, WI, USA) has introduced adaptive statistical iterative reconstruction (ASIR), which uses a blend of filtered back-projection images with

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iteratively reconstructed images. Centres that have this technology use a varying degree of ASIR with most adopting a value between a 20 and 40 % ASIR blend. More recently, GE has brought out model-based iterative reconstruction (MBIR) and obtained FDA approval for this technique in September 2011. The specifics of each reconstruction algorithm will be discussed in detail later. Phantom studies have shown promising results using MBIR in noise reduction [5]. Some clinical studies have also shown promising results using ASIR [6–8], but to date few assessments have been made of the use of MBIR in clinical practice [9–11]. There is no recent literature on the use of MBIR in CT KUB. The purpose of this study was to perform a comparison of the image quality of CT KUB examinations acquired with three different reconstruction algorithms—FBP, ASIR and MBIR.

Materials and methods

The study was approved by our institutional review board. Due to the nature of the study, no consent or ethical approval was required. Eighteen consecutive patients (in a 4-week period) who underwent standard protocol CT KUB as an outpatient episode for investigation of suspected or known urolithiasis at our institution were chosen. The mean age was 42 years (range, 20–67; SD, 14.8) with a mean weight of 74.8 kg (range, 62–128; SD 17.5). Retrospectively, the same raw data were reconstructed using FBP, ASIR and MBIR. This resulted in 54 image data sets in total. The DLP for each examination was recorded and the effective dose calculated using a conversion factor of 0.015 mSv/(mGy × cm) [12].

CT technique

CT was performed with a commercial CT system (Discovery CT750 HD; GE Healthcare). We use automatic tube current modulation using noise index (NI) parameters for prescribing an acceptable image noise in clinical practice so that the amount of noise in an image would remain constant despite differing patient sizes [13]. At our institution we use an NI of 50 for CT KUB with acquisition performed at 1.25-mm slice thickness. Other scanning parameters are as follows: tube voltage, 120 kVp; pitch, 0.984:1; table speed, 39.37 mm per gantry rotation; helical acquisition mode; detector configuration, 64*0.625 mm; gantry rotation time, 0.5 s; reconstructed section thickness, 0.625, 2.5 mm and 5 mm; reconstructed section interval, 0.625 mm, 2.5 mm and 5 mm; standard reconstruction kernel.

Reconstruction algorithms

The differences among the three reconstruction techniques are related to the assumptions that each method makes in producing the final image from the raw data. FBP assumes that the focal spot on the x-ray tube is a point source, with a perfect pencil beam shape, and a point at the patient's body and at the detector is assumed to be a pixel (two- rather than three-dimensional). ASIR uses FBP as the building block for image reconstruction assuming the beam to be a perfect point source. It aims to improve image quality by focusing on noise reduction. In our institution we use a blending of 30 % of ASIR with FBP. Whilst ASIR still relies on FBP data sets, model-based iterative reconstruction builds a forward projection using dedicated system optics, taking into account every x-ray projection (in its true three-dimensional domain), and produces an image based on the raw data. Multiple iterations are performed to correct the residual error between the forward projection and acquired image. These algorithms also incorporate statistical noise information in the reconstruction process. The combination of system optic modelling and statistical modelling helps in noise reduction and results in truer image characteristics compared to FBP and ASIR. In addition, MBIR also accounts for noise from photon flux as well as system noise (e.g. electronic noise) from the CT system itself.

Table 1 Average quantitative values for image noise, mean attenuation values and contrast-to-noise ratio of three different reconstruction algorithms

	FBP		ASIR		MBIR	
Mean noise						
Mean	47.65		39.36		15.74	
SD	15.84		13.40		3.74	
Mean attenuation values						
Mean	−106.74		−106.75		−106.58	
SD	9.68		9.70		9.66	
Mean contrast-to-noise ratio						
	LT kidney	RT kidney	LT kidney	RT kidney	LT kidney	RT kidney
Mean	3.18	3.19	3.86	3.88	9.13	9.09
SD	0.97	0.97	1.20	1.20	2.02	1.82

Table 2 Bonferroni's multiple comparison test of mean differences in image noise for three different reconstruction algorithms

	Mean Diff.	95 % CI	
FBP vs. ASIR	8.285	1.252 to 15.32	$p<0.0001$
FBP vs. MBIR	31.91	24.88 to 38.94	$p<0.0001$
ASIR vs. MBIR	23.63	16.59 to 30.66	$p<0.0001$

