

Quantitative analysis of emphysema and airway measurements according to iterative reconstruction algorithms: comparison of filtered back projection, adaptive statistical iterative reconstruction and model-based iterative reconstruction

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Abstract

Objectives To evaluate filtered back projection (FBP) and two iterative reconstruction (IR) algorithms and their effects on the quantitative analysis of lung parenchyma and airway measurements on computed tomography (CT) images.

Methods Low-dose chest CT obtained in 281 adult patients were reconstructed using three algorithms: FBP, adaptive statistical IR (ASIR) and model-based IR (MBIR). Measurements of each dataset were compared: total lung volume, emphysema index (EI), airway measurements of the lumen and wall area as well as average wall thickness. Accuracy of airway measurements of each algorithm was also evaluated using an airway phantom.

Results EI using a threshold of -950 HU was significantly different among the three algorithms in decreasing order of FBP (2.30 %), ASIR (1.49 %) and MBIR (1.20 %) ($P < 0.01$). Wall thickness was also significantly different among the three algorithms with FBP (2.09 mm) demonstrating thicker walls than ASIR (2.00 mm) and MBIR (1.88 mm) ($P < 0.01$).

Airway phantom analysis revealed that MBIR showed the most accurate value for airway measurements.

Conclusion The three algorithms presented different EIs and wall thicknesses, decreasing in the order of FBP, ASIR and MBIR. Thus, care should be taken in selecting the appropriate IR algorithm on quantitative analysis of the lung.

Key Points

- Computed tomography is increasingly used to provide objective measurements of intra-thoracic structures.
- Iterative reconstruction algorithms can affect quantitative measurements of lung and airways.
- Care should be taken in selecting reconstruction algorithms in longitudinal analysis.
- Model-based iterative reconstruction seems to provide the most accurate airway measurements.

Keywords Iterative reconstruction · Computed tomography · Quantitative analysis · Pulmonary emphysema · Chronic obstructive pulmonary disease

Abbreviations and acronyms

FBP	Filtered back projection
ASIR	Adaptive statistical iterative reconstruction
MBIR	Model-based iterative reconstruction
EI	Emphysema index

Introduction

With the increasing use of computed tomography (CT), radiation exposure is becoming a bigger issue in the clinical field. Many approaches have been developed to reduce radiation

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exposure while maintaining image quality [1, 2] and recently introduced iterative reconstruction (IR) techniques have shown potential in replacing the conventionally used filtered back projection (FBP) algorithm in this regard [3–9]. IR synthesises the projections by modelling the data collection process at CT. The modelling of photon and noise statistics is incorporated into the adaptive statistical iterative reconstruction (ASIR) algorithm (GE Healthcare, Waukesha, WI, USA) and the modelling of system optics is added to this in the model-based iterative reconstruction (MBIR) algorithm [4]. During reconstruction, a regularisation step that penalises statistical fluctuations is used to control the trade-off between noise and resolution in the reconstructed image. ASIR focuses on modelling the noise properties of the imaged object to allow dose reduction by 32–65 % without increasing noise in the reconstructed images [5], while MBIR models both system statistics and optics and is able to reduce noise and improve the spatial resolution of CT images at the same time. However, there is a trade-off as these methods use edge-preserving regularisation in controlling noise while improving spatial resolution, which inevitably affects various measurements in its quantitative analysis.

At present, CT is widely performed in patients with chronic obstructive pulmonary disease (COPD) as it can provide a quantitative morphological method of investigating airflow obstruction in COPD patients [10, 11]. The most commonly used CT measurements for this task include CT densitometric parameters such as emphysema index, mean lung density and airway dimensions. It is essential to understand the many factors that can affect these measurements [12–14]. Until recently, only a few studies have dealt with the effect of IR on the assessment of emphysema and airway dimensions [15, 16]. However, there have been no studies that have evaluated the effect of different IR algorithms including MBIR on the quantitative measurements of COPD, and furthermore no reference standard such as airway phantoms has been employed in comparison.

