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Model-Based Iterative Reconstruction Versus Adaptive Statistical Iterative Reconstruction and Filtered Back Projection in Liver 64-MDCT: Focal Lesion Detection, Lesion Conspicuity, and Image Noise

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Abstract

OBJECTIVE—The purpose of this study is to compare three CT image reconstruction algorithms for liver lesion detection and appearance, subjective lesion conspicuity, and measured noise.

MATERIALS AND METHODS—Thirty-six patients with known liver lesions were scanned with a routine clinical three-phase CT protocol using a weight-based noise index of 30 or 36. Image data from each phase were reconstructed with filtered back projection (FBP), adaptive statistical iterative reconstruction (ASIR), and model-based iterative reconstruction (MBIR). Randomized images were presented to two independent blinded reviewers to detect and categorize the appearance of lesions and to score lesion conspicuity. Lesion size, lesion density (in Hounsfield units), adjacent liver density (in Hounsfield units), and image noise were measured. Two different unblinded truth readers established the number, appearance, and location of lesions.

RESULTS—Fifty-one focal lesions were detected by truth readers. For blinded reviewers compared with truth readers, there was no difference for lesion detection among the reconstruction algorithms. Lesion appearance was statistically the same among the three reconstructions. Although one reviewer scored lesions as being more conspicuous with MBIR, the other scored them the same. There was significantly less background noise in air with MBIR (mean [$\pm$ SD], 2.1 ± 1.4 HU) than with ASIR (8.9 ± 1.9 HU; $p < 0.001$) or FBP (10.6 ± 2.6 HU; $p < 0.001$). Mean lesion contrast-to-noise ratio was statistically significantly higher for MBIR (34.4 ± 29.1) than for ASIR (6.5 ± 4.9 ; $p < 0.001$) or FBP (6.3 ± 6.0 ; $p < 0.001$).

CONCLUSION—In routine-dose clinical CT of the liver, MBIR resulted in comparable lesion detection, lesion characterization, and subjective lesion conspicuity, but significantly lower background noise and higher contrast-to-noise ratio compared with ASIR or FBP. This finding suggests that further investigation of the use of MBIR to enable dose reduction in liver CT is warranted.

Keywords

adaptive statistical iterative reconstruction; CT; filtered back projection; lesion contrast-to-noise ratio; liver CT; model-based iterative reconstruction

CT images have been reconstructed from raw data using filtered back projection (FBP) for several decades. The standard FBP algorithm is based on several assumptions that simplify CT geometry as a compromise between reconstruction speed and image noise. More complex assumptions about CT geometry combined with multiple iterations of reconstruction, termed adaptive statistical iterative reconstruction (ASIR), may result in slightly longer reconstruction times but also in less image noise from the same raw data. Starting with an initial FBP reconstruction, ASIR reduces image quantum noise without having an impact on spatial or contrast resolution through more complex analysis of detector response and of the statistical behavior of CT measurements [1–7].

With today's faster image reconstruction processing, an even more complex algorithm, termed model-based iterative reconstruction (MBIR), uses detailed models of several of the characteristics of radiation and of CT equipment. From a raw dataset and without an initial FBP reconstruction, MBIR uses backward and forward projections to match the reconstructed image to the acquired data iteratively according to a statistical metric. This iterative process requires longer reconstruction times, even with today's fastest processor speeds. For example, a raw dataset reconstructed with FBP at 15 images per second or with ASIR at 10 images per second might be reconstructed with MBIR at one image per second. However, the MBIR images may have substantially less noise than the ASIR or FBP images when reconstructed from the same dataset.

The effect of MBIR on liver lesion detection or lesion appearance is unknown. If lesion detection and lesion appearance were not compromised by the MBIR algorithm when compared with ASIR and FBP from the same raw dataset, future research might investigate whether patient radiation dose in multiphase CT of the liver could be decreased with MBIR. For the current investigation, we hypothesized that MBIR, compared with ASIR and FBP reconstructed from the same raw dataset, would result in CT images with at least equal liver lesion detection, similar lesion appearance, and equal subjective lesion conspicuity yet with substantially lower image noise, resulting in greater lesion contrast-to-noise ratios (CNRs). The purpose of this study was to compare these variables among MBIR, ASIR, and FBP images reconstructed from the same raw dataset. To make this comparison, we assembled a group of clinical liver CT examinations in patients with focal lesions in the setting of advanced cirrhosis.

Materials and Methods

This single-institution study was both HIPAA compliant and approved by our university's institutional review board, which waived the requirement for written informed consent because of the retrospective use of clinically acquired data.

