Ultra Low-Dose Chest CT using Sinogram-Affirmed Iterative Reconstruction: Image Quality and Radiation Dose Reduction

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Aims and objectives

The introduction of helical and multi-detector row CT scanners has greatly increased the clinical indications and diagnostic accuracy of CT. As a result, the total numbers of CT examinations have increased, raising concern among radiologists regarding radiation exposure from CT among the population, which must be weighed against diagnostic image quality.

Various imaging techniques have been developed to reduce the radiation dose, including tube current modulation techniques [1, 2], lower tube voltage techniques [3], noise-reduction filters [4], and iterative reconstruction algorithms [5-7]. Among these methods, iterative reconstruction technique is a recently introduced method that offers an alternative to the conventional reconstruction by filtered back-projection (FBP). This method repeatedly eliminates image noise and artifacts arising from low radiation dose during the iterative reconstruction process, substantially reducing radiation dose to produce diagnostic image quality.

Sinogram-affirmed iterative reconstruction (SAFIRE) is a new iterative reconstruction algorithm using a noise modeling technique supported by raw data. To our knowledge, only a single preliminary report of ULDCT using SAFIRE [6] has yet been published; further investigation is needed for its clinical application.

The purpose of our study was to assess both objective and subjective image quality of ULDCT obtained using SAFIRE at a tube potential of 80 kVp and SAFIRE. We compared the image quality of ULDCT with RDCT, and also evaluated the relationship between image quality and body mass index (BMI) and the characteristics and location of various pulmonary lesions.
Methods and materials

Patients

This retrospective study was approved by the Institutional Review Board, and written informed consent was waived. Images were obtained from 81 consecutive patients who underwent chest CT scans that included non-contrast enhanced ULDCT, followed by a post contrast enhanced RDCT. Imaging took place from December 2012 to January 2013, and all patient CT scans were analyzed retrospectively. The CT protocol was designed for our hospital after the introduction of an automated attenuation-based tube potential selection and iterative reconstruction algorithm enabling the reduction of total radiation dose in two CT scans.

A total of 29 men and 52 women were enrolled, with a mean age of $57.2 \pm 12.8$ years (mean ± standard deviation [SD]; range, 18-85 years). The body mass index (BMI) of each patient was calculated from the data available in the medical records; the average BMI of patients was $23.6 \pm 3.8$ kg/m$^2$ (range, 18.8 - 33.1 kg/m$^2$). Clinical indications for chest CT scan included follow-up study of primary or metastatic lung malignancy, solitary pulmonary nodule on radiograph, or fluorine-18-fluorodeoxyglucose positron emission tomography (FDG-PET) abnormality. Clinical diagnoses were lung cancer ($n = 18$), breast cancer ($n = 24$), extrathoracic malignancy ($n = 18$), tuberculosis ($n = 12$), and others ($n = 8$).

CT examination

All CT scans were obtained in the supine position using a dual-source multi-detector row scanner (SOMATOM Definition Flash; Siemens Medical Solutions, Forchheim, Germany).

Objective image noise

Image noise was defined as the standard deviation of attenuation measured in the air of the tracheal lumen above the aortic arch. CT attenuation was measured in lung and mediastinal window images of ULDCT and RDCT series by one investigator. The region of interest (ROI) was delineated at the tracheal lumen above the aortic arch, and the size and location of the ROI were kept constant across the four image series. The standard deviation was measured three times, and the mean value was used for analysis.

Subjective visual assessment of image quality
The subjective image quality assessment was performed by two radiologists (Kim Y and Sim SS; 17 years and 10 years of experience in thoracic CT, respectively) by consensus on a workstation.

