Impact of a 4th Generation Iterative Reconstruction Technique on Image Quality in Low-Dose Computed Tomography of the Chest in Immunocompromised Patients

Einfluss der iterativen Rekonstruktionstechnik der vierten Generation auf die Bildqualität in der Niedrigdosis-Computertomographie des Thorax immunkomprimierter Patienten

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Zusammenfassung

Ziel: Beurteilung des Einflusses der iterativen Rekonstruktion (IR) auf die Bildqualität in der Niedrigdosis-Computertomographie (LDCT) des Thorax immunkomprimierter Patienten anhand eines intraindividuellen Vergleichs zur gefilterten Rückprojektion (FBP) sowie Begutachtung des Dosisreduktionsvermögens.
Material und Methoden: 30 LDCTs wurden bei immunkomprimierten Patienten durchgeführt (Brilliance iCT: 20 – 40 mAs; mittlere CTDIvol: 1,7 mGy). Die Rohdaten wurden mittels FBP und IR (iDose4™, Philips, Best, Niederlande) mit 7 Iterationsstufen rekonstruiert. 30 mit FBP rekonstruierte Standarddosis-Computertomographien (RDCT) dienten als Kontrollgruppe (mittlere mAs:116; mittlere CDTIvol: 7,6 mGy). Drei verblindete Radiologen führten eine Begutachtung der subjektiven Bildqualität und Abgrenzbarkeit pathologischer Befunde durch. Als quantitative Parameter wurden die mittlere Dichte und das Bildrauschen (OIN) ermittelt.
Ergebnisse: In der LDCT führten hohe iDose4™-Stufen zu einer signifikanten Reduktion des OIN (FBP vs. iDose7: M. subscapularis 139.4 vs. 40.6 HE). Trotz niedriger Strahlendosis ermöglichten hohe iDose4™-Stufen signifikante Verbesserungen der Bildqualität und der Artefakt- und Rauschreduktion. Die Abgrenzbarkeit von subtilen Läsionen wurde in LDCT FBP Bildern als eingeschränkt bewertet. Dies verbesserte sich signifikant mit Einsatz höherer iDose4™-Stufen (> iDose4). Der LDCT mit iDose6 wurde eine der RDCT mit FBP gleichwertige Bildqualität zugesprochen.
Schlussfolgerungen: iDose4™ verbessert die Bildqualität und Abgrenzbarkeit pathologischer Befunde erheblich und führt gleichzeitig zur Rauschreduktion in der LDCT des Thorax. Verglichen mit der RDCT kann durch hohe iDose4™-Stufen trotz

Abstract

Purpose: To determine the image quality of an iterative reconstruction (IR) technique in low-dose MDCT (LDCT) of the chest of immunocompromised patients in an intraindividual comparison to filtered back projection (FBP) and to evaluate the dose reduction capability.
Materials and Methods: 30 chest LDCT scans were performed in immunocompromised patients (Brilliance iCT; 20 – 40 mAs; mean CTDIvol: 1.7 mGy). The raw data were reconstructed using FBP and the IR technique (iDose4™, Philips, Best, The Netherlands) set to seven iteration levels. 30 routine-dose MDCT (RDCT) reconstructed with FBP served as controls (mean exposure: 116 mAs; mean CDTIvol: 7.6 mGy). Three blinded radiologists scored subjective image quality and lesion conspicuity. Quantitative parameters including CT attenuation and objective image noise (OIN) were determined.
Results: In LDCT high iDose4™ levels lead to a significant decrease in OIN (FBP vs. iDose7: subscapular muscle 139.4 vs. 40.6 HU). The high iDose4™ levels provided significant improvements in image quality and artifact and noise reduction compared to LDCT FBP images. The conspicuity of subtle lesions was limited in LDCT FBP images. It significantly improved with high iDose4™ levels (> iDose4). LDCT with iDose4™ level 6 was determined to be of equivalent image quality as RDCT with FBP.
Conclusion: iDose4™ substantially improves image quality and lesion conspicuity and reduces noise in low-dose chest CT. Compared to RDCT, high iDose4™ levels provide equivalent image quality in LDCT, hence suggesting a potential dose reduction of almost 80 %.

niedriger Strahlendosis in der LDCT eine gleichwertige Bildqualität erreicht werden, dies verspricht im Umkehrschluss eine potentielle Dosisreduktion von bis zu 80 %.

Introduction

With rapidly evolving multidetector CT (MDCT) technology, the number of performed CT examinations has markedly increased [1 – 5]. Since 1996, the estimated lifetime risk of cancer from CT-related radiation exposure has increased from 0.4 % to nearly 2 % [1].

These results are of particular relevance for patient groups with a need for repetitive CT examinations, e. g. immunocompromised patients. Pneumonia is a leading cause of morbidity and mortality in immunocompromised patients [6 – 8]. As diagnostic delay increases the risk for mortality [6], repetitive chest CT scans are usually obtained for the evaluation of potential pulmonary infiltrates [9 – 12]. Use of a low-dose chest CT technique is desirable, but dose reduction is limited by increasing image noise and therefore reduced image quality [13]. Filtered back projection (FBP), representing a commonly applied reconstruction algorithm, cannot consistently offer diagnostic image quality in low-dose CT examinations. Therefore, it is desirable to use a technique that can provide both a low radiation dose and high image quality. Iterative reconstruction (IR) techniques [14 – 17] were introduced for dose and noise reduction while maintaining high image quality.

The purpose of the present study is to determine the image quality resulting from a prototype iterative reconstruction (IR) algorithm (4th generation IR technique iDose4™) used for the reconstruction of low-dose MDCTs of the chest in an intraindividual comparison to standard FBP.

