Chest CT with iterative reconstruction algorithms for airway stent evaluation in patients with malignant obstructive tracheobronchial diseases

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Abstract
The aim of the study was to investigate the image quality of low-dose CT images with different reconstruction algorithms including filtered back projection (FBP), hybrid iterative reconstruction (HIR), and iterative model reconstruction (IMR) algorithms by comparison of routine dose images with FBP reconstruction in patients with malignant obstructive tracheobronchial diseases.

In total, 60 patients (59 ± 9.3 years, 37 males) with airway stent who are randomly assigned into 2 groups (routine-dose [RD] and low-dose [LD] group, 30 for each) underwent chest CT on a 256-slice CT (RD-group 120 kV, 250 mAs, LD-group 120 kV, 120 mAs). Images were reconstructed with filtered back projection (FBP) algorithm in the RD group, whereas with FBP, HIR and IMR algorithms in the LD group. Effective radiation dose of both groups was recorded. Image-quality assessment was performed by 2 radiologists according to structure demarcation near stents, artifacts, noise, and diagnostic confidence using a 5-point scale (1 [poor] to 5 [excellent]). Image noise and CNR were measured.

The effective radiation dose of LD group was reduced 52.7% compared with the RD group (10.8 mSv ± 0.58 vs 5.1 mSv ± 0.26, P = 0.00). LD-IMR images enabled lowest image noise and best subjective image quality scores of all 4 indices, when compared with RD images reconstructed with FBP (RD-FBP) images (all P < 0.05). LD images reconstructed with and with HIR (LD-HIR) images enabled higher score in subjective image quality of artifacts (P < 0.05), whereas it showed no difference in the other subjective image-quality indices and image noise. Significant higher image noise and lower score of subjective image quality were observed in LD-FBP images (all P < 0.05).

Both IMR and HIR improved image quality of low-dose chest CT by comparison of routine dose images reconstructed with FBP. Meanwhile, IMR allows further image quality improvement than HIR.

Abbreviations: AIDR = adaptive iterative dose reduction, ASiR = adaptive statistical iterative reconstruction, BMI = body mass index, CNR = contrast to noise ratio, DLP = dose-length product, ED = effective radiation dose, FBP = filtered back projection, FOV = field of view, HIR = hybrid iterative reconstruction, iDose4 = hybrid iterative reconstruction, IMR = iterative model reconstruction, IR = iterative reconstruction, LD group = low-dose group, MDCT = multi-detector computed tomography, RD group = routine-dose group, ROI = region of interest, SAFIRE = Sinogram-affirmed Iterative Reconstruction, SD = standard deviation.

Keywords: airway stent, iterative model reconstruction, low dose, multi-detector computed tomography

1. Introduction
Airway stent placement is increasingly used to treat patients with obstructive tracheobronchial diseases that are caused by malignant tumors such as lung cancer, gastro-esophageal cancer, and thyroid cancer; due to these conditions, patients are often symptomatic and not amenable to surgical resection because of poor clinical status.11 However, the complications associated with airway stenting are not uncommon and can occur during the procedure, shortly after the procedure, or over the long term. In addition, some studies2-3 reported that the complication rate is relatively high, especially with long-term use. Multi-detector computed tomography (MDCT), as a highly accurate noninvasive alternative to the reference standard bronchoscopy, plays an important role in evaluation of stent-related complications and is widely used in clinical practice.4 Usually, CT scan is performed more than once to provide useful diagnostic information of stent-related complications during the follow-up, but consequently they contribute to a high burden of radiation dose. Therefore, it is valuable to find an approach that can optimize CT protocols to reduce radiation dose while maintaining the image quality and diagnostic accuracy.

Reduced tube current has been investigated as a useful approach to reduce radiation dose; however, it may also accompanied with deteriorated diagnostic quality of CT images due to substantial increases of image noise with a corresponding reduction of CT spatial resolution.5 One solution to improve image quality at reduced tube current is the use of iterative reconstruction (IR) algorithms. In the last decade, IR algorithms were introduced to help reduce the quantum noise associated with standard filtered back projection (FBP) reconstruction algorithms.6 Previous studies demonstrated that images acquired with hybrid-type IR algorithms such as ASiR for GE, iDose4 for Philips, SAFIRE for Siemens, and AIDR for Toshiba...
can maintain image quality with a radiation dose reduction of 23% to 66%, but a certain amount of image noise and artifacts are still present.[7] Recently, iterative model reconstruction (IMR), a fully iterative algorithm, has been introduced to enable further dose reduction and image-quality improvement in low-dose CT scans,[8–10] with a knowledge-based approach that yields improved image quality and virtually noise-free images through the iterative minimization of the penalty-based cost function.[11]

Under the hypothesis that IMR could offer better image quality at low-dose chest CT, we investigated the effect of IMR on the quantitative and qualitative image evaluation by comparing to hybrid IR and FBP images acquired at low doses and FBP images obtained at routine doses.