Quantitative image analysis

Objective image analysis was performed using circular regions of interest (ROIs) drawn over several areas (size of between 1 and 3 cm^2). For each patient, ROIs were drawn over five contiguous images for each anatomical area. Image noise was taken from standard deviation values derived over three areas of subcutaneous fat (anterior abdominal wall, left buttock and right buttock). Mean attenuation values were taken as an average of the mean Hounsfield numbers over these same areas of subcutaneous fat. ROIs were also drawn over the upper poles of both kidneys. These values were used to calculate the contrast-to-noise ratio (CNR) for kidneys across three different reconstruction algorithms using the following equation:

$$CNR = (ROI_o - ROI_{sf}) / SD_n$$

ROI_o is the mean attenuation for the organ of interest, ROI_{sf} is the mean attenuation for the subcutaneous fat, and SD_n is the mean image noise.

Qualitative image analysis

Subjective analysis was performed by anonymising 54 data sets and displaying this in randomised order to two radiologists (with 7 and 15 years of consultant urogenital radiology experience). Each radiologist had access to axial and multiplanar reformats. Parameters assessed were: A: image noise (1: minimal, 2: less than average, 3: average, 4: above average, 5: unacceptable), B: image contrast (1: excellent, 2: above average, 3: acceptable, 4: suboptimal, 5: very poor), C: overall visibility of kidneys/ureters/bladder, D: visibility of small structures, e.g. small lymph nodes and adrenal glands (1: excellent visualisation, 2: above average visibility, 3: acceptable visibility, 4: suboptimal visibility, 5: unacceptable) and E: overall diagnostic confidence (1: completely confident, 2: probably confident, 3: confident only for limited clinical entity, 4: poor confident, 5: non-diagnostic examination). The scoring criteria were based on the European Guidelines for Quality Criteria for CT [14].

Statistical analysis

Quantitative data such as objective image noise and mean attenuation were analysed by comparing standard deviations, the 95 % confidence interval and statistical differences analysed using repeated analysis of variance (ANOVA) with post-test correction using the Bonferroni method. The interobserver variation between the two radiologists for each of the assessed subjective image quality parameters was estimated by using weighted kappa statistics. The Friedman test (with Dunn post-test) was used to test for equality of median scores among all subjective parameters.

Results

Quantitative

Table 1 shows the average quantitative values for the image noise, mean attenuation values and contrast-to-noise ratio of three different reconstruction algorithms. Table 2 shows

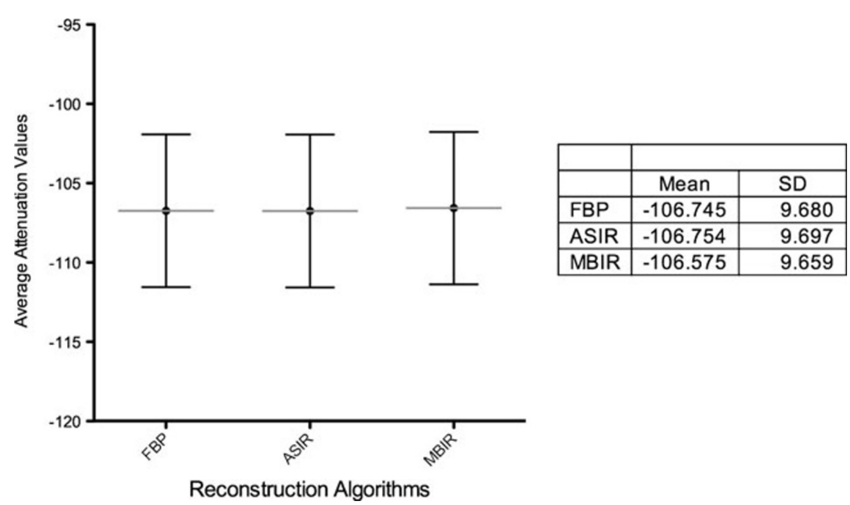

Fig. 1 Comparison of mean attenuation values among three reconstruction algorithms for subcutaneous fat in the left buttock. *Middle line* indicates average mean. *Error bars* indicate 95 % confidence intervals

repeated ANOVA with Bonferroni multiple comparison tests of mean differences in image noise. This supports the hypothesis that objective image noise shows a significant reduction with the new MBIR technique ($P<0.0001$). No significant differences were seen when comparing mean attenuation values for each method ($P>0.05$ with non-overlapping 95 % CI); see Fig. 1. MBIR shows superior CNR for the kidneys in comparison with subcutaneous fat ($P<0.05$), but this effect is likely to be predominantly due to the marked reduction in image noise seen with MBIR (see Fig. 2).

