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SAGE

Iterative CT reconstruction in abdominal low-dose CT used for hybrid SPECT-CT applications: effect on image quality, image noise, detectability, and reader's confidence

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Abstract

Background: Iterative computed tomography (CT) image reconstruction shows high potential for the preservation of image quality in diagnostic CT while reducing patients' exposure; it has become available for low-dose CT (LD-CT) in high-end hybrid imaging systems (e.g. single-photon emission computed tomography [SPECT]-CT).
Purpose: To examine the effect of an iterative CT reconstruction algorithm on image quality, image noise, detectability, and the reader's confidence for LD-CT data by a subjective assessment.
Material and Methods: The LD-CT data were validated for 40 patients examined by an abdominal hybrid SPECT-CT (U = 120 kV, I = 40 mA, pitch = 1.375). LD-CT was reconstructed using either filtered back projection (FBP) or an iterative image reconstruction algorithm (Adaptive Statistical Iterative Reconstruction [ASIR]®) with different parameters (ASIR levels 50% and 100%). The data were validated by two independent blinded readers using a scoring system for image quality, image noise, detectability, and reader confidence, for a predefined set of 16 anatomic substructures.
Results: The image quality was significantly improved by iterative reconstruction of the LD-CT data compared with FBP ($P \leq 0.0001$). While detectability increased in only 2/16 structures ($P \leq 0.03$), the reader's confidence increased significantly due to iterative reconstruction ($P \leq 0.002$). Meanwhile, at the ASIR level of 100%, the detectability in bone structure was highly reduced ($P = 0.003$).
Conclusion: An ASIR level of 50% represents a good compromise in abdominal LD-CT image reconstruction. The specific ASIR level improved image quality (reduced image noise) and reader confidence, while preserving detectability of bone structure.

Keywords

Single-photon emission computed tomography, SPECT CT, multimodal imaging, computed tomography, X-ray, image reconstruction

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Introduction

Since the turn of the millennium, computed tomography (CT) was introduced as part of nuclear medicine hybrid imaging devices (e.g. single-photon emission computed tomography [SPECT]-CT and positron emission tomography [PET]-CT). In both techniques, the CT data serve for anatomic orientation and CT-based attenuation correction (CTAC) of the emission data (1). Due to the synergies of anatomic and metabolic imaging, this integrated visualization has greatly improved the diagnostic information derived from either examination (2–7). Despite the predominant use of low-dose (LD)-CT protocols in many hybrid imaging examinations, non-insignificant radiation exposures have been reported (8,9), requiring a further balancing of image quality versus radiation dose.

Meanwhile, fair detectability in normal structures, usable for the correlation of findings from SPECT imaging with anatomic structures, was reported for a hybrid SPECT/LD-CT imaging protocol. Although further reduction of X-ray tube current and therefore of CT exposure may be irrelevant for the mere creation of a μ-map used for CT-based attenuation correction (CTAC) (11), a drastic degradation of image quality by image noise can be observed (12). Nowadays, iterative CT reconstruction algorithms are also part of advanced hybrid imaging devices (e.g. SPECT-CT) to compensate for image quality degradation (e.g. from increased image noise) by decreased CT photon flux/exposure. The capability for noise reduction by iterative reconstruction was demonstrated for diagnostic CT applications (13–15) by simulation in LD/ultra-LD-CT (16) and by phantom measurements in LD-CT hybrid applications (12). However, clinical validation of altered CT data is still pending.

The aim of the study was therefore to assess the effect of a dedicated iterative CT image reconstruction algorithm on image quality and detectability of anatomic structures for a defined LD-CT protocol used in abdominal SPECT-CT imaging. Furthermore, readers' confidence in image quality was evaluated.

Material and Methods

Patients

The image data of 40 consecutive patients (11 women, 29 men; mean age = 65.7 ± 11.3 years; interquartile range [IQR] = 57.0–75.0; age range = 39.6–81.5 years) receiving an abdominal SPECT-CT for different indications were analyzed retrospectively (see Supplementary Data, Table 1).