Therefore, this study attempts to compare the differences in emphysema indexes and airway dimensions between FBP and two IR algorithms on low-dose CT images.

Materials and methods

Study population

In order to evaluate the effect of different reconstruction algorithms on the quantitative analysis of lung parenchyma and airways, low-dose chest CT obtained from 281 consecutive patients were used in this study. Patients comprised 183 men and 98 women with a mean (\pm SD) age of 58 (\pm 18) years (range, 23–91) and they were referred for follow-up or surveillance of lung nodules.

To evaluate the difference according to the severity of emphysema, all subjects were classified into two groups based

on their emphysema index (threshold of -950 HU) obtained from FBP images: no or minimal emphysema (emphysema index <5) or mild to moderate emphysema (emphysema index ≥ 5) [17]. Group I consisted of 250 subjects with no or minimal emphysema and Group II consisted of 31 subjects with mild to moderate emphysema. The 250 consecutive subjects of Group I and 31 subjects of Group II were reviewed for airway analysis. The apical segmental bronchus of the right upper lobe was selected for airway analysis and cases of bronchial obstruction were excluded.

The study protocol was approved by our institutional review board and patients' informed consent was not required to generate the three series of reconstructions; retrospective analysis of data was possible with waiver of patients' informed consent.

CT data acquisition and image reconstruction

Low-dose chest CT was performed with the subject in supine position during end-inspiratory breath-holding using a 64 slice multidetector CT system (Discovery CT 750 HD; GE Healthcare). Imaging parameters were held constant in helical imaging mode: 64×0.625 mm detector configuration, 0.5 s rotation time, tube voltage of 120 kVp and tube current of 37 mAs. Tube current modulation was not applied and contrast enhancement was not performed.

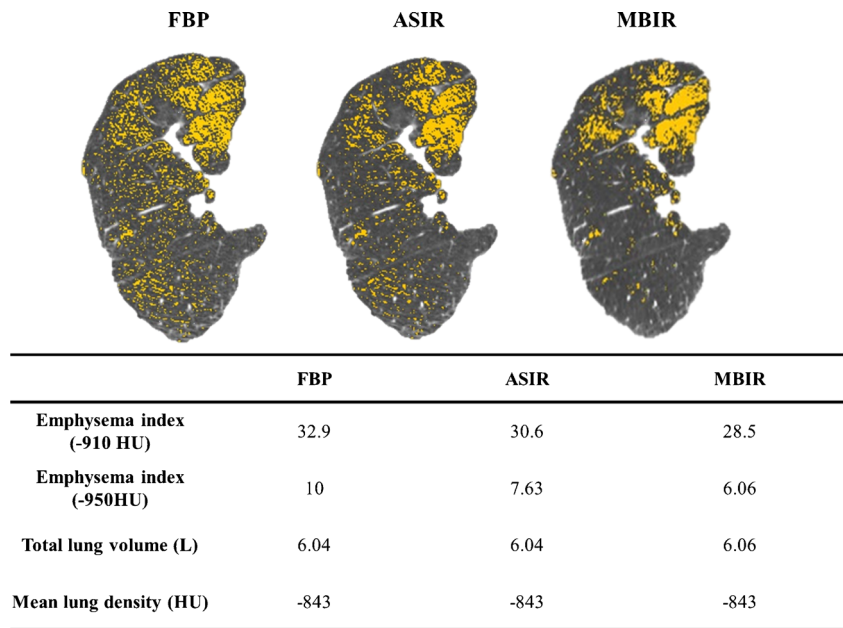
All images were reconstructed at 0.625 mm with FBP, ASIR and MBIR techniques using a standard kernel. As for ASIR image reconstruction, 50 % level blending was selected based on previous literature [18]. As the computational burden on modelling system statistics is not nearly as heavy as modelling system optics, ASIR was much faster than MBIR; ASIR required 3–4 min, and MBIR needed approximately 1 h for image reconstruction of a single dataset.