Qualitative

Mean qualitative scores between two raters are summarised in Table 3. MBIR scored best in all the subjective assessments of image parameters (image noise, image contrast, visibility of kidneys/ureters/bladder, visibility of small structures and overall diagnostic confidence) followed by ASIR then FBP ($P<0.001$). This is graphically illustrated in Fig. 3 (image noise), Fig. 4 (visibility of kidneys/ureters/bladder) and Fig. 5 (overall diagnostic confidence). Table 4 shows a summary of the Friedman test with Dunn's post-test for multiple comparisons for qualitative image noise. This illustrates that the scoring between FBP and ASIR shows no difference ($P>0.05$), but significance exists between ASIR vs. MBIR and FBP vs. MBIR ($P<0.05$). The interobserver variation (weighted kappa and standard errors) between the two radiologists were fair to moderate as follows: image noise [0.549 (SE:0.091)], image

Table 3 Mean qualitative scores between two raters

	FBP	ASIR	MBIR
Image noise			
Mean	3.23	2.95	2.05
SD	0.53	0.46	0.22
Lower 95 % CI	2.98	2.74	1.95
Upper 95 % CI	3.47	3.16	2.16
Image contrast			
Mean	3.31	2.81	2.25
SD	0.42	0.55	0.31
Lower 95 % CI	3.09	2.53	2.10
Upper 95 % CI	3.52	3.08	2.40
Visibility of kidneys/ureters/bladder			
Mean	3.08	3.05	2.65
SD	0.24	0.28	0.33
Lower 95 % CI	2.96	2.92	2.50
Upper 95 % CI	3.19	3.18	2.80
Visibility of small structures			
Mean	3.13	3.10	2.73
SD	0.43	0.42	0.34
Lower 95 % CI	2.93	2.91	2.56
Upper 95 % CI	3.32	3.30	2.89
Overall diagnostic confidence			
Mean	3.08	3.08	2.58
SD	0.44	0.44	0.29
Lower 95 % CI	2.87	2.87	2.44
Upper 95 % CI	3.28	3.28	2.71

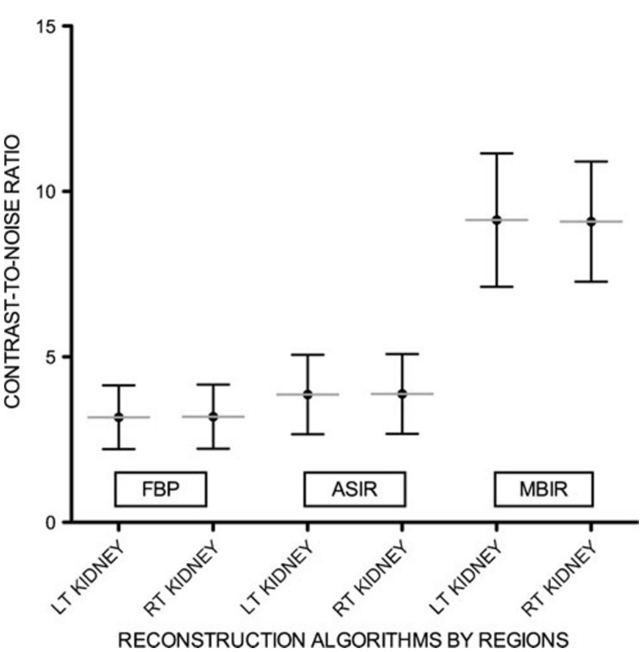

Fig. 2 Contrast-to-noise ratio of left and right kidneys of three reconstruction algorithms. *Middle line* indicates average mean. *Error bars* indicate 95 % confidence intervals