Overall image quality

The overall image quality was assessed for various normal pulmonary structures on lung window images using a five-point scale rating system. Radiologists were asked to evaluate five normal lung structures: large central airways including the main bronchi and bronchus intermedius, segmental bronchi and vessels, subsegmental bronchi and vessels, pulmonary vessels in the peripheral 1/3 of the lung, and pleura and subpleural lung. The structures were assessed on a five-point scale (5 = excellent image quality without any artifact, 4 = slight blurring of the structures that do not restrict image assessment, 3 = moderate blurring that slightly restricts assessment, 2 = severe blurring causing uncertain evaluation, 1 = non-diagnostic image quality with strong artifacts. Image scores of 4 and 5 were determined to be of diagnostic image quality (Fig. 1).

Before the overall image quality assessment, five training cases including two patients with a BMI > 25 and three with a BMI < 25 were selected among the 81 patients. Their CT scans (five sets of ULDCT, five sets of RDCT) were given to the radiologists with their CT parameters and were scored by consensus. For overall image quality assessment, all image sets, from which the patient information and image parameters had been deleted, were assigned numbers in a random order and given to the radiologists for image analysis.

To assess the effect of BMI on image quality, the relationship between BMI and image scores was evaluated.

Pulmonary lesions were categorized as follows: solid nodule (#10 mm in long diameter), ground-glass opacity nodule (#15 mm in long diameter), increased attenuation (ground-glass opacity, consolidation), decreased attenuation (pulmonary emphysema, mosaic attenuation), linear opacity (reticular or linear opacity, interlobular septal thickening), or airway lesions (bronchiectasis, bronchial wall thickening). The lesion location was recorded according to three lung zones (upper, above the carina; middle, between the carina and inferior pulmonary vein; lower, below the inferior pulmonary vein).

Finally, the image quality of calcified lung nodules, calcification of coronary arteries and aorta, and calcification or high attenuation in the mediastinal lymph nodes [8] detected on mediastinal window images were compared between ULDCT and RDCT.
Fig. 1: Image quality assessment of five normal pulmonary structures on a five-point scale. (a) Image score of 4 (slight blurring of the structures that does not restrict image assessment) for the main bronchi and 3 (moderate blurring of the structures that restricts assessment) for segmental bronchi and vessels, subsegmental bronchi and vessels, pulmonary vessels in the peripheral 1/3 of the lung, and pleura and subpleural lung. (b) Image score for the main bronchi was 5, and that for each of the other four structures was 4. (c) Image score of 5 for all five structures.

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Results

Image noise

The mean image noise at the tracheal lumen showed significant difference between ULDCT (35.6 ± 12.7 HU at mediastinal window, 86.7 ± 25.9 HU at lung window) and RDCT (14.5 ± 5.0 HU at mediastinal window, 33.0 ± 7.3 HU at lung window) (p = 0.000).

Overall image quality of normal structures

The overall image quality scores of ULDCT (19.7 ± 1.2) and RDCT (23.9 ± 1.5) differed significantly (p < 0.001). The results of image quality assessment on a five-point scale for normal pulmonary structures are illustrated in Table 1.

Table 1. Subjective assessment of image quality for normal pulmonary structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>ULDCT</th>
<th>RDCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pulmonary structures</td>
<td>Image Score¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Large central airways</td>
<td>0²</td>
<td>74 (91.4)</td>
</tr>
<tr>
<td>Segmental bronchi and vessels</td>
<td>2 (2.5)</td>
<td>75 (92.6)</td>
</tr>
<tr>
<td>Subsegmental bronchi and vessels</td>
<td>6 (7.4)</td>
<td>74 (91.4)</td>
</tr>
<tr>
<td>Peripheral 1/3 pulmonary vessels</td>
<td>17 (21.0)</td>
<td>63 (77.8)</td>
</tr>
<tr>
<td>Pleura and subpleural lung</td>
<td>11 (13.6)</td>
<td>68 (84.0)</td>
</tr>
</tbody>
</table>
The image quality of normal lung structures was considered sufficient for reliable diagnosis (i.e., score of 4 or 5) in 91.1% of ULDCT and 100% of RDCT images. Significantly more RDCT images were rated as suitable for diagnosis (p < 0.001) (Fig. 2).