Image analysis

Quantitative analysis measurements of the lung parenchyma and airways were obtained using an automated lung image analysis tool (Thoracic VCAR; GE Healthcare) installed on an image processing workstation (AW server version 2; GE Healthcare) for each dataset. Total lung volume, mean lung density and emphysema index represented by relative area (RA) under two thresholds of -950 HU and -910 HU were obtained (Fig. 1) with the three algorithms. Emphysema was assessed through segmentation of the lung parenchyma and airways from the chest wall and large central blood vessels [19]. Total emphysema percentage was defined as all lung voxels less than a certain CT attenuation value. Previous studies validated attenuation threshold values of -950 HU and -910 HU for quantitative determination of emphysema indexes [20–25].

Airway dimensions of luminal diameter, airway wall thickness (WT), airway wall area (WA), luminal area (LA) and wall area ratio (%WA: $WA/[WA+LA]$) were measured at the

Fig. 1 Quantitative analysis of lung parenchyma—emphysema index, total lung volume and mean lung density. A 62-year-old man underwent low-dose chest CT for cancer screening. The yellow-coloured overlay is RA (relative area) under -950 HU. This overlay demonstrated more extensive low-attenuated area on filtered back projection (FBP) image than adaptive statistical iterative reconstruction (ASIR) or model-based iterative reconstruction (MBIR) images. On CT image reconstructed with FBP, emphysema index (RA≤-950 HU) was 10.0 %, the total lung volume was 6.04 l and the mean lung density was -843 HU



proximal portion of the apical segmental bronchus of the right upper lobe in 258 subjects. The remaining 23 subjects were excluded from airway analysis because of the failure of airway segmentation or obstruction of the right upper lobar bronchus. In cases with variation in the bronchial trees of the right upper lobe, we selected the most vertical segmental bronchus in the right upper lobe. A schematic diagram of airway tracking and the process of quantitative analysis is shown in Fig. 2. An automated lung image analysis tool (Thoracic VCAR; GE Healthcare) using a watershed segmentation algorithm was used to detect the airway walls, and clinical validation of this tool has been reported [26].

Phantom analysis

Phantom analysis was performed using a CTP674 Lung Phantom (The Phantom Laboratory, Salem, NY, USA), which

consists of an elliptical foam region (250 mm×150 mm) to simulate a lung surrounded by a soft tissue ring (outer dimensions, 350 mm×250 mm). In the foam, tubes, air holes and holes for a water bottle were present. Six polycarbonate tubes simulating airways with walls were embedded in the foam, among which two tubes (CTP666-1 and CTP666-4) were embedded at an angle of 30° from the z-axis of the CT couch. CT of the phantoms was performed with the same low-dose chest CT protocol and reconstructed images using the same three algorithms.

Airway dimensions of an acrylic rod embedded in the foam were measured with Thoracic VCAR at the same level as each reconstructed image of the three algorithms (Fig. 3). As two tubes (CTP666-1, 2) with a luminal diameter of 3 mm and 0.6-mm wall thickness failed to be measured on the software, they were excluded from this study. The other four tubes (CTP 666-3, 4, 5, 6) had luminal diameters of 6 mm with wall

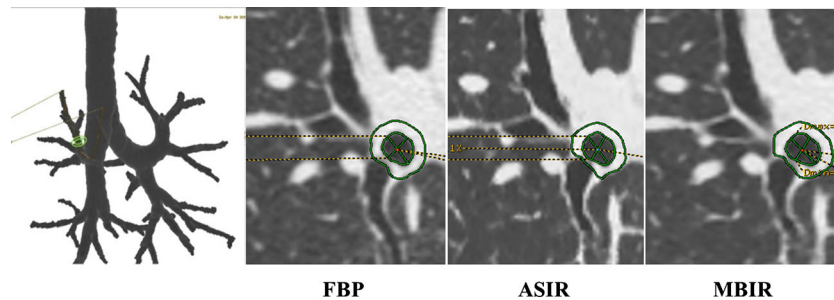


Fig. 2 Quantitative analysis of airway—bronchial wall thickness, wall area, luminal area, %WA of the proximal right upper lobar apical segment. After uploading the case data, a three dimensional image of the tracheobronchial tree was automatically generated. Once the apical segmental bronchus of right upper lobe is selected, the path from the trachea to the segmental bronchus was automatically generated. After selection of