2. Materials and methods
The prospective study received Institutional Review Board approval; prior informed consent was obtained from all patients.

2.1. Study population
We prospectively enrolled 60 consecutive patients who underwent chest CT between August 2014 and May 2015. All had airway stent placement because of malignant tracheal stenosis resulted by lung or esophageal cancer. The inclusion criteria were (1) body mass index (BMI) not larger than 25 kg/m²; (2) metallic stents made of Ni–Ti alloys, considering that this type of metallic stents may cause severe artifacts in low-dose CT images, which especially need improvement. Exclusion criteria included unstable clinical condition, and inability to perform a breath hold.

In the first 5 months, 32 patients underwent chest CT using routine dose protocols (RD group), 2 of them were excluded because of unstable clinical condition. In the second 5 months, 31 patients underwent CT using a low-dose protocol (LD group), and 1 of them was excluded because of large BMI.

2.2. CT acquisition and image reconstruction
All CT examinations were performed on a 256-slice CT scanner (Brilliance iCT; Philips Healthcare, Cleveland, OH), with a scan range from glottis to diaphragm in the craniodorsal direction. The data acquisition parameters were as follows: detector configuration, 128 × 0.625 mm; pitch, 0.99; rotation time, 0.75 s; FOV, 350 mm; slice thickness, 1.0 mm; slice increment, 0.5 mm, matrix 512 × 512; tube voltage, 120 kVp; tube current time products, 250 mAs for the RD group and 120 mAs for the LD group. Images from the RD group were reconstructed with FBP algorithm, whereas images from the LD group were reconstructed with FBP, iDose⁴, and IMR algorithms, respectively. iDose⁴ is a kind of hybrid iterative reconstruction (HIR) algorithm as a routine clinical application in our hospital.

2.3. Image assessment
All images were reviewed and interpreted on a commercially available workstation (Extended Brilliance Workspace, Philips). Objective image assessment was performed by a thoracic radiologist with 5-year experience on reconstructed 1.0 mm thick axial images A 100 mm² region of interest (ROI) was placed within the ascending aorta at the level of pulmonary trunk bifurcation, the CT value (in Hounsfield units) of the ROI was recorded, and its standard deviation (SD) was used as image noise. Measurements were performed 3 times and expressed as the mean value.

On the other hand, 2 thoracic radiologists who were not aware of any image reconstruction settings or scan protocols with 3 and 5 years of experience were asked to perform subjective image assessment, independently. The image quality was evaluated according to structure demarcation near stents, artifacts, noise, and diagnostic confidence using a 5-point scale. The scoring details are as follows: (1) sharpness: 1 = unacceptable, 2 = poor, 3 = good, 4 = excellent, 5 = fully diagnostic; (2) artifacts: 1 = severe unacceptable artifacts, 2 = major artifacts acceptable under limited conditions, 3 = average artifacts not interfering with evaluation of anatomic structure, 4 = slightly artifacts, 5 = optimal or indicated no artifacts; (3) noise, 1 = marked and unacceptable noise, 2 = major but acceptable noise, 3 = average noise, 4 = slightly noise, 5 = indicated free noise; (4) diagnostic confidence, 1 = unacceptable, completely nondiagnostic, 2 = poor, only suggesting lesion, 3 = good, diagnostic, 4 = better, diagnostic confidence, 5 = excellent, fully diagnostic confidence. When the 2 radiologists disagreed, a third thoracic radiologist with >15 years of experience was asked to adjudicate the differences in order to obtain a consensus score.

2.4. Radiation dose management
Total dose-length product (DLP) that represented the total absorbed dose for all the scans were recorded from CT’s dose report. Estimated effective dose (ED) was calculated from DLP using a revised normalized effective dose constant of 0.014.[12]

2.5. Statistical analysis
All continuous values were expressed as mean ± standard deviation (SD). To compare the variable relationships of the patients demographic and dose measurements between groups, we used the χ² test when the predictor was categorical and independent t test when the predictor was quantitative. The quantitative image noise was compared with ANOVA analysis, and if there was a significant difference, pairwise comparisons would be performed with the Dunnett test. The qualitative scores were compared by using the Friedman test, and if there was a significant difference, pairwise comparisons would be performed with the Steel–Dwass test. Inter-observer agreement for subjective image scores was measured using the kappa test. All statistical analyses were performed with commercially available software (SPSS Version 22.0 and MedCal 15.2). A value of P < 0.05 was considered a statistical significant difference.