The study protocol was approved by the local ethics committee (reference number 158/11, RAD186). Informed consent was obtained from all patients regarding the analysis of data.

Table 1. Abdominal target structures.

Structure ID no.	Anatomic structure and reading condition
Liver structures	
1.1	Common hepatic duct
1.2	Superior mesenteric artery
1.3	Abdominal aorta and inferior vena cava
1.4	Celiac trunk
Splenic structures	
2.1	Harmonic splenic contour
2.2	Assessment of splenic parenchyma homogeneity
2.3	Splenic artery inside the splenic hilus
Renal structures	
3.1	Renal parenchyma
3.2	Renal pelvis and calices
3.3	Proximal part of the ureter (on the level of the caudal pole of the kidney)
3.4	Renal arteries
3.5	Renal veins
3.6	Adrenal glands (left and right)
Pancreas structures	
4.1	Lobulation of the pancreas contour
4.3	Common bile duct in the pancreas head
Bone	
5.1	Sharpness of the delineation of the cortex of the twelfth thoracic vertebral body (T12)
Aorta	
6.1	Image noise in the aorta at the level of the caudal pole of the kidneys
6.2	Image noise in the aorta at the level of the celiac trunk

CT acquisition and reconstruction

All examinations were performed with a hybrid SPECT-CT (Discovery NM/CT 670, GE Healthcare). The CT component is identical to a 16-slice CT used in diagnostic CT imaging (model: Bright Speed 16, GE Healthcare). In addition, the system included iterative CT reconstruction (Adaptive Statistical Iterative Reconstruction [ASIR], GE Healthcare) established in diagnostic CT imaging (17–20). Examinations were performed in the supine position with the arms raised above the head to prevent artefacts from beam hardening and truncation. LD-CT was in concordance with the local clinical standard for abdominal hybrid applications with an X-ray tube voltage of U = 120 kVp and an X-ray tube current of I = 40 mA (table pitch $P = 1.375$, $t_{rot} = 0.8$ s, primary collimation = 16 × 1.25 mm). Scans were performed by helical scanning without angular variation of the X-ray tube current with an axial field of view (FOV) of 50 cm diameter. CT images were reconstructed in slices with a thickness of 3.75 mm (512 × 512 matrix, 0.977 × 0.977 mm) with filtered back projection (FBP with convolution kernel = "standard" [manufacturer predefined kernel]) and the iterative reconstruction algorithm ASIR. ASIR reconstructions were performed with two different ASIR levels of 50% (ASIR 50) and 100% (ASIR 100). ASIR uses the images reconstructed by FBP as starting information. The parameter ASIR-level defined the merging of the iterative reconstruction and the FBP reconstruction.

Assessed anatomic structures

The anatomic structures used for analysis were chosen following benchmarks defined for diagnostic CT (21). A subset of structures (Table 1) was chosen, to identify effects from the ASIR and the different ASIR levels on the image quality, image noise, detectability, and reader confidence.

Two independent readers blinded to the patients' clinical information, the CT reconstruction algorithm (FBP versus ASIR), and the parameterization of the ASIR algorithm (ASIR 50 versus ASIR 100) assessed image quality for each structure. Both readers (DL and MT) were trained in diagnostic radiology, with a minimum of seven years of experience. The readers were not involved in the preceding clinical optimization of the hybrid system, were unbiased regarding the selected LD-CT image quality, and were blinded to the patients' clinical information.

The CT scans were independently assessed by readers for the reproduction of the anatomic structures (Table 1) in each reconstruction algorithm and reconstruction set-up. Image sets were reviewed in a random order (for patients and reconstruction) with a standardized windowing of 350/40 (window wide/level) Hounsfield units (HU; 300/1500 HU for bone structure) on a dedicated workstation. Individual optimization of the window was allowed.