In addition, the image quality of this IR algorithm at a low tube current setting was compared with the image quality of FBP at a standard curr ent setting.

Materials and Methods

This study was approved by the local institutional review board which waived the requirement for written informed consent.

Patient population

60 consecutive patients undergoing non-enhanced chest MDCT were enrolled in this study. 30 immunocompromised patients (13 men, 17 women; age range 19 – 81 years; mean age 49.07) underwent low-dose MDCT (LDCT) for the evaluation of pulmonary infections between January and February 2011. The underlying immunocompromising conditions are listed in ▶ **Table 1**.

For the control group, non-enhanced routine-dose MDCT (RDCT) scans of the chest of 30 consecutive patients were reviewed (20 men, 10 women; age range 42 – 88 years; mean age 70.8 years, 19 patients weighing ≤ 80 kg and 11 patients weighing ≥ 80 kg). They underwent MDCT examinations for clinical indications including preoperative assessment of atherosclerosis of the thoracic aorta for planned cardiac surgery (n = 24), follow-up for pulmonary nodules (n = 2), unresolved pneumonia (n = 3) and follow-up of interstitial lung disease (n = 1).

Scan protocol of low-dose MDCT

Data were acquired with a 256-MSCT scanner (Brilliance iCT, Philips, Best, The Netherlands) using the following protocol: collimation 256 × 0.625 mm; tube voltage 120 kV; fixed current-time product 20 mAs (effective) for patients weighing ≤ 80 kg (n, 20) and 40 mAs (effective) for patients weighing ≥ 80 kg (n, 10), corresponding to $CDTI_{vol}$: 1.3 and 2.6 mGy, respectively; gantry rotation time 0.5 sec; pitch 0.993.

Data reconstruction of low-dose MDCT with FBP and iDose4™

For IR, a prototype of the Philips iDose4™ system (Philips Healthcare, Cleveland, OH, US) was used for subsequent offline raw data reconstructions. iDose4™ is an IR algorithm providing noise reduction in both the raw data and the image data domain [18]. The iDose4™ levels ranged from 1 to 7 and defined the strength of the iterative reconstruction algorithm. Increasing iDose4™ levels indicate increased noise reduction.

Furthermore, iDose4™ provides multi-frequency reconstruction (MFR). This technique strives to preserve the noise frequency spectrum which is also known as the Noise Power Spectrum (NPS), characterizing the image texture ("look and feel" of an image) [18, 19]. Images were reconstructed with a slice thickness of 1 mm using a lung reconstruction kernel (filter L) as follows:

- Conventional FBP
- iDose4™ level 2 (iDose2)
- iDose4™ level 4 (iDose4)
- iDose4™ level 4 with MFR (iDose4 MFR)
- iDose4™ level 6 (iDose6)
- iDose4™ level 6 with MFR (iDose6 MFR)
- iDose4™ level 7 (iDose7)
- iDose4™ level 7 with MFR (iDose7 MFR)

Thus, after post-processing of the 30 raw data sets with both FBP and seven different iDose4™ levels, a total of 240 data sets of LDCT scans were available (8 sets per patient).

Table 1 Underlying immunocompromising conditions of patients undergoing low-dose MDCT.

Tab. 1 Zugrundeliegende immunkomprimierende Erkrankungen in Folge derer ein Niedrigdosis MDCT durchgeführt wurde.

underlying immunocompromising conditions	number of patients (n: 30)
hematopoietic stem cell transplant (hsct) recipients due to	**13**
osteomyelofibrosis	5
chronic myeloid leukemia	3
amyloidosis	1
acute myeloid leukemia	1
acute lymphoblastic leukemia	1
aplastic anemia	1
lymphoma	1
acquired immunodeficiency syndrome (AIDS)	**4**
AIDS-associated Burkitt's lymphoma	**2**
Non-Hodgkin's lymphoma	**4**
acute myeloid leukemia	**2**
solid organ transplant recipients	**4**
bronchial carcinoma being treated with chemotherapy	**1**

Scan protocol and reconstruction of routine dose MDCT

Data were acquired with the same 256-slice MDCT scanner system using the following protocol: collimation 256 × 0.625 mm; tube voltage 120 kV; variable mAs settings determined by the automatic exposure control system (automatic current selection: ACS and Z-axis dose modulation: Z-DOM), with an average exposure of 116 mAs (effective) corresponding to CTDIvol: 7.6 mGy; gantry rotation time 0.5 seconds; pitch 0.993.

Image data were reconstructed with conventional FBP at a slice thickness of 1 mm using a lung reconstruction kernel (filter L).

Quantitative measurements

Patient size

As differences in patient body size can affect the image quality between the two cohorts with low-dose and routine-dose MDCT, body weight, height and body mass index (BMI) were determined. In addition, transverse and longitudinal chest diameters at the level of the tracheal bifurcation were recorded. This anatomical level was chosen for our measurements in unenhanced CTs as the tracheal bifurcation can be referred to as a consistent and reproducible anatomic landmark.

Radiation dose measurements

The computed tomography dose index volume ($CTDI_{vol}$) was recorded reading the patient dose report.

Objective image quality

Mean CT values (Hounsfield units: HU) and objective image noise (OIN) were obtained for all MDCT scans (LDCT with FBP and 7 IR levels and RDCT with FBP). Circular 150-mm^2 regions of interest (ROI) were drawn in the lung apex and in the subscapularis muscle by one investigator. These regions were chosen because of the high local noise related to the osseous shoulder girdle. The objective image noise (OIN) was defined as the averaged value of standard deviation (SD) in HUs of the obtained ROI.