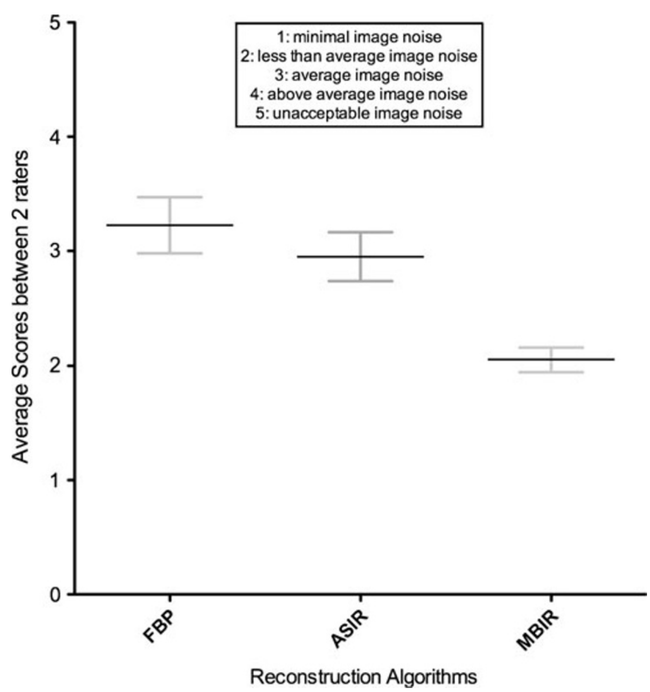

Fig. 3 Average scores between two raters on image noise. *Middle line* indicates mean scores. *Error bars* indicate 95 % confidence intervals

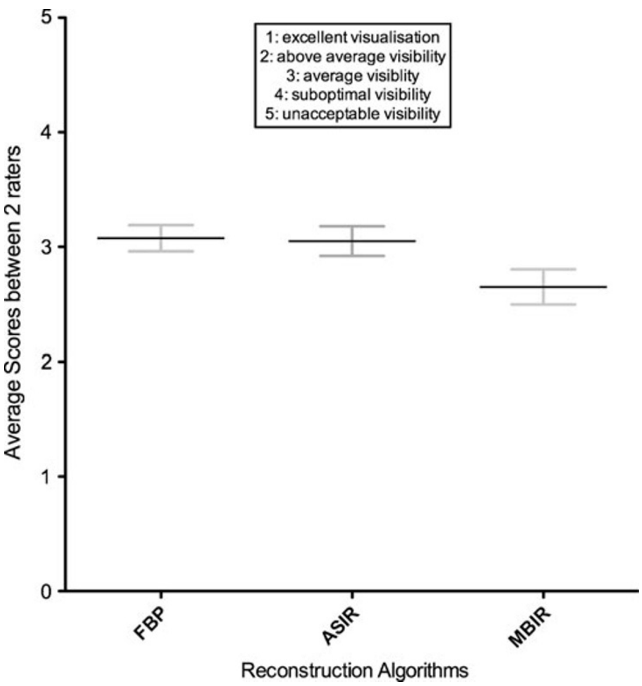

Fig. 4 Average scores between two raters on visibility of kidneys, ureters and bladder. *Middle line* indicates mean scores. *Error bars* indicate 95 % confidence intervals

contrast [0.261 (SE: 0.096)], visibility of kidneys/ureters/bladder [0.231 (0.098), visibility of small structures [0.394 (0.105) and overall diagnostic confidence [0.434 (0.094).

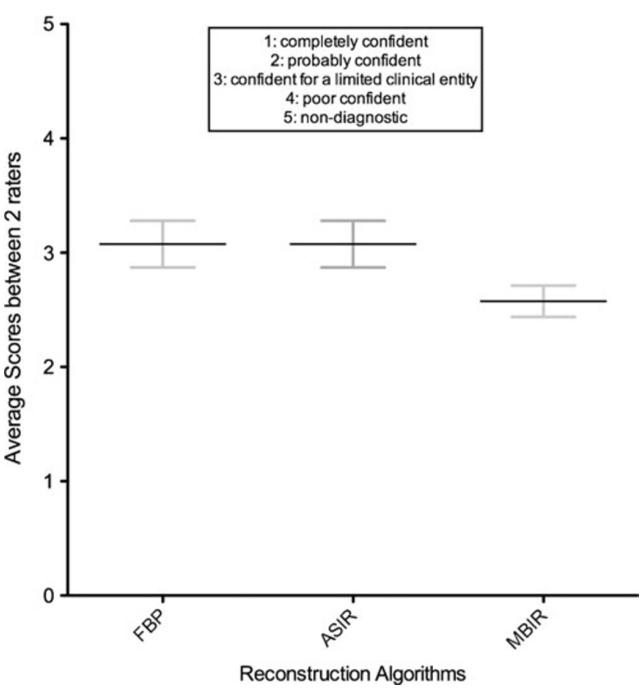

Fig. 5 Average scores between two raters on overall diagnostic confidence. *Middle line* indicates mean scores. *Error bars* indicate 95 % confidence intervals

Table 4 Friedman test with Dunn's multiple comparison test

Friedman test		
P value	<0.0001	
Friedman statistic	36.21	
Dunn's multiple comparison test	Difference in rank sum	Significant? $P<0.05$?
ASIR vs. FBP	−9.5	No
ASIR vs. MBIR	24.5	Yes
FBP vs. MBIR	34	Yes

Radiation dose

Images were acquired at a mean effective dose of 3 mSv (SD 2 mSv; mean DLP 202 mGy, SD 145.7); see Table 5.