The subjective image quality, detectability of structures (e.g. defining key structures for anatomic mapping), the confidence of the readers in scoring the image quality of anatomic structures, and the image noise were scored by 3-point Likert scales (Table 2). Image noise was assessed in two regions in the aorta at the level of the celiac trunk and at the level of the caudal pole of the kidneys. The presence of examined anatomic structures was verified before the blinded read by an independent observer using contemporary diagnostic CT data.

The effect from the iterative reconstruction algorithm was analyzed regarding the respective scores estimated for the standard FBP reconstruction.

Statistics

The R software package (version 3.4.3; R Foundation for Statistical Computing, Vienna, Austria) was used for statistical evaluations. The study design was explorative to estimate base effects from iterative reconstructions in LD-CT. For every CT reconstruction, the image quality scores and the detectability scores were calculated for the examined structures. In addition, the scores for image noise and the reader confidence in scoring the image quality of anatomic structures were estimated. The body mass index (BMI) was subdivided into four groups (defined by the quartiles of the observed BMI values) to test its impact on image quality, image noise, detectability, and readers' confidence. Analysis of variance (ANOVA) was used to assess the impact of the CT reconstruction algorithms (FBP, ASIR 50, and ASIR 100), reader, BMI, and the anatomic structure on the different scores. Changes in scores were tested by the Wilcoxon signed rank test. All tests performed were two-sided at a significance level of 0.05.

Table 2. Qualitative analysis of FBP and ASIR reconstructed low-dose CT data.

Score	Subjective image quality	Detectability of structures	Subjective image noise*	Readers' confidence
1	Poor and non-evaluable image quality, due to high image noise, distortion of spatial or contrast resolution, or impossible edge definition	Insufficient	Very high; reading restricted	Insufficient
2	Sufficient image quality, compromised by image noise, or some distortion of spatial or contrast resolution; but with possible edge definition	Sufficient	Existing; not distracting reading	Sufficient
3	Good image quality, only minimally compromised by image noise, or minimal distortion of spatial or contrast resolution	Sufficient	Small	Good

*Assessed in two regions in the aorta in a transaxial slice at the level of the celiac trunk and at the level of the caudal pole of the kidneys.

In addition, the inter-rater agreement was calculated for the assessment of the image noise score, detectability, and reader confidence for the different CT reconstructions. Kappa statistics were used for the two readers' assessments of scoring image quality and the detectability of structures by using the modified Cohen's kappa with chance correction by Brennan and Prediger (21,22). The inter-rater agreement was interpreted according to Landis and Koch (23).

Results

Effect of CT reconstruction on subjective image quality

The image quality was assessed by both readers in 40 LD-CT datasets for 16 structures each (n = 2 patients after splenectomy, structures 2.1–2.3 were not evaluable) with a total of 1268 evaluations. In summary, image quality score increased in data reconstructed with ASIR 50 compared with FBP by one or two levels in 343/1268 (27.1%) and 24/1268 (1.9%) evaluations, respectively. Whereas the score decreased by one or two levels in 69/1268 (5.4%) and 4/1268 (0.3%) evaluations, image quality was not affected in 828/1268 evaluations (65.3%). The increase in the image quality score by ASIR 50 compared with the FBP reconstruction was significant ($P < 0.001$).

Furthermore, ASIR 100 reconstruction increased the image quality compared with FBP by a level of one or two in 366/1268 (28.9%) and 36/1268 (2.8%), evaluations, respectively. The image quality score decreased by one level in 71/1268 (5.6%) and by two levels in 19/1268 (1.5%) evaluations. In 776/1268 evaluations (61.2%), the image quality significantly increased using ASIR 100 when compared with FBP ($P < 0.001$). However, no significant difference in image quality score was observed on comparing ASIR 50 and ASIR 100 reconstructions ($P = 0.25$).

In contrast to the generally observed effect from ASIR, the image quality score for bony structures was significantly decreased (44/80 readings, $P = 0.005$) in ASIR 100 reconstructed CT data compared with FBP or ASIR 50. Moreover, image quality was not affected by ASIR 50 compared with FBP ($P = 0.56$).