Qualitative analysis

For iterative reconstruction the raw data were transferred to an offline PC provided by the vendor. For the assessment of image quality, the iteratively reconstructed images were dicomized and sent to a picture archiving and communication system diagnostic workstation (Centricity PACS-IW, GE Healthcare, Munich, Germany; 21 inch and 3 megapixel high-resolution diagnostic monitor) on which the images were evaluated.

For image analysis, 270 scans (30 RDCT data sets with FBP and 240 LDCT data sets with FBP and seven different iDose4™ reconstructions) were randomized, rendered anonymous and evaluated one after the other. The reviewers were allowed to zoom in and change the window level and width for assessing structures ad libitum. To avoid a loss of attention, nine separate review sessions were performed on different days. The interval between the separate sessions varied between one and four days. At each review, 30 datasets were displayed and analyzed by three radiologists (4, 5 and 10 years of experience reading chest CTs). They had initial experience reading IR images after having participated in other research projects. IR had not been integrated into the clinical routine at our institution at the time of the experiments.

Subjective image quality

In order to become familiar with the evaluation system for the subjective image quality including the presence of streak artifacts and a blotchy pixilated appearance, the radiologists were trained using images obtained from four patients who had not been part of the study population. Excessive smoothing of images and a pronounced change in image texture should be evaluated as blotchy pixilated appearance. All data sets were reviewed with lung window settings (window width = 1800 HU; window center = -450 HU). Each MDCT data set was assessed at the 1) central lung zone including the main and segment bronchi within 20 mm of hila, 2) peripheral lung zone within 20 – 40 mm of hila including small bronchi and bronchioles, 3) subpleural region within 10 mm of the chest wall, 4) centrilobular region and 5) apical lung zone.

The subjective image quality was individually rated based on the distinction of anatomic details, image noise, artifacts and diagnostic quality using a 4-point Likert scale defined as follows:

- 4, excellent image quality, distinct anatomic details, no/minimal image noise or artifacts, full diagnostic confidence;
- 3, good image quality, clear anatomic details, minor image noise or artifacts not affecting diagnostic confidence;
- 2, reduced image quality, limited resolution of anatomic details, increased image noise or artifacts with impairment of diagnostic confidence;
- 1, poor image quality, poorly defined anatomic details, high image noise or artifacts resulting in poor diagnostic confidence.

Image appearance was assessed for the presence of a blotchy pixilated texture and was also rated on a 4-point Likert scale (4, no pixilation or blotchy appearance; 3, minor pixilation or blotchy appearance not affecting diagnostic confidence; 2, increased pixilation or blotchy appearance reducing diagnostic confidence; 1, high pixilation or blotchy appearance with poor diagnostic confidence).

Lesion conspicuity in low-dose MDCT

In order to assess the impact of different iDose4™ reconstructions on lesion conspicuity in LDCT images, a co-investigator not involved in the evaluation process selected representative images from the LDCT data set reconstructed with FBP, which demonstrated at least one of the following findings: ground-glass opacity (GGO), mosaic attenuation pattern, small nodules up to 10 mm, subtle ill-defined infiltrates. Images at the corresponding anatomical level post-processed with 7 different iDose4™ reconstructions and the selected image with FBP were then both anonymized and randomized so that readers were blinded to reconstruction techniques and levels. The resulting paired images of each lesion were simultaneously assessed for conspicuity on a 4-point Likert scale (4, excellently definable lesion; 3, well definable lesion; 2, limited definable lesion; 1, not definable lesion). Finally, a consensus reading of all FBP and iDose4™ data sets was performed in a side-by-side comparison in order to ensure the assessment of all pneumonia associated lung lesions. These results were used as the reference standard.

Statistical analysis:

Statistical analysis was performed using SPSS 20.0 (SPSS Inc., Chicago, IL). Patient characteristic data including transverse and longitudinal diameter and radiation dose measurements were assessed using Student's *t*-test. Subjective image quality and lesion conspicuity parameters as well as OIN and mean CT values were compared using a random intercept model. Patients and raters were defined as random intercept. IR level setting was defined as a fixed effect. The statistical significance was defined as $p < 0.05$. Interobserver agreement between the radiologists was determined using Intraclass Correlation Coefficients (ICC).

Results

Patient distribution

There was no significant difference in mean patient size within the LDCT or RDCT group. On average, the patient age was higher for the group of patients investigated with RDCT. **Table 2** summarizes the patient data in both groups.

Radiation dose

The mean value of effective mAs was 26.7 ± 9.59 (range 20 – 40 mAs) for patients with LDCT scans. Taking into account the effect of automatic exposure control by ACS and Z-DOM in the patient collective with RDCT scans, the mean value of the effective mAs was 116 ± 29.6 (range 68 – 151 mAs). The radiation dose was 78 % lower with LDCT than with RDCT ($CTDI_{vol}$: 1.7 mGy vs. 7.6 mGy).

Objective image quality

Compared to FBP reconstructed images, application of increasing iDose4™ levels in LDCT images resulted in a significant reduction of OIN, with a maximum at iDose7 MFR (**Table 3**).

While a maximum image noise reduction of 72 % was reached by applying iDose4™ in LDCT images (mean reduction of 72 % at the level of the subscapularis muscle and 50 % at the level of the lung apex), the mean CT value, measured in LDCT images with FBP and different iDose4™ levels, remained constant.

The noise index was nearly identical for LDCT at iDose level 4 (mean HU subscapularis muscle: 59.9) and RDCT with FBP (mean HU subscapularis muscle: 56.6).

Subjective image quality

The interrater agreement between the three radiologists was excellent ($p < 0.05$). LDCTs reconstructed with FBP were rated as the lowest image quality, whereas the scores improved with increasing iDose4™ levels.