Some side-by-side examples are shown in Figs. 6, 7, 8 and 9 for different-sized stones.

Discussion

Computed tomography has largely replaced excretory urography as the investigation of choice for assessment of renal colic and ureteric stones, with high sensitivity and specificity of 94 %–100 % and 97 % respectively [15–17]. In recent years, iterative reconstruction techniques have been introduced, predominantly by reducing noise to improve image quality. ASIR, one of the most widely studied iterative reconstruction techniques, is associated not only with improved image quality but also with significant dose reduction [5–8]. Better image quality with ASIR as compared to FBP was also observed in our series of patients, which is in keeping with previous study [18]. The novel iterative technique MBIR was associated with greater noise reduction and improved image quality compared to both ASIR and FBP. This was observed on both objective and subjective analysis in our study. Our results are in keeping with recent findings of some dose studies in other examinations such as spine [19, 20], posterior fossa angiography [21], abdomen [22] and ex vivo heart [23]. All these studies show that there is improved image quality, in particular reduced objective and subjective image noise compared with traditional FBP and ASIR.

Table 5 Radiation dose

	DLP	Effective dose (mSv)
Average	195.03	2.93
SD	138.91	2.08
Min.	93.57	1.40
Max.	692.49	10.39

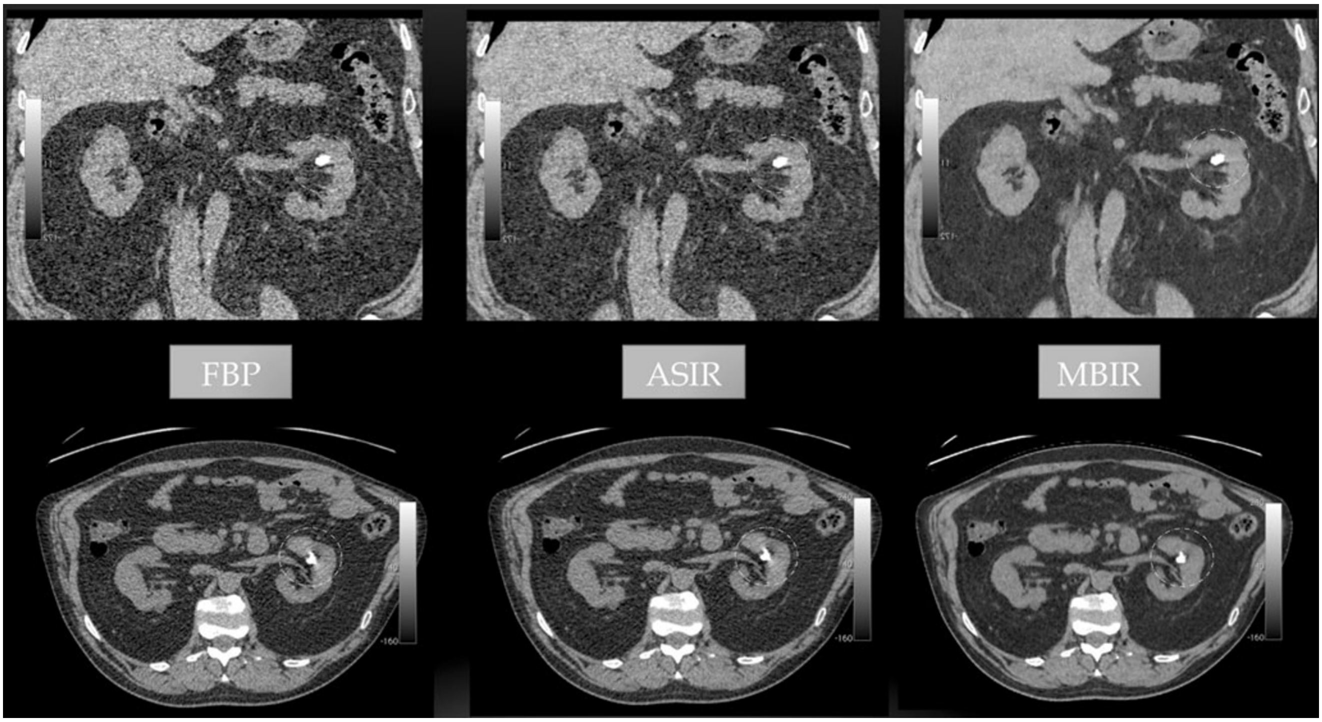

Fig. 6 Large left kidney stone (*circled*). Side-by-side comparisons of coronal (*top*) and axial (*bottom*) images among three reconstruction algorithms