In addition to the reported effects from LD-CT reconstruction and structures, the image quality score was also affected by BMI and the reader (all $P < 0.0001$, result from ANOVA). The effects of the different factors on image quality score are presented by interaction plots (Fig. 1). Meanwhile, the readers showed an inter-observer agreement for all examined structures of $\kappa_{BP} = 0.55$ (95% confidence interval [CI] = 0.53–0.56, percentage agreement = 63.7%) for the image quality score. Reader R2 was significantly more critical in scoring image quality and reported lower values ($P < 0.001$, Fig. 1a).

Effect of CT reconstruction on image noise

According to ANOVA, the image noise score was significantly dependent on the respective target structure evaluated (structures 6.1 and 6.2; $F = 4.18$, $P = 0.04$), reader ($F = 18.75$, $P < 0.0001$), LD-CT reconstruction ($F = 41.92$, $P < 0.0001$), and BMI ($F = 7.55$, $P < 0.0001$). Reader R2 reported a significantly higher noise level compared with reader R1 ($P = 0.0002$, Fig. 2a). Compared with FBP reconstructed LD-CT data, the image noise decreased significantly using ASIR 50 and ASIR 100 ($P < 0.0001$, Fig. 2b), whereas image noise was not significantly different in ASIR 50 and ASIR 100 reconstructed LD-CT data ($P = 0.2$, Fig. 2b). The effect of ASIR levels compared with FBP is exemplified (Fig. 3).

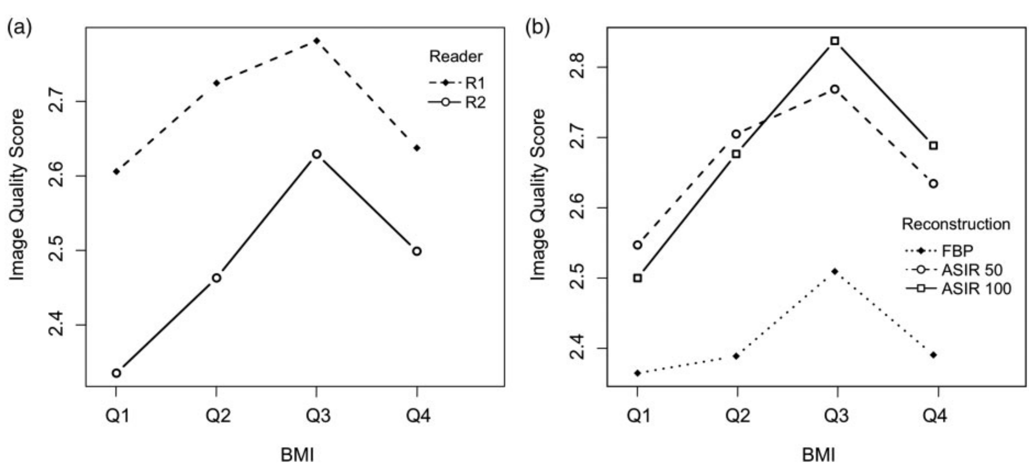

Fig. 1. Effect of BMI (by quartiles Q1–Q4), (a) reader, and (b) CT reconstruction on image quality score.