3. Results
3.1. Patient demographics and radiation dose
The results of patient demographics and radiation dose are summarized in Table 1. There was no significant difference between the 2 groups with respect to age, gender, body weight, body mass index, and scan length. The DLP and effective dose of LD group were significantly reduced compared to the RD group.
Table 1
Comparisons of patient characteristics and radiation doses between groups.

| Characteristics               | RD group       | LD group       | P      |
|-------------------------------|----------------|----------------|--------|
| Age, y, mean±SD (range)       | 60.2±7.2 (42–77) | 57.0±9.5 (47–74) | 0.09   |
| Men/Women, n/n                | 20/10          | 22/8           | 0.57   |
| Body weight, kg, mean±SD      | 56.3±11.0       | 57.8±11.2      | 0.60   |
| Body mass index, kg/m², Mean±SD | 19.9±3.0       | 20.3±3.2       | 0.62   |
| Scan length, cm, mean±SD      | 42.4±2.3        | 42.2±2.2       | 0.73   |
| DLP, mGy*cm, mean±SD          | 717.8±39.0      | 340.8±17.6     | 0.00   |
| Effective dose, mSv, mean±SD  | 10.8±0.58       | 5.1±0.26       | 0.00   |

DLP = dose-length product.
P< 0.05 as significant difference.

3.2. Objective image assessment

The mean image noise was 14.7HU±3.4 on RD images reconstructed with FBP (RD-FBP) images, and 36.2HU±7.3, 15.6HU±4.5, 5.2HU±1.4 on LD-FBP, LD images reconstructed with and with HIR (LD-HIR), and LD-IMR images, respectively. When compared to RD-FBP images as a reference, LD-IMR images enabled significant lower noise (P = 0.00), LD-HIR images showed no significant difference in noise (P = 0.82), and LD-FBP images demonstrated significant higher noise (P = 0.00). Details are demonstrated in Fig. 1.

3.3. Subjective image assessment

There was no significant disagreement between the 2 radiologists (κ = 0.82–0.92). All the qualitative image assessment score for each algorithm of both groups are summarized in Table 2 and Fig. 2. Similar to objective results, when compared to RD-FBP images, LD-IMR images enabled significant higher score in all the indices including sharpness, artifacts, noise, and diagnostic confidence; however, LD-HIR images showed no significant difference in sharpness, noise, and diagnostic confidence, but a higher score in artifacts; LD-FBP images demonstrated significant lower score in all indices and failed to acquire diagnostic acceptable image quality.

4. Discussion

To our knowledge, HIR has been investigated to compensate for increased noise at low-dose CT scans during decade. However, a certain amount of image noise and some artifacts continue to be present due to its inherent approach.[13–15] Unlike HIR, IMR is an advanced iterative reconstruction that applied a knowledge-based approach to accurately determine the data and image statistical models that are coupled with the model of the CT system and involve the geometry and physical characteristics of the CT scanner.[16] It is mathematically more complex and accurate, and theoretically enables lower image noise and better image quality. Consistent with the theory, our results revealed that IMR significantly improved both objective and subjective image quality at LD chest scans using < 50% of routine tube current (Figs. 3–6). As compared to the reference of RD-FBP images, IMR yielded LD images of better subjective image quality of sharpness, artifacts, noise and diagnostic confidence, and significantly reduced image noise, whereas HIR yielded LD images of diagnostic acceptable quality and higher image quality score of artifacts compared to RD-FBP images. This observation is of practical importance because 50% low-dose chest CT with both IR algorithms are able to help reduce the risk of radiation exposure without compromising the quality of diagnostic information in patients with airway stent to repeated chest CT for evaluation of stent-related complications.