A significant correlation was observed between BMI and image score on ULDCT (correlation coefficient, -0.480; p < 0.001), but not on RDCT (correlation coefficient, -0.141; p = 0.209) (Fig. 2). The frequency of non-diagnostic image quality (i.e., scores 1 - 3) was 25.5% (14/55) in patients with a BMI of 25-30 kg/m² and 40.0% (8/20) with BMI of more than 30 kg/m², while 2.0% (1/50) with BMI of less than 20 kg/m² and 4.6% (13/280) with BMI of 20-25 kg/m² (Table 2).

Table 2 Distribution of non-diagnostic image quality on ultra-low-dose CT according to body mass index (BMI).

<table>
<thead>
<tr>
<th>BMI (kg/m²)</th>
<th>Number of patients (n=33)</th>
<th>Frequency of non-diagnostic image quality¹</th>
</tr>
</thead>
<tbody>
<tr>
<td># 20</td>
<td>10</td>
<td>1/50 (2.0%)</td>
</tr>
<tr>
<td>20, # 25</td>
<td>56</td>
<td>13/280 (4.6%)</td>
</tr>
<tr>
<td>25, # 30</td>
<td>11</td>
<td>14/55(25.5%)</td>
</tr>
<tr>
<td>30 &lt;</td>
<td>4</td>
<td>8/20(40.0%)</td>
</tr>
<tr>
<td>Total</td>
<td>81</td>
<td>36/405(8.9%)</td>
</tr>
</tbody>
</table>

¹Proportion of images (five per patient) of various pulmonary structures assigned scores < 3 on a 1-5 scale.
A total of 232 pulmonary lesions from 81 patients were included in the subjective image quality analysis. There were 67 solid nodules (28.9%) (Fig. 4), 17 ground-glass nodules (7.3%) (Fig. 5), 57 lesions of increased pulmonary attenuation (24.6%) (Fig. 6), 23 lesions of decreased pulmonary attenuation (9.9%) (Fig. 6), 44 lesions of linear opacity (19.0%) (Fig. 7), and 24 lesions of bronchiectasis or bronchial wall thickening (10.3%).

The mean solid nodule size was $6.9 \pm 2.4$ mm (range, 3-10 mm), and that of ground-glass nodules was $7.7 \pm 2.8$ mm (range, 5-13 mm). Lesions were anatomically distributed as follows: 76 lesions (32.8%) in the upper, 116 lesions (50.0%) in the middle, and 40 lesions (17.2%) in the lower lung zone.

Lesion conspicuity on ULDCT was equal to that on RDCT in 152 lesions (65.5%) and inferior in 80 lesions (34.5%), and image quality on ULDCT was diagnostic for 206 lesions (88.8%) and non-diagnostic for 26 lesions (11.2%) (Table 3).

Table 3 Subjective assessment of image quality for various pulmonary lesions

<table>
<thead>
<tr>
<th>Lesion location</th>
<th>No. of lesions</th>
<th>Lesion conspicuity on ULDCT compared to RDCT</th>
<th>Image quality for diagnosis on ULDCT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inferior</td>
<td>Equal</td>
</tr>
<tr>
<td>Solid nodule</td>
<td>Upper</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>(# 10 mm)</td>
<td>Middle</td>
<td>39</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Ground-glass nodule</td>
<td>Upper</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>(# 15 mm)</td>
<td>Middle</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Increased attenuation</td>
<td>Upper</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Decreased attenuation</td>
<td>Upper</td>
<td>57</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(49.1%)</td>
<td>(50.9%)</td>
</tr>
</tbody>
</table>
Lesion conspicuity and diagnostic image quality according to location are summarized in Table 2. Non-diagnostic image quality was observed in two (3.0%) solid nodules, four (23.5%) ground-glass nodules, two lesions (3.5%) of increased attenuation, 14 lesions (60.9%) of decreased attenuation, three lesions (6.8%) of linear opacity, and one lesion (4.2%) of bronchiectasis or bronchitis.