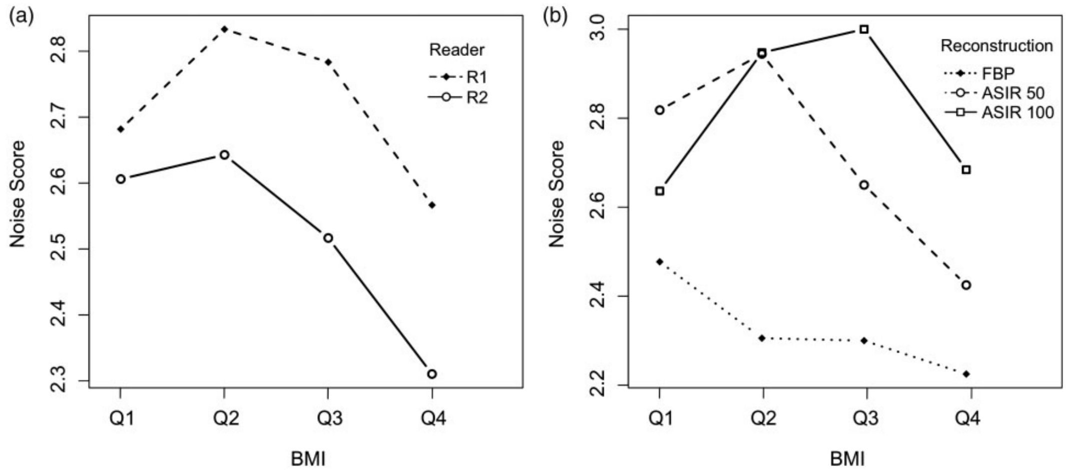

Fig. 2. Effect of BMI, (a) reader, and (b) CT reconstruction on image noise score.