Unlike previous low-dose chest CT studies, our study is the first clinical study of IR application focusing on airway stent evaluation in patients with malignant tracheobronchial stenosis. Previous studies[8,17–19] indicated that HIR was able to yield diagnostic image quality at around 1 mSv, IMR was able to yield sub-mSv chest CT scans without compromising image quality. However, relatively high radiation dose acquired in our study is

Table 2
Subjective scores of image quality according to reconstruction method.

|                         | RD group |                  |       |                  |       |       |        |        |
|-------------------------|----------|------------------|-------|------------------|-------|-------|--------|--------|
|                         | FBP      | FBP              | IMR   |                 |       |       |        |        |
|                         | Reader 1 | Reader 2         | Reader 1 | Reader 2       | Reader 1 | Reader 2       | Reader 1 | Reader 2 | kappa value |
| Sharpness               | 0/0/15/12/3 | 0/0/13/13/4 | 3/2/21/20 | 2/4/22/20 | 0/0/9/20/1 | 0/0/8/20/2 | 0/0/2/16/12 | 0/0/1/15/14 | 0.824 |
| Artifacts               | 0/1/19/10/0 | 0/1/17/11/1 | 0/1/17/15/3 | 0/1/10/15/4 | 0/1/0/21/4/14 | 0/0/1/4/15/3 | 0/0/1/16/6 | 0/0/0/22/8 | 0.883 |
| Noise                   | 0/1/18/2 | 0/1/16/18/3 | 0/0/9/20/1 | 0/1/10/10/0 | 0/1/13/17/0 | 0/0/12/6/18 | 0/0/0/21/8 | 0/0/0/22/8 | 0.887 |
| Diagnostic confidence   | 0/0/13/14/3 | 0/0/11/15/4 | 1/6/20/3/0 | 0/7/21/2/0 | 0/0/15/7/0 | 0/0/7/16/7 | 0/0/0/10/20 | 0/0/0/9/21 | 0.921 |

Data show the frequency of numerical scores given in each category (grade 1/2/3/4/5).

FBP = filtered back projection, HIR = hybrid iterative reconstruction, IMR = iterative model reconstruction, LD group = low-dose group, RD group = routine-dose group.
Figure 2. Comparison of subjective image quality score with different reconstruction algorithms in different dose groups: (A) sharpness; (B) artifacts; (C) noise; (D) diagnostic confidence. LD-FBP images failed in acceptable image quality of all indices (score ≤ 3). P < 0.05 was considered as a statistical significant difference.

Figure 3. Axial CT images of airway stent of a 59-year-old male (body mass index, 21.3) (RD group) (A) and 63-year-old male (body mass index, 24.9) (LD group) (B–D) with malignant tracheobronchial stenosis. LD images reconstructed with IMR (D) showed best subjective image quality and lowest image noise. LD images reconstructed with HIR (C) showed similar image quality compared to RD images reconstructed with FBP (A). LD images reconstructed with FBP (B) showed significant increased noise. CT = computed tomography, FBP = filtered back projection, HIR = hybrid iterative reconstruction, IMR = iterative model reconstruction, LD group = low-dose group, RD group = routine-dose group.
resulted by relatively conservative dose reduction protocol with large scan range. First, the scan range is from the level of glottis to diaphragm, considering that the vocal cords are needed to display as a marker to locate the airway stents. Second, it is of importance to display mediastinal structure clearly to evaluate stent-related complications such as stent malposition, stent migration, granulation tissue formation, tumor ingrowth, mucoid impaction, infection, and stent fracture. Thus, relatively conservative dose reduction protocol with a routine tube voltage (120 kV) was performed to ensure acceptable image quality of mediastinal structure and to avoid increased artifacts caused by metal stent itself due to photon starvation and beam hardening effects.

Nevertheless, IMR-enabled superior and significant better image quality as well as HIR-enabled slightly better image quality as compared to RD-FBP images indicated that there is great potential to reduce radiation dose further for chest CT of airway stent evaluation. In addition, it is worth noting that both IMR and HIR were observed to reduce artifacts caused by metal stents, and IMR-enabled best quality score of artifacts, which is similar to the result of previous study in evaluation of prosthetic heart valve-related artifacts.\(^{[20]}\)

Our study has several limitations. First, IMR and HIR images were not reconstructed from the RD group, only 4 series were compared, with RD-FBP images as reference. IMR, HIR, and FBP images can be reconstructed from both LD and RD groups in further study, and all 6 series comparison can be performed to provide more complete view. Second, our study adopted a relatively conservative dose reduction protocol; however, further dose reduction should be achieved in future studies. Third, our study population was relatively small, which may result in some deviations, but it should not influence the study results.