the proximal portion of the apical segmental bronchus on a cross-sectional image perpendicular to the central path, airway measurements (FBP/ASIR/MBIR) including bronchial wall thickness (2.1/2.0/1.9 mm), wall area (43.2/46.4/39.3 mm²), luminal area (28.5/27.2/29.0 mm²) wall and luminal area ratio (60.3/63.1/57.6 %) were obtained for all three sets of images reconstructed with each algorithm

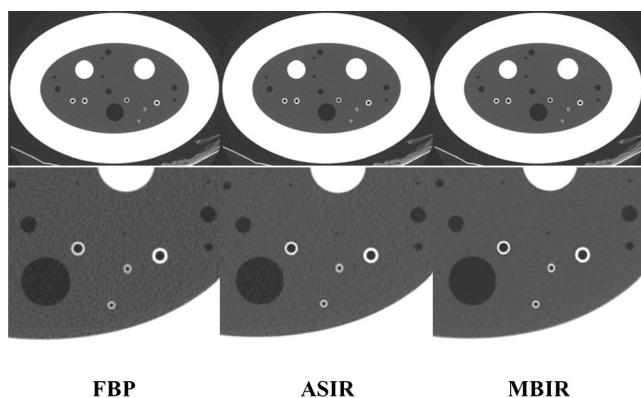


Fig. 3 Phantom analysis with CTP674 Lung Phantom. In the foam simulating the lung, there are air holes, holes for a water bottle and acrylic rods. Airway dimensions were measured with acrylic rods. Note the least noise and the sharpest border of structures on the image reconstructed with MBIR

thicknesses of 0.9 mm, 1.2 mm, 1.2 mm and 1.5 mm, respectively. LA, WA, WT and %WA of each tube were measured five times at different levels for each tube. These measurements were compared with the reference actual value of the tubes.

Data and statistical analysis

Repeated-measures analysis of variance was performed for statistical analysis. Each measure or parameter according to the three algorithms was compared and a *P* value less than 0.05 was considered to be a significant difference. Adjustment for multiple comparisons was performed using Bonferroni correction. The phantom study was analysed using the Wilcoxon signed-rank test and percentage measurement error was calculated as $100 \times (MV - RV) / RV$, where MV and RV are the measured value and reference value, respectively.

Results

Emphysema index

Emphysema index in total subjects was significantly different among the three algorithms ($P < 0.01$), with the mean value of emphysema index decreasing in the order of FBP (RA-950 HU=2.30 %; RA-910 HU=12.89 %), ASIR (RA-950 HU=1.49 %; RA-910 HU=10.79 %) and MBIR (RA-950 HU=1.20 %; RA-910 HU=10.00 %) at both thresholds of -950 HU and -910 HU (Table 1).

In the mild to moderate emphysema group (emphysema index ≥ 5 % on FBP image), emphysema index (RA-950 HU) was also observed to decrease in the order of FBP (10.24 %), ASIR (8.45 %) and MBIR (8.12 %), but emphysema index (RA-910 HU) was observed to decrease in the order of FBP

(33.26 %), MBIR (32.37 %) and ASIR (32.25 %). With RA-910 HU, there was a significant difference between FBP and ASIR, as well as between FBP and MBIR, but there was no significant difference between ASIR and MBIR (Table 2, Fig. 4).