With improved image quality, the next logical step would be to reduce the radiation dose whilst maintaining diagnostic image quality. There is emerging evidence that MBIR has significant dose reduction potential in chest [24–26], abdominal [11, 27] and paediatric cardiac CT [28]. Of note, Pickhardt et al. [27] have shown that MBIR has significant potential when aggressive dose reduction strategies are utilised. This was a preliminary trial with pooled data from low-dose contrast-enhanced abdominal CT, CT colonography and unenhanced CT KUB. The small sample size and diversity of examinations included in this study

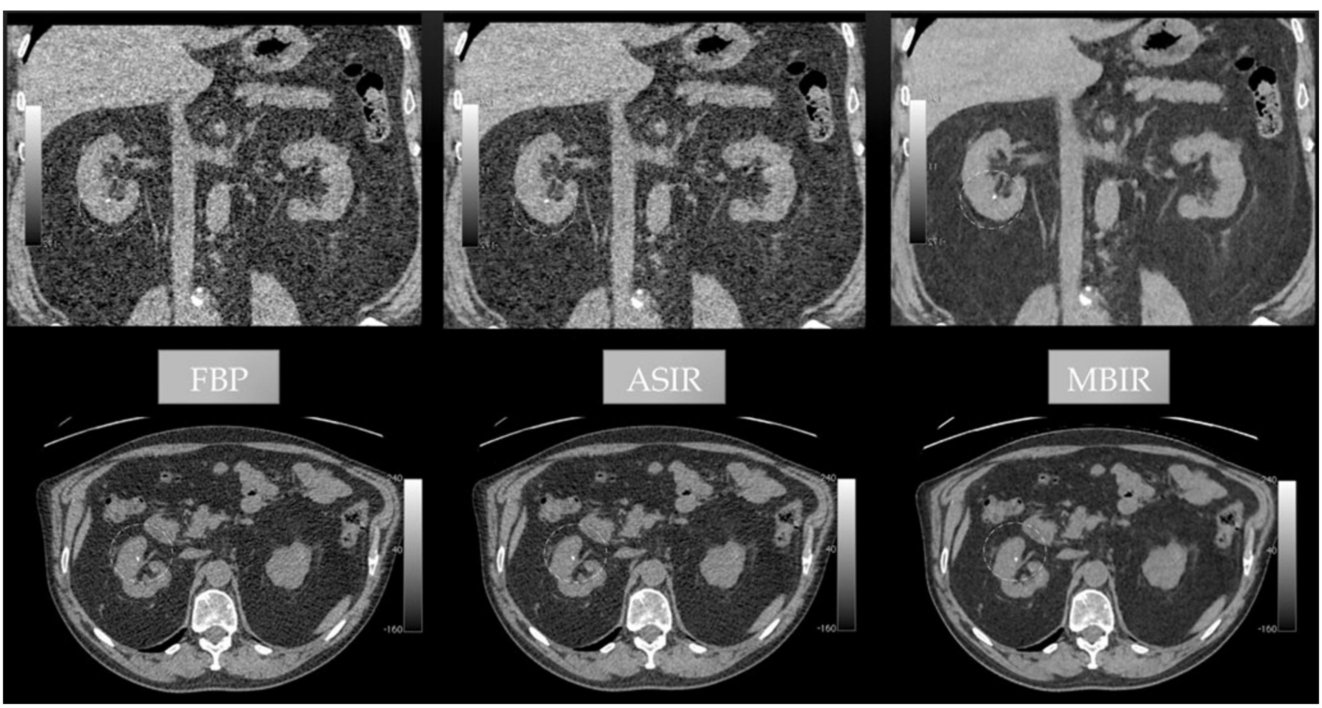

Fig. 7 Small right kidney stone (*circled*). Side-by-side comparisons of coronal (*top*) and axial (*bottom*) images among three reconstruction algorithms