Subjects

Patients were clinically excluded from undergoing CT if they had severe allergy to iodinated contrast material or compromised renal function with creatinine clearance of less than 40 mL/min/1.73 m². Between February and April of 2010, on a daily basis we retrospectively assembled raw image data files from a temporally sequential series of 39 clinical patients whose routine diagnostic multiphase CT examination performed with our standard protocol showed findings consistent with advanced cirrhosis and at least one focal liver lesion.

CT Scanning Technique

CT examinations were performed on one of two 64-MDCT scanner models (VCT XTe or CT 750HD, both from GE Healthcare). The standard clinical CT scan parameters included a tube voltage of 120 kVp, variable tube current with automated tube current modulation based on a noise index of 30 for patients under 120 pounds or 36 for all others (specified 0.625-mm slice thickness in source images), pitch of 1.3, and a 0.5-second rotation time. All patients had circulation time from the antecubital fossa to the abdominal aorta at the level of the celiac artery estimated by a timing bolus of 15 mL of IV contrast material (Omnipaque 350, GE Healthcare) followed by 15 mL of saline administered through a dual-head power injector (Stelland D, Medrad) at 5 mL/s. For the multiphase liver CT examination, scanning was performed during injection of 150 mL of contrast agent at a rate of 5 mL/s. The start of scanning for the initial late hepatic arterial phase began 20 seconds after aortic peak attenuation on the timing bolus. Subsequent scanning was performed at 65 seconds for hepatic portal venous phase and at 300 seconds for delayed equilibrium phase. Scanning of the abdomen for each phase was performed during relaxed inspiration in craniocaudal direction from just above the diaphragm to the top of the iliac crests.

CT Reconstructions

For the purpose of this investigation, the deidentified raw data from each CT examination were sent to a single facility for image reconstruction (GE Healthcare). Raw data from three of the CT examinations were corrupted in the transfer process and could not be reconstructed. In the remaining 36 examinations, axial 2.5-mm images were reconstructed every 2.5 mm for each of the three hepatic phases first with FBP, then with 40% ASIR, and finally with MBIR, resulting in 108 image sets (Fig. 1). Each image set contained all three hepatic phases reconstructed with a single algorithm. All images were anonymized, and visible scan parameters were removed.

Subjective Image Quality Evaluation

Image sets were numbered with a random number generator and were loaded onto a PACS workstation (Centricity, GE Healthcare). These randomized image sets were initially viewed by two reviewers who were blinded to reconstruction type and who worked independently at separate times. Each reviewer was a fellowship-trained board-certified radiologist with 30 and 16 years of experience in body CT. Images were presented to reviewers with a window width and level of 400 and 40 HU, respectively, but reviewers were also encouraged to vary the window width and level at will. Reviewers initially received standardized instructions and were trained on five identical image sets from five patients not included in this study. No

time limits were placed on the image review process. As with other similar investigations of focal liver lesion detection in patients with cirrhosis, lesion assessment was performed on the late hepatic arterial phase but using information from all phases [2, 8, 9]. Each reviewer identified the five largest focal liver lesions, including all hyperdense lesions or mixed-density lesions, regardless of size, and any hypodense lesion larger than 5 mm. For the purpose of subsequent identification, each reviewer numbered lesions from superior to inferior, anterior to posterior if on the same axial slice, and right to left if in the same anteroposterior plane. The reviewers also recorded the liver segment and the examination slice number where each lesion was best seen. The appearance of each lesion was subjectively categorized relative to adjacent liver parenchyma as hyperdense, hypodense, or mixed density. Subjective conspicuity of each lesion was graded on a 1–4 Likert scale, where 1 was barely perceptible with presence debatable, 2 was subtle finding but likely a lesion, 3 was a detected definite lesion, and 4 was strikingly evident and easily detected.

Objective Measurements

Each blinded reviewer measured the longest axis of the lesions detected for each image reconstruction type. They also measured and recorded the density of each lesion (in Hounsfield units) using a region of interest that encompassed at least two thirds of the cross-sectional area of the lesion. In addition, the senior reviewer measured the density (in Hounsfield units) of each segment of each lobe of the liver three times using a region of interest of at least 4 cm² and averaged the three measurements for each segment. Each region of interest was carefully placed in a separate relatively homogeneous area of liver parenchyma away from discernible vessels or focal density. This reviewer also obtained three measurements of image noise (defined as the SD of the density in Hounsfield units) at different locations in background air anterior to the abdominal wall (away from artifact or blankets) and in subcutaneous fat of the anterior abdominal wall (away from artifact or vessels). These measurements of noise were averaged for each region. CNRs were calculated two ways: first, as the difference between lesion density minus averaged liver density (in the same segment as the lesion) divided by the SD of noise in subcutaneous fat, and, second, divided by the SD of noise in air [10–12]. Each patient's weight and height at the time of the CT examination were noted and body mass index was calculated. The total examination dose-length product was recorded and converted to effective dose in millisieverts using the following conversion factor for the abdomen: 0.015 mSv/(mGy × cm) [13].