The highest scores were reached reading low-dose images reconstructed with iDose6 MFR.

Table 2 Patient characteristics and CT acquisition data in LDCT versus RDCT.

Tab. 2 Patientencharakteristika und CT-Akquisitionsdaten in LDCT versus RDCT.

	low-dose CT (LDCT) (n = 30)	routine-dose CT (RDCT) (n = 30)	p-value
patient size			
transverse diameter (cm)	34.2	35.8	> 0.05
longitudinal diameter (cm)	21.6	23.2	> 0.05
height (cm)	172.5	174.3	> 0.05
weight (kg)	73.7	73.9	> 0.05
BMI (kg/m²)	23.9	24.1	> 0.05
demographics			
age (years)	49.1	70.8	< 0.05
gender (male)	13	20	< 0.05
CT acquisition data			
mean tube current-time product (mAs)	26.7	116.0	< 0.05
mean $CTDI_{vol}$ (mGy)	1.7	7.6	< 0.05

The overall image quality did not significantly differ between the higher iDose4™ levels iDose6, iDose6 MFR, iDose7 and iDose7 MFR.

In particular, the application of iDose4™ in LDCT improved the subjective image quality of the apical lung zone, the small bronchi and bronchioles and the centrilobular and subpleural region. For these regions, image quality was evaluated as reduced for LDCT FBP images (mean scores, 1.97; 2.35; 2.29 and 2.35, respectively) while high image quality was achieved for LDCT iDose6 MFR images (mean scores, 4; 3.45; 3.6; 3.72, respectively) (**Fig. 1**). Streak artifacts in the apical lung zones were notably

Table 3 Quantitative noise measurements obtained within the subscapularis muscle and lung apex in LDCT reconstructed with FBP and different iDose4™ levels. CT value (in Houndsfield units (HU)); OIN: objective image noise (in HU).

Tab. 3 Quantitative Rauschmesswerte, erhoben innerhalb des musculus subscapularis und in der Lungenapex, in LDCT rekonstruiert mit FBP und verschiedenen iDose4™-Stufen. CT-Dichtewerte (in Hounsfield units (HU)); OIN: objectives Bildrauschen (in HU).

	subscapularis muscle		lung apex	
iteration level	CT value (HU)	OIN (HU)	CT value (HU)	OIN (HU)
FBP	37.3	139.4	-751.0	171.3
iDose 2	35.9	69.9	-756.7	109.3
iDose 4	35.8	59.9	-755.9	101.5
iDose 4 MFR	35.6	60.2	-755.3	101.8
iDose 6	35.6	48.3	-755.2	92.3
iDose 6 MFR	35.2	45.8	-755.4	91.0
iDose 7	35.3	40.6	-756.1	86.4
iDose 7 MFR	35.4	39.4	-757.4	86.1

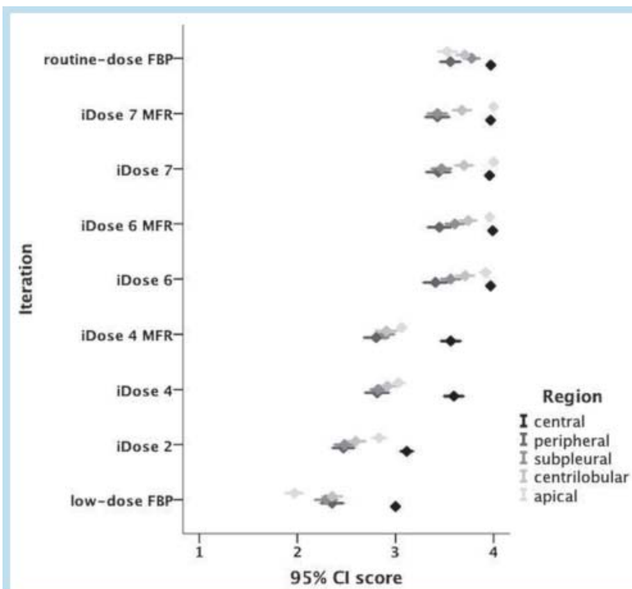

Fig. 1 Figure shows the score distribution for different anatomical chest regions being rated in LDCT images reconstructed with FBP and 7 different iDose4™ levels and RDCT images reconstructed with FBP.

Abb. 1 Die Abbildung zeigt die Verteilung der Bewertungen für die verschiedenen anatomischen Thoraxregionen für LDCT-Bilder, welche mit FBP und 7 verschiedenen iDose4™-Stufen rekonstruiert wurden sowie für RDCT-Bilder, welche mit FBP rekonstruiert wurden.

reduced, enabling better depiction of the underlying anatomical structures (Fig. 2a–h).

The image quality for the assessment of large bronchi was good in LDCT FBP images (mean score FBP: 3), but it increased when using iDose4™ (mean score iDose6 MFR: 4).

A minor blotchy appearance was observed in the LDCT images reconstructed with the highest iDose4™ levels 7 and 7MFR, but did not affect the diagnostic confidence or the visualization of diagnostic details. No pixilation artifacts were seen on RDCT.

There was no significant difference in the overall image quality between the LDCT scans reconstructed with high iDose4™ levels (≥ iDose6) and RDCT scans reconstructed with FBP (mean scores, 3.7 vs. 3.7; $p > 0.05$) (**Fig. 3a, b**). With regard to the apical lung zones, LDCT images with high iDose4™ levels were rated slightly better than RDCT images with FBP (mean scores, 3.5 vs. 4; $p < 0.05$) (**Fig. 1**).