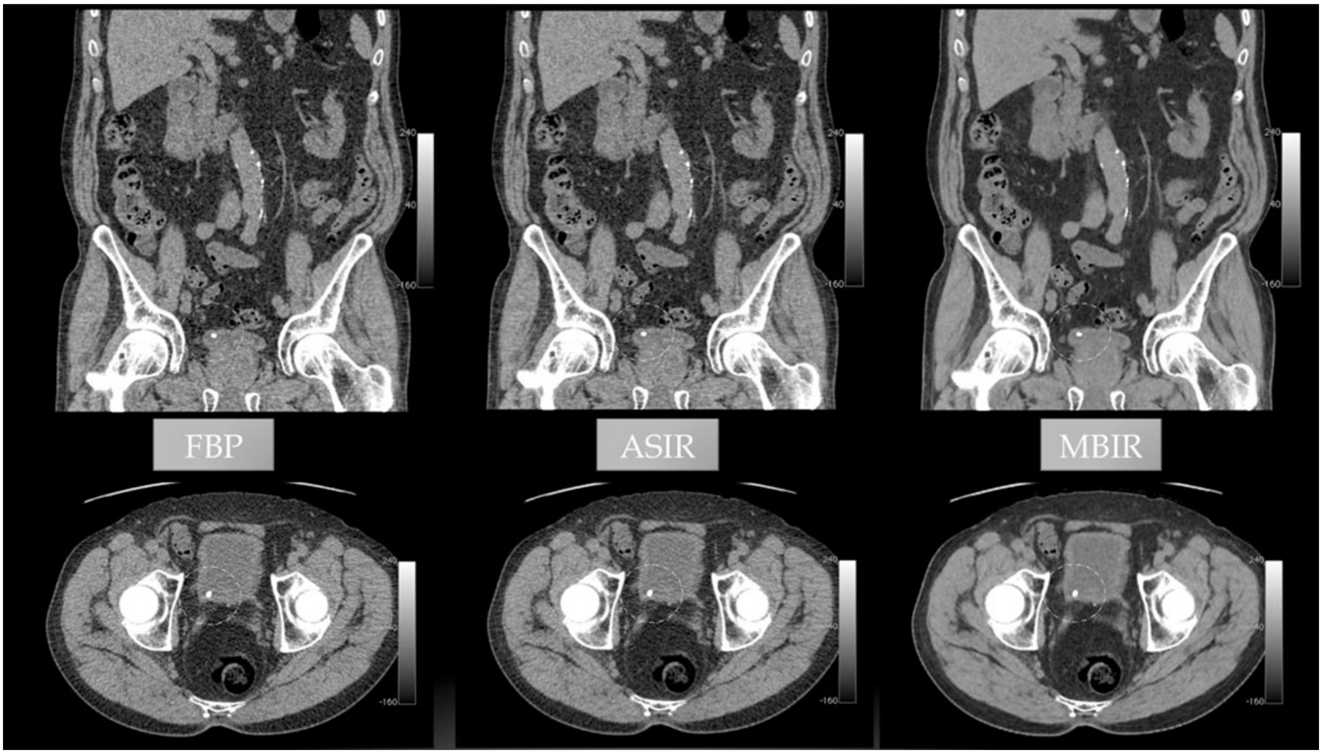

Fig. 8 Right vesico-ureteric stone (*circled*). Side-by-side comparisons of coronal (*top*) and axial (*bottom*) images among three reconstruction algorithms