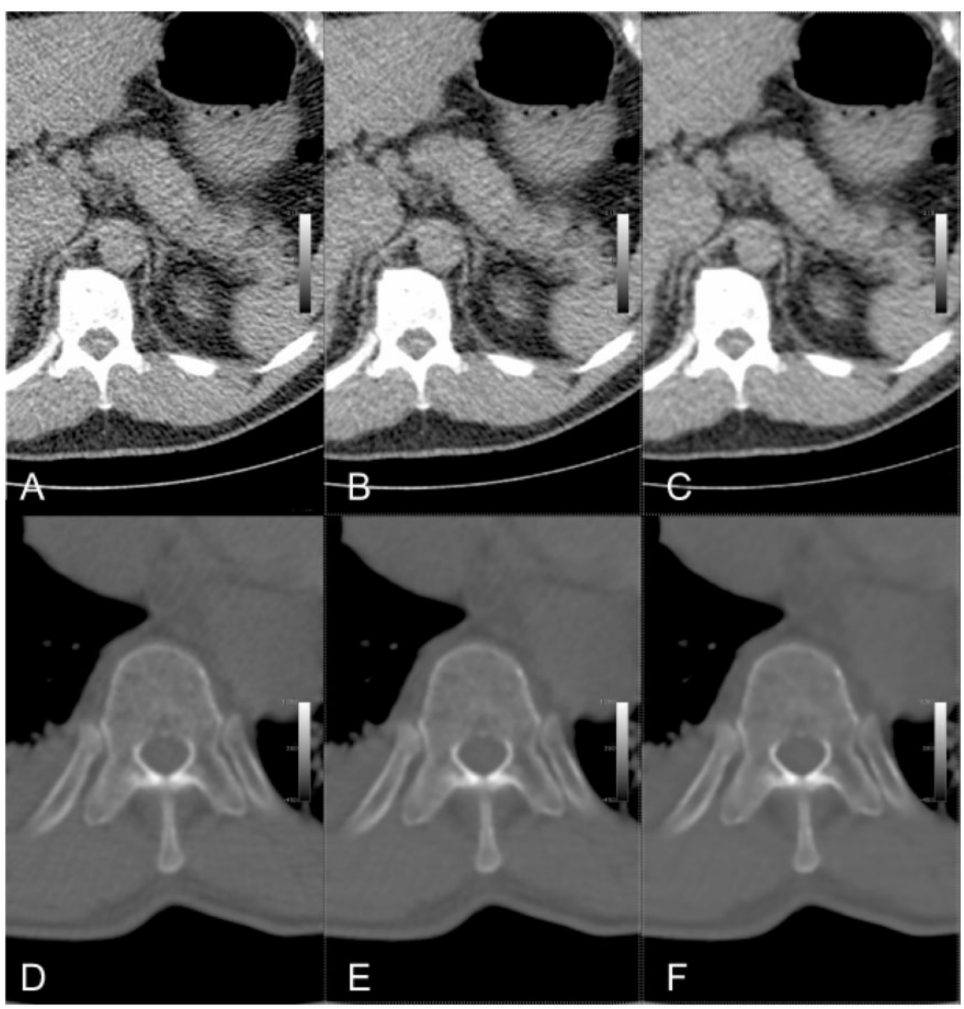

Fig. 3. Effect of CT reconstruction by FBP (a, d) and ASIR levels of 50% (b, e) and 100% (c, f) on image noise and detectability. In the top row (soft-tissue window), a decrease in noise and improvement of detectability of organ structures, especially at ASIR 100% (c) compared with standard FPB (a) is observed. The bottom row (d–f) again shows an improvement by ASIR, this time, however, with a finer delineation of bone structures (bone window) in combination with a reduced noise level at ASIR 50 (e) compared with ASIR 100 (f).

Effect of CT reconstruction on detectability

The detectability of structures in LD-CT was significantly dependent on the examined structure ($F = 32.06$, $P < 0.0001$), LD-CT reconstruction ($F = 6.84$, $P = 0.001$), and BMI ($F = 44.72$, $P < 0.0001$, all results from ANOVA). The change in the detectability rate by using ASIR (both levels) compared with FBP is shown in Fig. 4.

The use of ASIR significantly increased detectability in two structures (structure 1.1 and 4.1, Fig. 4a and b) compared with FBP. In contrast, detectability in bone structures deteriorated in the ASIR 100 reconstructed data (structure 5.1, Fig. 4b). Here, in 19/80 readings of the structure (structure 5.1), the corresponding rating changed from sufficient to insufficient. The effect of the different ASIR levels is exemplified in Fig. 3d–f.

The readers showed an almost perfect inter-observer agreement regarding the detectability score ($\kappa_{BP} = 0.76$, 95% CI = 0.74–0.80, percentage agreement = 88.4%).

Effect of CT reconstruction on reader confidence

The reader confidence in LD-CT image quality was significantly influenced by the used LD-CT reconstruction ($F = 11.78$, $P < 0.0001$, result from ANOVA). The reader confidence was significantly higher in ASIR 50 (change in score = 0.28 ± 0.57, $P = 0.002$) and ASIR 100 (change in score = 0.36 ± 0.56, $P < 0.0001$) compared with FBP (Fig. 4), but not significantly different for both ASIR levels ($P = 0.8$).

Scoring confidence was reader dependent ($F = 7.60$, $P = 0.006$, result from ANOVA), with Reader R2 being significantly more critical ($P = 0.009$; Fig. 5).

Discussion

In this explorative study, a qualitative analysis of the effect from iterative image reconstruction on image quality and detectability of anatomic structures in abdominal LD-CT data was performed. Furthermore, the effect on image noise was evaluated by subjective

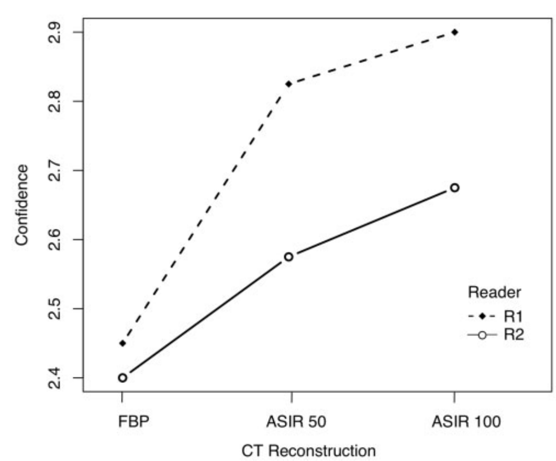

Fig. 5. Reader confidence in image quality for both readers.