Lesion conspicuity

Lesions were detected in 27 of 30 LDCT examinations. The final consensus reading of all FBP and iDose data sets did not disclose any additional pneumonia-related lung lesion. The 49 selected lesions included 20 GGO, 6 mosaic attenuation patterns, 5 small nodules and 18 subtle ill-defined infiltrates.

The conspicuity of these lesions was rated as limited in LDCT FBP images. For all types of subtle lesions, increasing levels of iDose4™ resulted in an improvement of lesion visualization in comparison to LDCT images using FBP. However, significant differences in lesion conspicuity were determined as from the application of iDose4™ level 4 (**Fig. 4**). For subtle lesion conspicuity high iDose4™ levels were rated superior to images reconstructed with FBP, thus enabling excellent detection of mosaic attenuation pattern, small nodules, subtle ill-defined infiltrates and GGO (mean scores iDose6 MFR: 3.4; 3.9; 3.5; 3.3; respectively) (**Fig. 5a–b, 6a–b**). These lesions were rated to be of limited de-

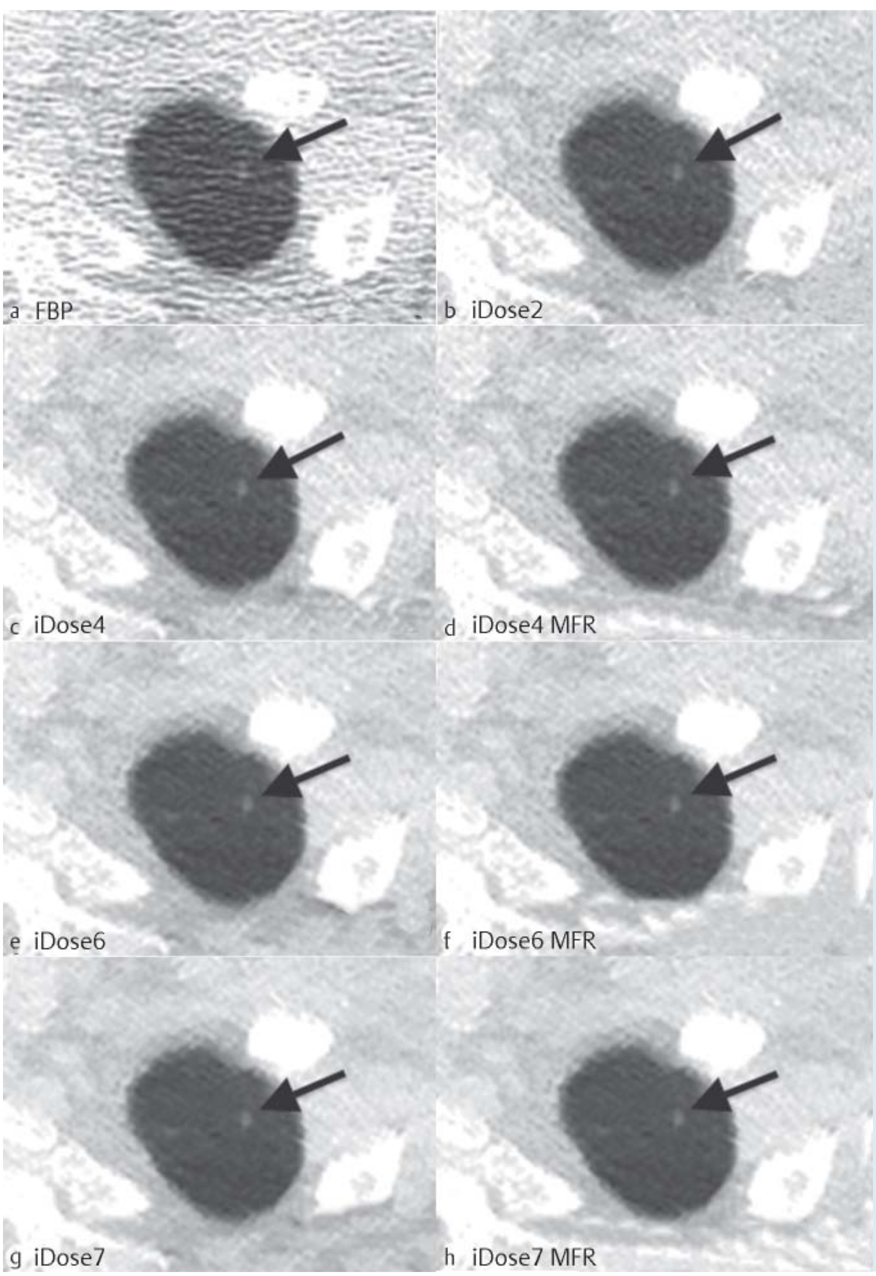

Fig. 2 49-year-old man referred for investigation of suspected pneumonia following s/p HSCT for small lymphocytic lymphoma. The non-enhanced low-dose chest CT images obtained with 40 mAs ($CDTI_{vol}$: 2.6 mGy) were reconstructed with **a** FBP and **b–h** seven different $iDose^{4TM}$ levels. With increasing $iDose^{4TM}$ levels, image noise and streak artifacts in the apical left upper lobe were remarkably reduced, enabling markedly better visualization of the underlying anatomical structures and the detection of a small nodule.

Abb. 2 49-jähriger Patient, welcher unter dem Verdacht einer Pneumonie nach hämatopoetischer Stammzelltransplantation in Folge eines kleinzelligen lymphozytären Lymphoms untersucht wurde. Die nativen Niedrigdosis Thorax CT-Daten, durchgeführt bei 40 mAs ($CDTI_{vol}$: 2.6 mGy), wurden mit **a** FBP und **b–h** sieben verschiedenen $iDose^{4TM}$-Stufen rekonstruiert. Mit steigenden $iDose^{4TM}$-Stufen wurden das Bildrauschen und die Streifenartefakte in dem apikalen linken Oberlappen deutlich reduziert, dies ermöglichte eine beträchtlich bessere Visualisierung der zugrundeliegenden anatomischen Strukturen und die Detektion eines kleinen Nodulus.