Establishing Lesion Presence

To establish lesion presence, two additional consensus “truth” readers who did not participate in the blinded image review looked at all three image sets for each examination at the same time, together with the clinical radiology report. The truth readers were fellowship trained in body imaging and had 16 and 12 years of experience. CT images were initially presented to these readers with a window width and level of 400 and 40 HU, respectively, but they were encouraged to vary the window width and level at will. No time limits were placed on the image reading process. These readers identified and measured the long axis of the five largest focal liver lesions, including all hyperdense lesions or mixed-density lesions, regardless of size, and any hypodense lesion larger than 5 mm. Similar to the blinded

reviewers, the truth readers noted the liver segment and slice number where each lesion was best seen. They also categorized the appearance of lesions relative to adjacent liver parenchyma as hyperdense, hypodense, or mixed density.

Statistical Analysis

Continuous measures were summarized using means and standard deviations. Wilcoxon rank-sum tests were used to test hypotheses comparing two groups, and the Kruskal-Wallis test was used when comparing more than two groups. Categorical data were summarized using counts and proportions. Chi-square or Fisher exact tests were used, as appropriate, to test statistical hypotheses. A p value less than 0.05 was considered statistically significant. The analysis for this study was generated using SAS software (version 9.3, SAS Institute).

Results

The mean ($\pm$ SD) age of the 36 patients was 57 ± 10 years; 22 were men. The mean body mass index was 27.6 ± 5.2 . The mean patient effective radiation dose of these three-phase liver CT examinations was 18.7 ± 11.3 mSv (6.2 mSv per phase).

Lesion Identification and Appearance

A total of 51 focal liver lesions was detected by the truth readers. Results for detection of these 51 lesions by each of the blinded reviewers with each of the three reconstruction types are described in Table 1. There was no significant difference between the individual lesion detection by the truth readers and individual lesion detection by either blinded reader for any of the reconstruction types. All lesions detected by the truth readers were detected by at least one of the blinded readers on all reconstruction types.

Categorization of subjective lesion appearance as hyperdense, hypodense, or mixed density by the blinded reviewers and by the truth readers is shown in Table 2. For the truth readers and for each of the blinded reviewers, categorization of individual lesion appearance was the same among the three reconstruction types (truth readers, $p = 0.99$; reviewer 1, $p = 0.90$; reviewer 2, $p = 0.70$). Subjective lesion conspicuity was not significantly different among the three reconstruction sequences for reviewer 1. For reviewer 2, subjective lesion conspicuity was significantly greater with MBIR compared with FBP but not compared with ASIR (Table 3).

Objective Measurements

The mean lesion long axis was 19 ± 10 mm (range, 6–44 mm). There was no evidence of a difference for the density (i.e., Hounsfield unit) measurements of the 51 lesions among the three reconstruction algorithms ($p = 0.86$) or of the liver segments among the three reconstruction algorithms ($p = 0.87$). Background noise in air was 76% lower with MBIR compared with ASIR and 80% lower with MBIR compared with FBP. Background noise in subcutaneous fat was 42% lower with MBIR compared with ASIR and 54% lower with MBIR compared with FBP. For MBIR, lesion-liver CNR calculated with noise in air was 429% greater compared with ASIR and 446% greater compared with FBP. For MBIR,

lesion-to-liver CNR calculated with noise in subcutaneous fat was 103% greater compared with ASIR and 125% greater compared with FBP (Table 4).

Discussion

FBP has dominated CT image reconstruction for the past 4 decades. FBP is able to accomplish fast reconstruction because it is a one-pass direct calculation method based on several simplifying assumptions: an infinitely small focal spot, a pencil-shaped x-ray beam, and CT detector cells without shape and with uniform response. FBP also assumes that all CT measurements are accurate and noise free [14]. Unfortunately, in the real world, CT is not ideal, noise free, or continuous. Although FBP is fast computationally with the large raw datasets of CT, it results in relatively noisy images.