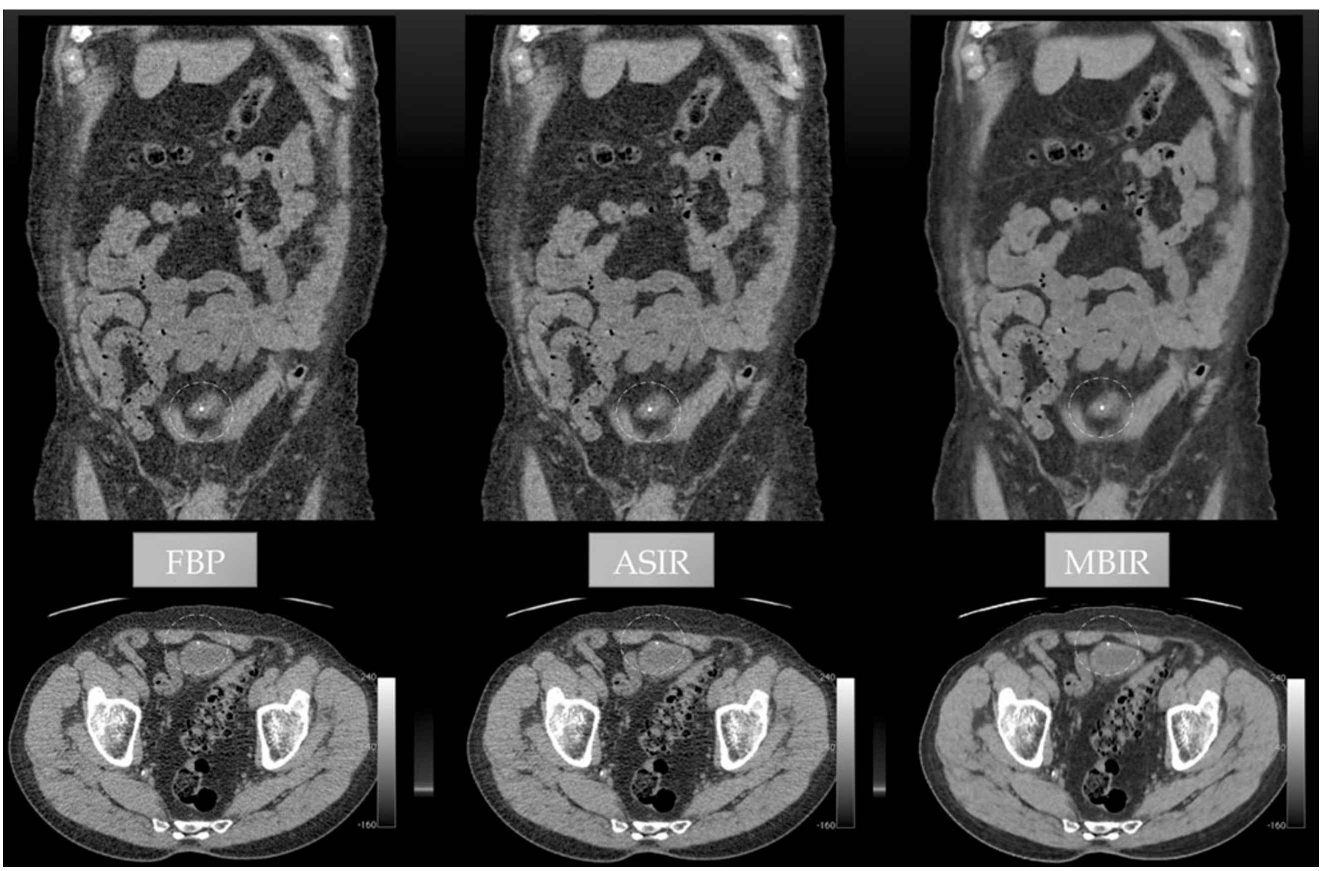

Fig. 9 Bladder stone (*circled*). Side-by-side comparisons of coronal (*top*) and axial (*bottom*) images among three reconstruction algorithms

did not allow firm conclusions to be drawn in respect to lesion detectability or diagnostic confidence in aggressive dose reduction protocols. Due to the retrospective nature of our study, we did not study the low-dose utility of MBIR. However, extrapolating from results of previous studies, application of MBIR can potentially be used to perform diagnostic examinations with further reduction in dose. In the context of CT KUB, this can be of particular value as many patients with urolithiasis are young and will require multiple CT examinations during their lives. However, further research is required to ascertain the exact levels of dose reduction achievable with MBIR. Further studies using lower dose scans with assessment of diagnostic accuracies should be performed to gain maximal benefit of the noise reduction achieved with MBIR.

The major limitation of MBIR is the time required to obtain multiple iterations. In our study 35–40 min was required for image reconstruction with a model-based iterative reconstruction algorithm. This limits the use of this technique in emergency situations, which was not the case with ASIR [28]. It is however still possible to perform an initial reconstruction with FBP or ASIR (to detect large or easily detectable lesions or life-threatening conditions, for example) followed by a second reconstruction with MBIR (where a detailed and thorough examination can be performed to formalise a final report).

In summary, MBIR is superior to both FBP and ASIR in terms of image noise and quality in both objective and subjective analysis at the same radiation dose, and if available should be utilised. Using this new iterative reconstruction algorithm, it may be possible to acquire images with diagnostic quality similar to FBP or ASIR at a reduced dose, but further studies are required to substantiate this claim.

Conflicts of interest The authors declare no conflicts of interest. No funding was received for this work. Written patient consent was waived by the Institutional Review Board.

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