In the normal to minimal emphysema group (emphysema index < 5 %), emphysema index was significantly different among the three algorithms in the same order as that of total subjects; FBP (RA-950 HU=1.29 %; RA-910 HU=10.34 %), ASIR (RA-950 HU=0.63 %; RA-910 HU=8.16 %) and MBIR (RA-950 HU=0.42 %; RA-910 HU=7.22 %) at both thresholds of -950 HU and -910 HU.

Mean lung density

Mean lung density in total subjects and the normal to minimal emphysema group (FBP, -800.58/-794.73 HU; ASIR, -800.84/-794.91 HU; MBIR, -801.12/-795.22 HU) was significantly different between FBP and MBIR ($P < 0.05$), but there was no significant difference between FBP and ASIR, ASIR and MBIR ($P > 0.05$). In the mild to moderate emphysema group, mean lung density (FBP, -847.77 HU; ASIR, -848.71 HU; MBIR, -848.77HU) was also significantly different between FBP and MBIR ($P < 0.05$), furthermore, significantly different between FBP and ASIR ($P < 0.05$), but there was no significant difference between ASIR and MBIR ($P > 0.05$).

Average wall thickness

Average wall thickness was significantly different among the three algorithms (FBP-total, 2.09; Group I, 2.07; Group II, 2.23 mm; ASIR-total, 2.00; Group I, 1.98; Group II, 2.15 mm; MBIR-total, 1.88; Group I, 1.86; Group II, 2.07 mm) in total subjects and both emphysema index groups ($P < 0.05$) (Fig. 4b).

Conversely, mean values of total lung volume (FBP, 4.13 l; ASIR, 4.15 l; MBIR, 4.15 l) and %WA (FBP, 71.89 %; ASIR, 71.22 %; MBIR, 74.39 %) were not significantly different among images reconstructed with the three different IR algorithms ($P > 0.05$) in total subjects and both groups.

Comparison with phantom analysis

All measurements were different from the reference value of the phantom (Wilcoxon-signed rank test, $P < 0.05$): CT measurements for the luminal area were significantly smaller than the reference value while those for wall area and wall thickness were significantly larger than the reference value (Table 3). Absolute measurement errors were biggest on CTs reconstructed using the FBP algorithm in the decreasing order of FBP, ASIR and MBIR.

Table 1 Mean values of quantitative analysis of lung parenchyma and airways in all subjects

	FBP		ASIR		MBIR	P value
Emphysema index (%) -950 HU	2.30	>	1.49	>	1.20	<0.01 ^a
Emphysema index (%) -910 HU	12.87	>	10.81	>	9.99	<0.01 ^a
Total lung volume (l)	4.13		4.15		4.15	>0.05
Mean lung density (HU)	-800.58	>	-800.84	=	-801.12	<0.05
%WA (wall area/luminal area)	71.89		71.22		74.39	>0.05
Wall thickness (mm)	2.11	>	2.05	>	1.97	<0.01 ^a

Emphysema index (both thresholds of -950 HU and -910 HU), wall thickness in total subjects significantly decreased in the order of FBP, ASIR and MBIR

FBP filtered back projection, ASIR adaptive statistical iterative reconstruction, MBIR model-based iterative reconstruction

^a Statistically significant

Discussion

The recent introduction of various IR algorithms have made it feasible to use low-dose CT techniques in order to lower radiation exposure without compromising image quality, which is essential for longitudinal quantitative analysis. Among the various IR algorithms, MBIR, which takes into account the modelling of data statistics, X-ray physics and system optics, is known to be the most advanced IR algorithm and can provide diagnostically acceptable chest CT images with low-dose or ultra-low-dose techniques [4, 9].