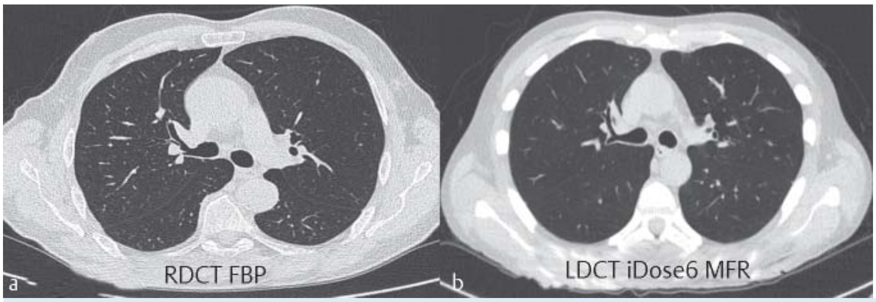

Fig. 3 **a** routine-dose non-enhanced MDCT in a 77-year-old man referred for preoperative assessment prior to cardiac surgery (120 kV;108 eff. mAs; $CDTI_{vol}$: 7.2 mGy) reconstructed with FBP; **b** low-dose non-enhanced MDCT in a 39-year-old man with s/p HSCT for osteomyelofibrosis (120 kV; 20 eff. mAs; $CDTI_{vol}$: 1.3 mGy) reconstructed with iDose6 MFR. Low-dose image with iDose6 MFR **b** is of similar image quality as routine-dose image with FBP **a** at an 82 % lower radiation dose.

Abb. 3 **a** Native Standarddosis MDCT eines 77-jährigen Patienten welcher im Rahmen einer präoperativen Diagnostik vor herzchirurgischem Eingriff untersucht wurde (120 kV;108 eff. mAs; $CDTI_{vol}$: 7.2 mGy) rekonstruiert mit FBP; **b** Native Niedrigdosis MDCT eines 39-jährigen Patienten nach hämatopoetischer Stammzelltransplantation bei Osteomyelofibrose (120 kV; 20 eff. mAs; $CDTI_{vol}$: 1.3 mGy) rekonstruiert mit iDose6 MFR. Die Niedrigdosis Aufnahme mit iDose6 MFR **b** ist von ähnlicher Bildqualität wie die Standarddosis Aufnahme mit FBP **a** bei 82 % geringerer Strahlendosis.

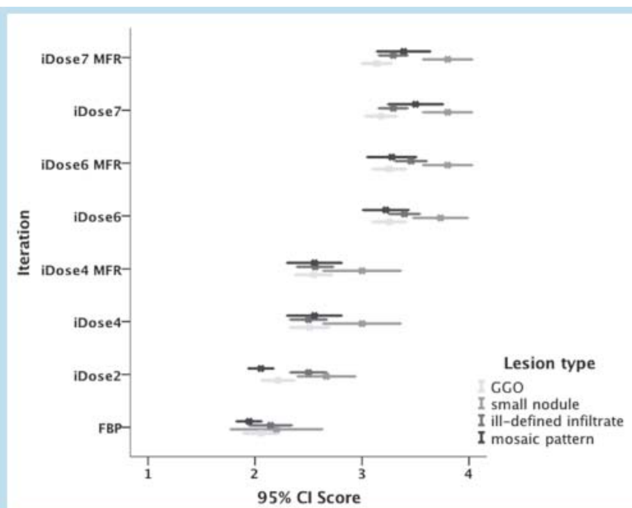

Fig. 4 Figure shows the score distribution for different subtle lesions being rated in LDCT images reconstructed with FBP and 7 iDose4™ levels.

Abb. 4 Die Abbildung zeigt die Verteilung der Bewertungen für die verschiedenen subtilen pathologischen Veränderungen für LDCT-Bilder, welche mit FBP und 7 verschiedenen iDose4™-Stufen rekonstruiert wurden.

lineation in the corresponding paired images reconstructed with FBP (mean scores FBP: 2; 2.3; 2.2; 2.1; respectively) (► **Fig. 5a, 6a**).

Discussion

Chest MDCT examinations play an important role in the early detection of pulmonary diseases in immunocompromised patients [20, 21]. Due to the high rate of pulmonary affection in this cohort, follow-up or short-term repeated MDCT examinations are often required, resulting in a high cumulative radiation dose. Implementation of low-dose MDCT protocols would be desirable, but dose reduction usually increases image noise which can impair image quality [13]. Since pulmonary findings in immunocompromised patients can be subtle [6, 9, 22], it is important to apply a technique that allows low radiation doses while maintaining image quality. Statistical iterative algorithms offer noise reduction and preserve spatial resolution [14, 15, 17, 23].

In this study, the impact of the 4th generation IR technique iDose4™ with regard to image quality and dose reduction in LDCT of the chest was compared to conventional FBP. At a low radiation dose of 1.7 mGy ($CTDI_{vol}$), iDose4™ provides significant improvements in overall image quality, artifact and noise reduction and even lesion conspicuity compared to LDCT reconstructed with FBP.

While the best overall image quality in LDCT images was achieved with iDose6 MFR, the lowest image quality was achieved with FBP reconstructions. Particularly with regard to the visualization and image quality of the apical lung zone as well as small and peripheral anatomical structures, LDCT images benefitted significantly from the use of iDose4™.