Among 14 decreased-attenuation lesions of non-diagnostic image quality, six were mild to severe pulmonary emphysema located in the upper lung zone that were severely affected by beam-hardening artifacts at shoulder joints, and eight were mosaic attenuation in upper or middle lung zones (Fig. 6).
In a correlation analysis, no significant relationship was noted between lesion location and diagnostic image quality for any category of pulmonary lesions except lesions of decreased attenuation. For these lesions, including pulmonary emphysema and mosaic attenuation, non-diagnostic image quality was more frequent in the upper lung zones (correlation coefficient, -0.501; \( p = 0.015 \)).

Radiation dose

The mean CTDI\(_{vol}\), DLP, and effective radiation dose were 0.61 ± 0.0 mGy (range, 0.60 - 0.61 mGy), 20.8 ± 2.0 mGy·cm (range, 16 - 25 mGy·cm), and 0.29 ± 0.03 mSv (0.22 - 0.35 mSv), respectively for the ULDCT protocol and 5.5 ± 2.1 mGy (range, 2.3 - 13.5 mGy), 204.1 ± 78.1 mGy·cm (range, 109 - 490 mGy·cm), and 2.88 ± 1.11 mSv (1.53 - 6.86 mSv), respectively for the RDCT protocol.
Images for this section:

Fig. 2: Subjective image scores of various lung structures on ultra-low-dose CT (ULDCT) (a) and reduced-dose CT (RDCT) (b). Overall, 91.1% of ULDCT and 100% of RDCT images were considered of diagnostic quality (i.e., score of 4 or 5).

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Fig. 3: Relationship between body mass index (BMI) and subjective image scores of various lung structures on ultra-low-dose CT (ULDCT) (a) and reduced-dose CT (RDCT) (b). Non-diagnostic image quality (i.e., score # 3) on ULDCT was more frequent in the groups of patients with a BMI > 25 kg/m²; 2.0 (1/50), 4.6 (13/280), 25.5 (14/55), and 40.0 (8/20)% for BMIs of < 20, 20-25, 25-30, and > 30, respectively. A significant correlation
was observed between BMI and image score on ULDCT (correlation coefficient, -0.480; p < 0.001), but not on RDCT (correlation coefficient, -0.141; p = 0.209).

Fig. 4: Image quality of solid nodules. A 3-mm solid nodule in a 74-year-old man with a BMI of 19.1 kg/m² was diagnosed on both RDCT (a) and ULDCT (b). Image quality of a 3-mm nodule in a 72-year-old man with a BMI of 27.4 kg/m² was diagnostic on RDCT (c), but non-diagnostic on ULDCT (d).

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Fig. 5: Ground-glass opacity nodules. An 8-mm ground-glass opacity nodule in a 68-year-old woman with a BMI of 30.0 kg/m² was diagnosed on both RDCT (a) and ULDCT (b). Image quality of an 8-mm faint ground-glass opacity nodule in an 81-year-old man with a BMI of 24.7 kg/m² was diagnostic on RDCT (c), but non-diagnostic on ULDCT (d).

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Fig. 6: In a 74-year-old man with a BMI of 19.1 kg/m2 centrilobular pulmonary emphysema visible on RDCT (a) was not diagnosed on ULDCT (b). Consolidation was well visualized on both RDCT and ULDCT.

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Fig. 7: Interlobular septal thickenings (arrows) and consolidation are well visualized on both RDCT (a) and ULDCT (b).

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Conclusion

ULDCT using iterative reconstruction (SAFIRE) at 80 kVp with an effective dose of 0.3 mSv generates images of diagnostic quality in patients with a BMI #25, but is of limited use for lesions with decreased attenuation, ground-glass nodules, or those located in the upper lobe.
References