5. Conclusion
In conclusion, both IMR and HIR improved image quality of low-dose chest CT by comparison of routine dose images reconstructed with FBP. Meanwhile, IMR allowed further image-quality improvement than HIR. IMR with significant better image quality may emphasize its potential to better delineate lesion structures around airway stents in patients with malignant tracheal stenosis.
References

[1] Walser EM, Robinson B, Raza SA, et al. Clinical outcomes with airway stents for proximal versus distal malignant tracheobronchial obstructions. J Vasc Interv Radiol 2004;15:471–7.

[2] Casal RF. Update in airway stents. Curr Opin Pulm Med 2010;16:321–8.

[3] Makris D, Marquette CH. Tracheobronchial stenting and central airway replacement. Curr Opin Pulm Med 2007;13:278–83.

[4] Godoy MC, Saldana DA, Rao PP, et al. Multidetector CT evaluation of airway stents: what the radiologist should know. Radiographics 2014;34:1793–806.

[5] Hausleiter J, Meyer T, Hadamitzky M, et al. Radiation dose estimates from cardiac multislice computed tomography in daily practice: impact of different scanning protocols on effective dose estimates. Circulation 2006;113:1305–10.

[6] Silva AC, Lawder HJ, Hara A, et al. Innovations in CT dose reduction strategy: application of the adaptive statistical iterative reconstruction algorithm. Am J Roentgenol 2010;94:191–9.

[7] Oda S, Utsunomiya D, Funama Y, et al. A knowledge-based iterative model reconstruction algorithm: can super-low-dose cardiac CT be applicable in clinical settings? Acad Radiol 2014;21:104–10.

[8] Khawaja RD, Singh S, Gilman M, et al. Computed tomography (CT) of the chest at less than 1 mSv: an ongoing prospective clinical trial of chest CT at submillisievert radiation doses with iterative model image reconstruction and iDose® technique. J Comput Assist Tomogr 2014;38:613–9.

[9] Khawaja RD, Singh S, Blake M, et al. Ultra-low dose abdominal MDCT: using a knowledge-based Iterative Model Reconstruction technique for substantial dose reduction in a prospective clinical study. Eur J Radiol 2015;84:2–10.

[10] Zhang F, Yang L, Song X, et al. Feasibility study of low tube voltage (80 kVp) coronary CT angiography combined with contrast medium reduction using iterative model reconstruction (IMR) on standard BMI patients. Br J Radiol 2016;89:20150766.

[11] Mehta D, Thompson R, Morton T, et al. Iterative model reconstruction: simultaneously lowered computed tomography radiation dose and improved image quality. Int J Med Phys 2013;147–54.

[12] EUR 16262. European guidelines on quality criteria for computed tomography[EB/OL]. [2015.06.10]. http://www.drs.dk/guidelines/ct/quality/download/eur16262.pdf.

[13] Oda S, Utsunomiya D, Funama Y, et al. A hybrid iterative reconstruction algorithm that improves the image quality of low-kilovoltage coronary CT angiography. AJR Am J Roentgenol 2012;198:1126–31.

[14] Leipis J, Labounty TM, Helberson B, et al. Adaptive statistical iterative reconstruction: assessment of image noise and image quality in coronary CT angiography. AJR Am J Roentgenol 2010;195:649–54.

[15] Itatani R, Oda S, Utsunomiya D, et al. Reduction in radiation and contrast medium dose via optimization of low-kilovoltage CT protocols.
using a hybrid iterative reconstruction algorithm at 256-slice body CT: phantom study and clinical correlation. Clin Radiol 2013;68:e128–35.

[16] Yuki H, Utsunomiya D, Funama Y, et al. Value of knowledge-based iterative model reconstruction in low-kV 256-slice coronary CT angiography. J Cardiovasc Comput Tomogr 2014;8:115–23.

[17] Laqmani A, Rutik JH, Henes FO, et al. Impact of a 4th generation iterative reconstruction technique on image quality in low-dose computed tomography of the chest in immunocompromised patients. Rofo 2013;185:749–57.

[18] Kim Y, Kim YK, Lee BE, et al. Ultra-low-dose CT of the thorax using iterative reconstruction: evaluation of image quality and radiation dose reduction. AJR Am J Roentgenol 2015;204:1197–202.

[19] Chen JH, Jin EH, He W, et al. Combining automatic tube current modulation with adaptive statistical iterative reconstruction for low-dose chest CT screening. PLoS One 2014;9:e92414.

[20] Suchá D, Willemink MJ, de Jong PA, et al. The impact of a new model-based iterative reconstruction algorithm on prosthetic heart valve related artifacts at reduced radiation dose MDCT. Int J Cardiovasc Imaging 2014;30:785–93.