With the advent of lower-dose protocols and higher-resolution CT scanners, more accurate modeling of the acquisition geometry and image noise can improve image quality. However, this introduces a level of computational complexity beyond the capabilities of FBP but that can be dealt with through iterative estimation methods. Partially iterative methods, such as ASIR, involve an initial FBP reconstruction followed by iterative modeling of noise statistics (both x-ray photon noise and electronic noise). Fully iterative methods, such as MBIR, further model the more complex scanner assumptions of shape to the focal spot and fan character to the x-ray beam and detectors, which have both shape dimensions and variable response functions and include more-advanced description of x-ray physics and statistical noise [15, 16]. MBIR involves serial estimation of images from raw CT data followed by forward projections of data from those images. These forward-projected data are then compared with the actual measured data according to statistical metrics, and the computed difference is itself back projected to create an image update. This sequence is followed serially until the difference between actual measured data and new forward-projected data drops below a predetermined threshold (Fig. 2).

For years, iterative reconstruction has been in common use in nuclear medicine, where images suffer from high noise levels similar to those found in low-dose CT but where the datasets are much smaller. However, recent advances in computer-processing speed have made iterative reconstruction feasible for the much larger datasets of CT. Even with faster computers, the complex fully MBIR process produces about one image per second, compared with 10 images per second for ASIR and 15 images per second for FBP.

In this study, when raw image data from routine clinical CT examinations in patients with advanced cirrhosis were reconstructed with three different algorithms, we noted several observations. First, lesion detection in the late arterial phase appeared to be equivalent among the three reconstruction algorithms according to independent blinded reviewers whose findings were compared with separate truth readers. Second, the subjective lesion appearance categorization was similar for any given reader among the three reconstruction algorithms. Variation in characterization between readers may reflect the subjective nature of such a process. Third, subjective lesion conspicuity was comparable among the reconstruction algorithms. Fourth, liver and lesion density measurements (in Hounsfield units) were the same among the three reconstruction algorithms. Fifth, objective

measurements of background noise were much lower and lesion CNRs were much higher with MBIR compared with the other two algorithms. Other authors have reported similar results when reconstructing CT image data with MBIR (Fleischmann D et al., presented at the 2011 Scientific Assembly and Annual Meeting of the Radiological Society of North America [RSNA]; Ichikawa Y et al., 2011 RSNA annual meeting; Lin X et al., 2011 RSNA annual meeting; Nieboer KH, et al., 2011 RSNA annual meeting).

In an anthropomorphic phantom with simulated liver lesions, Marin et al. compared MBIR with FBP reconstruction, varying both tube current and peak kilovoltage, and found that at equal peak kilovoltage and tube current settings, MBIR yielded 56–535% increase in CNR with 41–87% reduction in noise compared with FBP, yet with improved spatial resolution (Marin D et al., 2010 RSNA annual meeting). In patients, Nieboer et al. reported better lesion detection using MBIR for a liver imaging protocol using ultra-low radiation dose, compared with routine clinical CT with FBP (Nieboer KH et al., 2011 RSNA annual meeting). Also in patients, Lin et al. found greatly reduced image noise and improved image CNR with MBIR at an 80% reduced dose compared with routine scanning with FBP (Lin X et al., 2011 RSNA annual meeting).

Given the suggested diagnostic comparability of MBIR to the other reconstruction algorithms when the same raw data are used, the much lower background noise and higher lesion CNR imply that lowering patient radiation dose may be possible in the future when scanning with MBIR. This use of MBIR to lower radiation dose has been suggested by other authors (Marin D, et al., 2010 RSNA annual meeting; Fleischmann D, et al., 2011 RSNA annual meeting; Richard et al., 2010 RSNA annual meeting; O'Neill et al., 2011 RSNA annual meeting). Marin et al. reported that MBIR enabled up to 90% radiation dose reduction in a phantom without exceeding a 20 HU noise threshold. The same group suggested that MBIR could potentially reduce radiation dose by one half without compromising detection of spherical 5-mm lesions.

This study has several limitations. First, we did not attempt to determine lesion tissue type through imaging characteristics. Second, we used only the imaging parameters for one raw dataset for the three reconstruction algorithms; we did not vary imaging parameters for the different algorithms. These routine clinical CT parameters optimized for 40% ASIR evolved from both the equipment manufacturer's initial recommendations and our 2 years of experience balancing image noise and patient radiation dose. Other combinations of ASIR percentage blend and noise index may yield different results. The purpose of this study was not to evaluate how much dose reduction could be accomplished with MBIR or its clinical usefulness. Rather, the purpose was to investigate whether lesion detection and subjective lesion appearance were comparable among the reconstruction types when reconstructed from the same routine clinical image dataset and also to compare image noise and CNR levels. Although a relatively high noise index (high image noise) was used in our standard three-phase liver protocol, the patients in this series had advanced cirrhosis, many with ascites and fluid overload, and no body mass index exclusion, resulting in moderate average patient radiation dose. Third, we assessed only the late arterial phase of liver imaging. The impact of MBIR on other phases may merit further investigation. Finally, limiting lesion evaluation to only the five largest lesions could have masked a detection difference due to

lesion number or larger lesion size. However, the mean number of lesions per patient in this series was 1.4, and the mean lesion size was 19 mm with the largest lesion 44 mm.