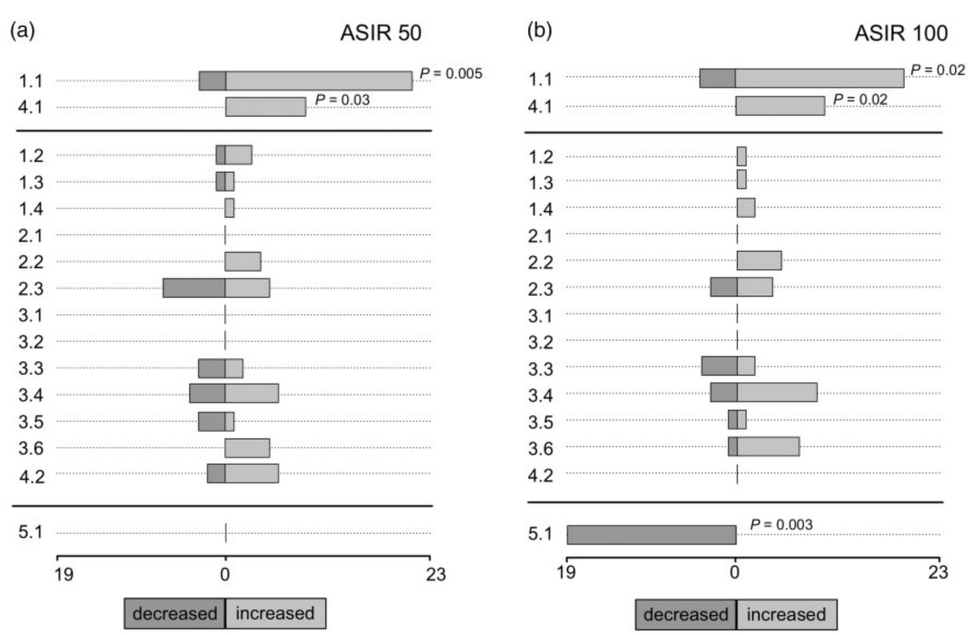

Fig. 4. Total number of changes in detectability score by structures for LD-CT data reconstructed by (a) ASIR 50 and (b) ASIR 100 compared with FBP. Structures were arranged regarding an influence on detectability by one of the examined ASIR levels (top segment: significant increase in detectability, middle segment: no significant change in detectability, bottom segment: significant decrease in detectability).

assessment in two texture-free regions (blood in the abdominal aorta); the confidence of the readers in scoring the LD-CT image quality of anatomic structures was estimated. The evaluation was performed for two different parameterizations (ASIR levels) of the iterative reconstruction algorithm compared with FBP reconstructions of the identical LD-CT raw data. The anatomic structures used for analysis represent a subset of structures originally defined for benchmarking diagnostic CT (21).

Compared with FBP reconstruction, a significant improvement of image quality (reduced noise level) was observed for both ASIR levels. These findings confirmed expectations on the algorithm's performance from diagnostic CT imaging (13–15) and also from the optimization of LD-CT in hybrid SPECT-CT applications by phantom measurement (12). In contrast, there was only a significant increase in detectability by using iterative reconstruction for some structures (in 2/16 structures). Moreover, in bone structures, we observed a drastic reduction in detectability and reader confidence when using ASIR 100 for LD-CT reconstruction, confirming previous reports on the degradation of diagnostic CT data when high ASIR levels are used (14,24,25). In these cases, the use of the high ASIR level results in a noise-free oversmoothed structure appearance, with a perceived lower LD-CT image quality in the bone structure.

Thus, further balancing between sufficient image quality, detectability, and reader confidence is warranted, and in our opinion, the ASIR 50 set-up represents a sufficient compromise regarding bony structures.

Moreover, it must be noted that the current results are based on the analysis of abdominal data. In different body regions (e.g. for thoracic examinations with an air/tissue contrast), the observed effects can vary, and the scan protocol and reconstruction protocol have to be adapted appropriately (26).

The extreme parameterizations of the iterative reconstruction were chosen for a proof of principle and do not provide the optimal parametrization for abdominal imaging in LD-CT for hybrid SPECT-CT. Thus, similarly to diagnostic CT applications, it can be hypothesized that an improved image quality, balancing between noise reduction and resolution, can be realized by further optimizing the parameterization of the iterative reconstruction algorithm, and also choosing specific ASIR levels for body regions (i.e. thoracic versus abdominal imaging). Moreover, this body region adaptation needs to take the observed influence of patient mass (i.e. BMI) into account, although we found a significant improvement on LD-CT image quality and image noise score by using ASIR for all examined BMI groups.