Emphysema index and airway dimensions on CT are effective parameters for the quantitative analysis of COPD

patients [27] and previous studies have reported that these quantitative measurements can be affected by various factors such as radiation dose, breath-hold, section thickness and the reconstruction algorithm used [12, 20, 24, 28]. Therefore, understanding the effect of various imaging parameters on quantitative CT parameters is important in designing optimal CT protocols for COPD evaluation especially in longitudinal studies. However, until now, only a few studies have dealt with the effect of IR algorithms on the quantitative measurements of COPD [15, 16]. In one study, Mets et al. [15] compared emphysema index and airway dimensions of the segmental bronchus on images reconstructed using FBP and IR (iDose; Philips Healthcare, Best, The Netherlands). In this study, while RA-950 led to a significant difference between images reconstructed using FBP and IR, airway dimensions were not significantly different. In another study by Nishio et al. [16], low-dose CT reconstructed with IR (ADIR3D; Toshiba Medical Systems, Tochigi, Japan) showed better consistency in emphysema quantification including RA-950 HU compared with standard-dose CT than low-dose CT reconstructed with FBP.

The main difference of our study compared with previous ones is that we also compared quantitative measurements between two different generations of IR algorithms of ASIR and MBIR in addition to comparison of images reconstructed with IR and FBP. In the quantification of emphysema indices, the results of this study are consistent with those of previous studies in that the emphysema index was significantly different among images using the three different algorithms [15]. A finding of note is that these measures were significantly different even between ASIR and MBIR, except in the case of RA-910 HU in patients with mild to moderate emphysema. The difference, however, is smaller between ASIR and MBIR than the difference between FBP and IRs. Figure 4 indicates that these differences are variable among the three algorithms; in some cases the differences are great, while in other cases the differences are small. Owing to the lack of reference for emphysema in this study, these results do not confirmatively

Table 2 Comparison of the quantitative analysis of lung parenchyma and airways among the three algorithms according to the severity of emphysema

	Total	Group I	Group II
Emphysema index (%) -950 HU (<i>P</i> <0.01)	F>A>M	F>A>M	F>A>M
Emphysema index (%) -910 HU (<i>P</i> <0.01)	F>A>M	F>A>M	F>A, F>M
Total lung volume (l)	<i>P</i> >0.05	<i>P</i> >0.05	<i>P</i> >0.05
Mean lung density (HU)	F>M	F>M	F>A, F>M
%WA (wall area/luminal area)	<i>P</i> >0.05	<i>P</i> >0.05	<i>P</i> >0.05
Wall thickness (mm) (<i>P</i> <0.01)	F>A>M	F>A>M	F>A>M

F FBP, A ASIR, M MBIR; Group I no or minimal emphysema subjects (emphysema index <5 %); Group II mild to moderate emphysema subjects (emphysema index ≥5 %)

This table demonstrates the order of parameter values in both groups and total subjects. In the normal to minimal emphysema group (emphysema index <5 %), emphysema index was significantly different among the three different algorithms in the same order as that of total subjects at both thresholds of -950 HU and -910 HU; FBP, ASIR and MBIR. In the mild to moderate emphysema group, emphysema index (RA-910 HU) decreased in the order of FBP, MBIR and ASIR. However, there was no significant difference between ASIR and MBIR of RA-910HU. Average wall thickness was significantly different among the three algorithms in both groups and total subjects