In conclusion, for liver CT in patients with advanced cirrhosis, MBIR resulted in equivalent lesion detection, similar subjective lesion appearance, and comparable subjective lesion conspicuity compared with FBP and ASIR. However, image background noise with MBIR was significantly lower and CNR was significantly higher. This finding suggests that further investigation of the use of MBIR to enable dose reduction in liver CT is warranted.

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Fig. 1. 64-year-old man with known focal liver lesion

A–C, Raw dataset of late arterial phase CT of liver lesion (*arrows*) was reconstructed with filtered back projection (**A**), adaptive statistical iterative reconstruction (**B**), and model-based iterative reconstruction (**C**).

Fig. 2.

Flowchart showing model-based iterative reconstruction process of iteration between raw data calculations with filtered back projection (FBP) of image estimates and CT image operations and with forward projection of raw CT data estimates. This iteration stops when it results in change of less than predetermined threshold in Hounsfield units (HU).

TABLE 1Liver Lesions ($n = 51$) Detected by Each Blinded Reviewer, by Image Reconstruction Algorithm Used

Reconstruction Algorithm	Reviewer 1	Reviewer 2	<i>p</i>	95% CI
Filtered back projection	48 (94)	49 (96)	1.00	−0.123 to 0.084
Adaptive statistical iterative reconstruction	47 (92)	50 (98)	0.36	−0.16 to 0.044
Model-based iterative reconstruction	49 (96)	49 (96)	1.00	−0.075 to 0.075

Note—Data are no. (%) of lesions.

TABLE 2

Categorization of Lesion ($n = 51$) Appearance by Truth Readers and by Blinded Reviewers, by Image Reconstruction Algorithm Used

Reader, Reconstruction Algorithm	Hyperdense	Hypodense	Mixed Density
Truth readers			
Filtered back projection	32 (63)	15 (29)	4 (8)
Adaptive statistical iterative reconstruction	32 (63)	15 (29)	4 (8)
Model-based iterative reconstruction	32 (63)	15 (29)	4 (8)
Blinded reviewer 1			
Filtered back projection	29 (60)	19 (37)	0
Adaptive statistical iterative reconstruction	27 (53)	19 (37)	1 (2)
Model-based iterative reconstruction	29 (60)	19 (37)	1 (2)
Blinded reviewer 2			
Filtered back projection	28 (55)	14 (27)	7 (14)
Adaptive statistical iterative reconstruction	26 (51)	15 (29)	9 (18)
Model-based iterative reconstruction	30 (59)	15 (29)	4 (8)

Note—Data are no. (%) of lesions.

TABLE 3

Subjective Lesion Conspicuity Score (Blinded Reviewers), by Image Reconstruction Algorithm Used

Reconstruction Algorithm	Reviewer 1	Reviewer 2
Filtered back projection	3.7 ± 0.7	2.3 ± 0.8
Adaptive statistical iterative reconstruction	3.7 ± 0.5	2.5 ± 0.7
Model-based iterative reconstruction	3.8 ± 0.5	2.8 ± 0.7 ^a
<i>p</i>	0.78	0.008

Note—Data are mean ± SD. *p* values are for differences among the three scores for each reviewer.

^aModel-based iterative reconstruction was significantly different from filtered back projection for this reviewer but not from adaptive statistical iterative reconstruction.

TABLE 4

Measured Noise and Lesion Contrast-to-Noise Ratio

Reconstruction Algorithm	Lesion Noise (HU)	Measured Noise (HU)		Lesion Contrast-to-Noise Ratio	
		Fat	Air	Using Fat	Using Air
Filtered back projection	100.2 ± 62.5	17.5 ± 3.9	10.6 ± 2.6	3.6 ± 3.0	6.3 ± 6.0
Adaptive statistical iterative reconstruction	96.7 ± 63.8	14.1 ± 2.5	8.9 ± 1.9	4.0 ± 3.2	6.5 ± 4.9
Model-based iterative reconstruction	99.3 ± 65.1	8.1 ± 2.7	2.1 ± 1.4	8.1 ± 5.4	34.4 ± 29.1

Note—Data are mean ± SD.