Likewise, the conspicuity of subtle lesions including mosaic attenuation pattern, small nodules, subtle ill-defined infiltrates and GGO improved noticeably when applying iDose4™. In view of the fact that these lesions were rated as "limitedly visualized" in the corresponding LDCT images reconstructed with FBP, these results are of great importance with regard to the immunocompromised patient collective, in whom the identification of subtle changes can be decisive [6].

As prior investigations [24] have shown that a slice thickness greater than 1 mm may limit the depiction of subtle findings, the present study evaluated anatomical structures and lung parenchymal findings in 1-mm sections. However, a slice thickness of 1 mm and a sharp filter lung kernel lead to a significant increase in image noise, making that approach inappropriate for low-dose acquisitions. This limitation of low-dose protocols can be resolved by applying iDose4™, which, in the presented study, provided a substantial reduction of image noise of up to 72 % for LDCT images reconstructed with iDose7 MFR compared to FBP. Higher conspicuity of small and subtle lesions may be explained by the iDose4™ algorithm, which penalizes noisy data while preserving the underlying edges associated with anatomical and pathological findings. These results are in concordance with those described in a prior phantom study, documenting the capability of iDose4™ to significantly reduce image noise while maintaining spatial resolution [16]. On the other hand, the final consensus reading of all data sets did not reveal any additional lesion that had been missed if FBP was used for low-dose MDCT ex-

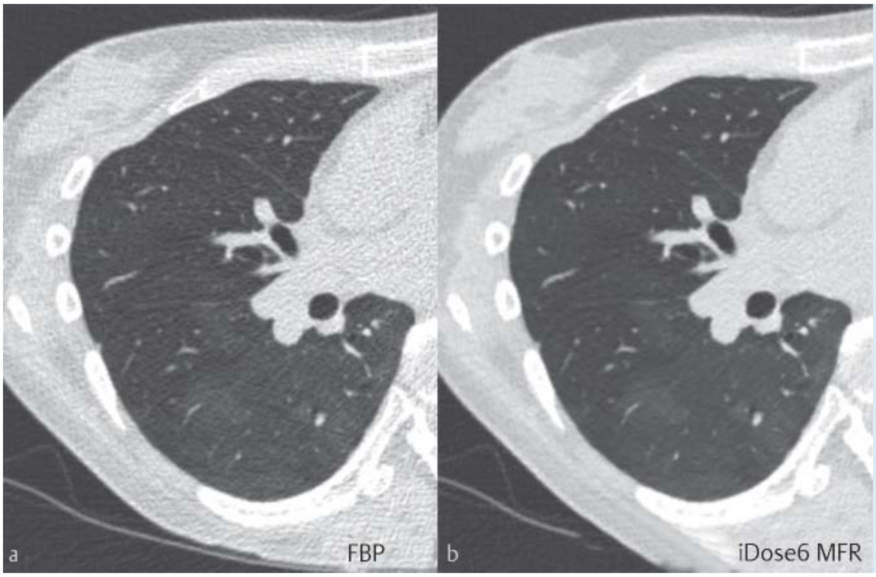

Fig. 5 Non-enhanced low-dose chest MDCT in a 35-year-old man with s/p HSCT for acute lymphoblastic leukemia referred for suspicion of pneumonia (120 kV; 20 eff mAs; $CDTI_{vol}$:1.3 mGy). FBP-reconstructed image **a** shows a mosaic pattern, which is better visualized in the reconstruction with iDose6 MFR **b**. The objective image noise measured within the subscapularis muscle decreased from 141 HU at FBP to 38 HU at iDose6 MFR.

Abb. 5 Native Niedrigdosis MDCT des Thorax eines 35-jährigen Patienten nach hämatopoetischer Stammzelltransplantation bei akuter lymphoblastischer Leukämie durchgeführt unter dem Verdacht einer Pneumonie (120 kV; 20 eff mAs; $CDTI_{vol}$: 1.3 mGy). Das mit FBP rekonstruierte Bild **a** zeigt eine Mosaikperfusion, welche in der Rekonstruktion mit iDose6 MFR **b** besser zur Darstellung kommt. Das objektive Bildrauschen, gemessen im musculus subscapularis, verringerte sich von 141 HE in der FBP auf 38 HE in der iDose6 MFR Rekonstruktion.

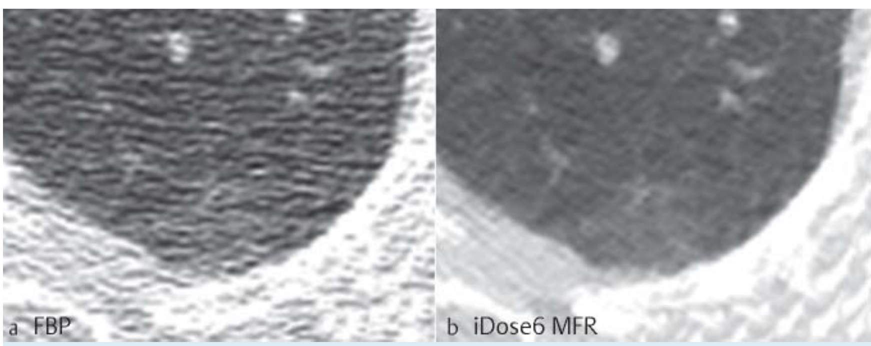

Fig. 6 Non-enhanced low-dose chest MDCT in a 72-year-old woman with s/p HSCT for Non-Hodgkin's lymphoma (40 eff. mAs; $CTDI_{vol}$: 2.6 mGy). Extracts of an axial CT image reconstructed with **a** FBP and **b** iDose6 MFR. Compared to LDCT FBP image, the subpleural ground-glass opacity in the upper lobe is better visualized in the iDose6 MFR reconstructed image. The objective image noise measured within the subscapularis muscle decreased from 228 HU at FBP to 53 HU at iDose6 MFR.