To the best of our knowledge, no data on the effect of iterative CT reconstruction algorithms on detectability of anatomic structures on LD-CT have been published to date. An actual study examined the detectability and reader confidence in FBP reconstructed LD-CT data (10). Moreover, Sibille et al. (11) analyzed LD-CT data with a predefined ASIR level of 70% and the resulting effect from using this data for attenuation correction on SPECT images.

A further limitation in our study was the parametrization of the FBP reconstruction used for comparison and also representing the starting distribution for iterations in the ASIR reconstruction. The FBP reconstruction was performed with a fixed convolution kernel (kernel = "standard"), as recommended by the manufacturer for LD-CT in hybrid SPECT/CT, and particularly used for routine examinations (e.g. abdomen and pelvic scan) in diagnostic CT. Here, again, further investigations are needed to find a more specific set-up to potentially optimize LD-CT reconstruction in hybrid applications. Meanwhile the general validity of the parametrization known from diagnostic CT has to be questioned critically. Various studies reported different indication-specific ASIR levels (20–100%) in diagnostic CT applications, with a corresponding dose reduction in the range of 23–76% (27). Herein, validation was performed for image quality defined by comprehensive target figures (e.g. detectability including low-contrast detectability and tissue texture). LD-CT in hybrid applications is generally dedicated to attenuation correction and anatomic correlation. The validation has to consider the low-dose character of the examination and has to adapt requirements to LD-CT data. It has to be hypothesized that the parametrization of the iterative algorithm in LD-CT can deviate from diagnostic CT applications in the identical body region. Although only a limited number of anatomic structures were evaluated regarding effects from iterative reconstruction (especially regarding different parametrizations of the algorithm) in this LD-CT study, effects in soft-tissue structures and in bone structures were reproduced with good agreement between the two readers. This demonstrates a (diametral) effect in LD-CT image optimization (soft tissue versus bone structure) and has to be respected for further assessment of iterative LD-CT image reconstruction algorithms (12,16).

Thus, despite the limitations of the present study, our data might contribute to defining requirements for LD-CT data, including quality criteria for LD-CT in anatomic registration of findings from SPECT imaging.

Finally, the potential of iterative CT reconstruction for optimized dose management, in analogy to diagnostic CT imaging, has to be discussed. Based on data from the present study, the study by Sibille et al. (11), and by phantom examinations in LD-CT (12) iterative

CT reconstructions, algorithms can be used to improve the image quality of low-dose CT data. On the other hand, this effect can be used to perform LD-CT with a decreased level of CT exposure (e.g. by reducing X-ray tube current) while preserving image noise (26). Our currently used LD-CT protocol used in abdominal hybrid SPECT-CT results in an estimated exposure of 1.4 mSv (1.7 mSv) in a male (female) normal patient for a single bed position (length of FOV in z-direction = 40 cm) (28). Under the objective of preserving a comparable image noise level, a further reduction in CT exposure (e.g. in the range of 1 mSv/abdominal bed position, or even less) seems to be achievable for LD-CT imaging by using iterative CT reconstruction. Nevertheless, while optimizing (reducing) the CT dose level, a preserved detectability of anatomic structure by using iterative CT reconstruction cannot be postulated. Conservatively, we have to expect a decrease in detectability. Whereas, the influence of iterative reconstruction on detectability in LD-CT, while reducing CT exposure, has to be examined by further studies.

In conclusion, the use of iterative reconstruction algorithms results in a drastic reduction of image noise, and improvement in image quality and reader confidence, in low-dose CT data used for the anatomic correlation of findings from nuclear medicine hybrid imaging. The parameterization of the iterative algorithm has to be adapted in accordance with the specific imaging task. Whereby, the ASIR level of 50% represents a compromise in abdominal LD-CT used for hybrid registration of findings from nuclear medicine imaging.

Declaration of conflicting interests

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Supplemental material

Supplemental material for this article is available online.

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