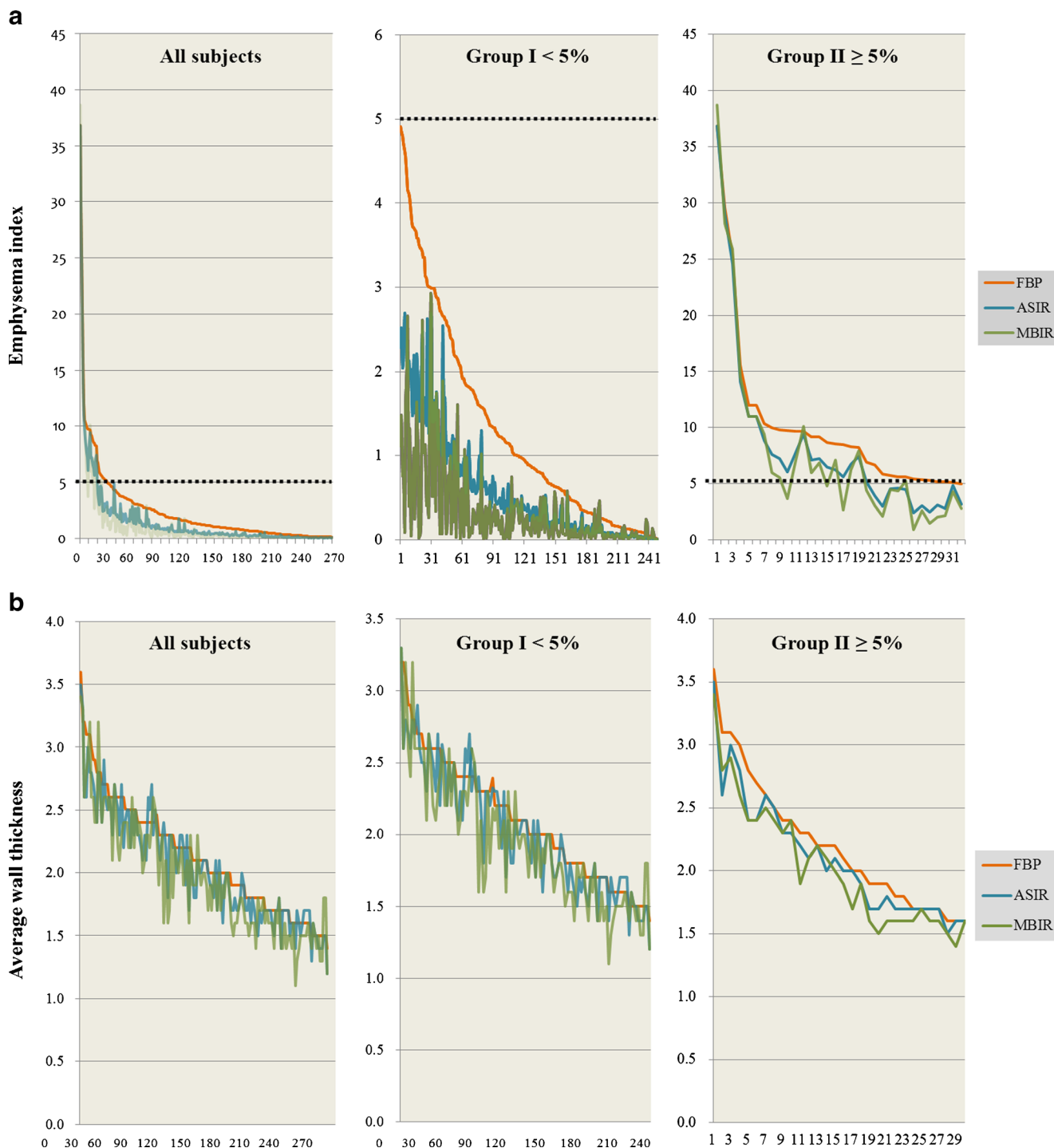


Fig. 4 Emphysema index and average wall thickness. The x-axis indicates patient number with the decreasing order of measurements on FBP images. **a** Emphysema index was significantly different among the three algorithms in both groups and all subjects at a threshold of -950 HU,

decreasing in order of FBP, ASIR and MBIR. **b** Average wall thickness was also significantly different among the three algorithms in both groups and all subjects. FBP demonstrates thicker wall than ASIR and MBIR

support that MBIR provides better results for an emphysema index, but we do believe that MBIR can provide a more accurate value for CT emphysema index, especially in low-dose exposure settings.