Abb. 6 Native Niedrigdosis MDCT des Thorax einer 72-jährigen Patientin nach hämatopoetischer Stammzelltransplantation bei NHL (40 eff. mAs; $CTDI_{vol}$: 2.6 mGy). Ausschnitte eines axialen CT Bildes rekonstruiert mit **a** FBP und **b** iDose6 MFR. Verglichen mit dem LDCT-FBP-Bild ist die subpleurale Milchglastrübung im Oberlappen besser in dem mit iDose6 MFR rekonstruiertem Bild abgrenzbar. Das objektive Bildrauschen, gemessen im musculus subscapularis, verringerte sich von 228 HE in der FBP auf 53 HE in der iDose6-MFR-Rekonstruktion.

clusively. Therefore, in concordance with the literature, low-dose CT of the chest using FBP seems to be a reliable approach for the identification of small ill-defined lung lesions [25] but lesion conspicuity can be substantially improved by applying iDose4™ for image reconstruction.

Beside image noise, streak artifacts caused by photon starvation due to the osseous shoulder girdle occurring in the apical lung zones are a major impairment of low-dose acquisitions [26]. Findings in the apical lung zones could be obscured by the high grade of streak artifacts in LDCT. With iDose4™, these artifacts can be markedly reduced allowing for significantly better visualization of the underlying anatomical structures of the apical lung zones.

The higher iDose4™ levels (iDose6, iDose6 MFR, iDose7 and iDose7 MFR) were rated the most effective reconstructions to achieve best overall image quality in LDCT images. The highest scores were achieved using an iDose level of 6. However, with the use of iDose7 and iDose7 with multi-frequency reconstruction, a minor blotchy appearance was noticed, but this did not affect the diagnostic confidence. Multi-frequency reconstruction [19] strives to retain the noise frequency spectrum, which is responsible for the “look and feel” of the images by allowing noise removal while preserving the image texture. These results may indicate that at a great level of noise removal as with the application of the highest iDose4™ level 7, multi-frequency reconstruction cannot fully prevent a slight shift in the noise frequency spectrum. Images with MFR did not have a significantly higher quality.

Applying a high iDose4™ level on LDCT data provides image quality that is diagnostically equivalent to RDCT acquisitions using FBP at a 78 % lower radiation dose. Low-dose non-enhanced chest MDCT images acquired with a mean current-time product of 26.7 mAs and a mean $CTDI_{vol}$ of 1.7 mGy using iDose4™ level 6 and 7 were determined to be of similar image quality compared to routine-dose images acquired with a mean tube-current time product of 116 mAs and a mean $CTDI_{vol}$ of 7.6 mGy.

To our knowledge, this is the first report on the impact of different levels of an iterative reconstruction algorithm on chest CT examinations with a radiation dose as low as 1.7 mGy and an average effective mAs of 26.7. Prior studies applying different statistical iterative algorithms to low-dose acquisitions [27 – 30] were obtained with a $CTDI_{vol}$ between 3.5 – 4.63 mGy and mean tube current-time products of 40 – 67 mAs. However, our data document a much higher potential for dose reduction using iDose4™ (up to 78 %) compared to two prior reports [29, 30], in which dose reduction of up to 40 % was achieved using iterative reconstruction algorithms from different vendors. Solely, using ASIR with a high iteration level, Singh et al. [28] described a potential dose reduction of up to 75 %.

Transferring our results to the clinical routine, the clinical implications of iDose4™ include a substantial improvement in image quality, lesion conspicuity and noise reduction capability in low-dose MDCT imaging. Furthermore, a considerable radiation dose reduction to 1.7 mGy for non-enhanced chest MDCT examinations using iDose4™ is feasible. Complying with the ALARA principle according to which examinations must be performed with the minimum radiation dose that provides the desired diagnostic information, implementation of iterative reconstruction techniques such as iDose4™ in routine MDCT imaging seems to be indispensable. This is of particular importance with regard to the special patient cohort of immunocompromised patients, who are often young and may need repetitive MDCT examinations.

The following limitations of the study have to be mentioned. First, the sample size is relatively small due to the one-month trial period for the IR prototype. Second, in order to compare the radiation dose reduction capability, an interindividual comparison between two groups with LDCT and RDCT acquisitions was performed. It would be desirable to have both dose protocols applied in the same individuals. However, this would have been ethically debatable. Apart from that, no relevant differences in patient size characteristics affecting the image noise were observed among the two investigated groups. But it has to be noted that patients in the LDCT group were younger than in the RDCT group. This might be a confounding factor in the evaluation of image quality, because anatomical structures may often be better depicted in younger patients than in older patients.

In addition, due to different clinical indications between the LDCT and RDCT groups, we compared the overall image quality. However, we did not compare the lesion conspicuity between these groups with different radiation doses, but an intraindividual comparison of FBP and IR at different iDose4™ levels demonstrated the positive effect of IR on lesion conspicuity in low-dose scans.

Conclusion

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In non-enhanced LDCT of the chest, IR using iDose4™ has the potential to improve image quality and reduce artifacts as well as image noise as compared to FBP. The conspicuity of subtle lesions, which is limited in LDCT FBP images, significantly improves as the level of iDose4™ increases (≥iDose4™ level 4).

Compared to routine-dose examinations reconstructed with FBP, high iDose4™ levels applied on low-dose MDCT images can provide equivalent image quality, consequently allowing for a radiation dose reduction of up to 78 %.

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