As the reconstruction algorithms can change the distribution of voxel values within a local region, it can be expected that emphysema index, which represents the percentage of voxels below a specified threshold, may be different when

Table 3 Comparison of airway measurements of reference and measured value of phantoms according to the three reconstruction algorithms

Simulated tube		CTP666-3	CTP666-4	CTP666-5	CTP666-6
Luminal area (mm ²)	Reference	28.3	28.6	28.6	28.3
	FBP	22.5±0.2 (-20.5 %)	23.1±0.3 (-19.2 %)	23.8±0.3 (-16.8 %)	25.1±0.2 (-11.3 %)
	ASIR	23±0.2 (-18.7 %)	22.8±0.7 (-20.3 %)	24.2±0.6 (-15.4 %)	25.8±0.4 (-8.8 %)
	MBIR	24.5±0.6 (-13.4 %)	25.6±0.7 (-10.5 %)	26.6±1.9 (-7.0 %)	26.8±0.1 (-5.3 %)
	Reference	19.5	27.1	27.1	35.3
	FBP	31.8±0.5 (63.0 %)	37.6±1.5 (38.7 %)	36.2±0.3 (33.6 %)	40.5±0.3 (14.8 %)
	ASIR	29.9±0.9 (53.3 %)	36.8±0.1 (35.8 %)	34.9±0.9 (28.8 %)	39.8±0.2 (12.7 %)
	MBIR	26.5±0.4 (35.9 %)	30.5±2.0 (12.5 %)	29.7±1.4 (9.6 %)	35.6±0.5 (0.8 %)
	Reference	0.9	1.2	1.2	1.5
	FBP	1.5±0.1 (66.7 %)	1.7±0.1 (41.7 %)	1.6±0.1 (33.3 %)	1.8±0.1 (20.0 %)
	ASIR	1.4±0.1 (55.6 %)	1.7±0.0 (41.7 %)	1.6±0.1 (33.3 %)	1.7±0.1 (13.3 %)
	MBIR	1.2±0.0 (33.3 %)	1.4±0.0 (16.7 %)	1.3±0.1 (8.3 %)	1.5±0.1 (0 %)

The numbers in the parentheses refer to percentage measurement error

applying different IRs. In comparison, mean lung density, which represents the mean value of a large region of interest, would not change by applying different IRs. Although our study revealed that mean lung density obtained using FBP was significantly different from that with MBIR in all groups, the mean difference between algorithms was 1 HU or smaller, which indicates minimal clinical significance.

Among the airway dimensions analysed in our patient study, wall thickness of the apical segmental bronchus was measured to be significantly thicker on FBP images than on IR images, and on ASIR images than on MBIR images. This was also confirmed in the phantom study in which MBIR provided the most accurate value for airway dimensions. This result is consistent with the estimation of the modulation transfer function which showed that the spatial resolution of images reconstructed with MBIR was better than those with ASIR and FBP [4]. Although MBIR images showed the best accuracy for airway dimensions, the measurements were nonetheless significantly different from the reference value and, further, we were not able to measure two tubes with a luminal diameter of 3 mm and a 0.6-mm wall thickness. This may be related to the performance of the airway measuring software as, in the phantom study, this software tended to overestimate the wall area of airways with a thickness of 1 mm or less [26]. Although the physical and morphological characteristics of the tubular structures within the phantom we used are different

from those of the airways within a human lung, we thought this phantom could serve as a reference for the airway measurements because this phantom is a specifically designed CT reference standard for the COPDGene Study.

This study has several limitations. Firstly, there was no reference for emphysema quantification. It may have been expected that MBIR might provide the most accurate value but it may have removed low-attenuation areas because of tiny emphysema holes in addition to noise resulting in decreased emphysema index. Secondly, the study population included only a small portion of emphysema patients and we did not perform pulmonary function tests for correlation. Thirdly, we did not assess whether differences were dependent on the underlying image noise by body mass index of patients and whether these results were reproducible. Further investigations are necessary to resolve these issues.

In conclusion, FBP and the two IR algorithms analysed in our study present different emphysema indexes and average wall thicknesses measurements obtained from low dose CT, decreasing in the order of FBP, ASIR and MBIR. Therefore, in quantitative analysis of the lung, care should be taken in selecting the appropriate IR algorithms on chest CT. MBIR may provide the most accurate values for the emphysema and airway measurements, but further studies are necessary.

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