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Influence of radiation dose and iterative reconstruction algorithms for measurement accuracy and reproducibility of pulmonary nodule volumetry: A phantom study

Hyungjin Kim[a,1], Chang Min Park[a,b,*,1], Yong Sub Song[a,1], Sang Min Lee[a,1], Jin Mo Goo[a,b,1]

[a] Department of Radiology, Seoul National University College of Medicine, Institute of Radiation Medicine, Seoul National University Medical Research Center, 101, Daehangno, Jongno-gu, Seoul 110-744, Republic of Korea
[b] Cancer Research Institute, Seoul National University, 101, Daehangno, Jongno-gu, Seoul 110-744, Republic of Korea

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ABSTRACT

Purpose: To evaluate the influence of radiation dose settings and reconstruction algorithms on the measurement accuracy and reproducibility of semi-automated pulmonary nodule volumetry.
Materials and methods: CT scans were performed on a chest phantom containing various nodules (10 and 12 mm; +100, −630 and −800 HU) at 120 kVp with tube current–time settings of 10, 20, 50, and 100 mAs. Each CT was reconstructed using filtered back projection (FBP), iDose^4 and iterative model reconstruction (IMR). Semi-automated volumetry was performed by two radiologists using commercial volumetry software for nodules at each CT dataset. Noise, contrast-to-noise ratio and signal-to-noise ratio of CT images were also obtained. The absolute percentage measurement errors and differences were then calculated for volume and mass. The influence of radiation dose and reconstruction algorithm on measurement accuracy, reproducibility and objective image quality metrics was analyzed using generalized estimating equations.
Results: Measurement accuracy and reproducibility of nodule volume and mass were not significantly associated with CT radiation dose settings or reconstruction algorithms ($p > 0.05$). Objective image quality metrics of CT images were superior in IMR than in FBP or iDose^4 at all radiation dose settings ($p < 0.05$).
Conclusion: Semi-automated nodule volumetry can be applied to low- or ultralow-dose chest CT with usage of a novel iterative reconstruction algorithm without losing measurement accuracy and reproducibility.

1. Introduction

Lung nodule measurements on computed tomography (CT) are routinely performed in clinical practice to evaluate tumor response to treatment or to detect nodule growth over follow-ups. Uni-dimensional or bi-dimensional diameter measurements are the most common form of nodule measurements. However, computer-aided semi-automated volumetry of pulmonary nodules are reported as more accurate and reproducible than diameter measurement alone [1,2]. Pulmonary nodule volumetry is also used to guide diagnostic strategy in the follow-up of lung cancer screening [3].

Reducing the CT radiation dose is an issue in medical society. An analysis of the National Lung Screening Trial (NLST) demonstrated that lung cancer mortality was lower with the use of 3 years of annual screening with low-dose computed tomography (LDCT) than with the use of chest radiography [4,5]. Simultaneously, the potential harm from radiation exposure has become a controversial subject despite the significant advantage of LDCT screening. For chest CT, modification of tube current is the simplest method to reduce radiation exposure and remains a mainstay of radiation dose reduction [6]. In addition, noise-reducing iterative reconstruction (IR) algorithms have become available. A lowered radiation dose is often accompanied by increased noise in CT images reconstructed with a conventional filtered back projection (FBP) algorithm [7]. IR algorithms improve image quality by reducing image noise and artifacts that result from common irregularities like photon starvation, beam hardening, and nonlinearity of individual detector

* Corresponding author at: Department of Radiology, Seoul National University College of Medicine, 101, Daehangno, Jongno-gu, Seoul 110-744, Republic of Korea. Tel.: +82 2 2072 0367; fax: +82 2 743 7418.
E-mail addresses: khj.snuh@gmail.com (H. Kim), cmpark@radiol.snu.ac.kr (C.M. Park), terasong@gmail.com (Y.S. Song), sangmin.lee.md@gmail.com (S.M. Lee), jmgoo@plaza.snu.ac.kr (J.M. Goo).
[1] Tel.: +82 2 2072 2519.

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Table 1
Descriptive statistics for radiation dose protocols.

Tube voltage (kVp)	Tube current–time product (mAs)	$CTDI_{vol}$ (mGy)	DLP (mGy cm)	ED[a] (mSv)	Dose reduction[b] (%)	Radiation dose compared to NLST mean ED[c] (%)
120	10	0.68	27.0	0.378	89.9	25.2
	20	1.32	52.8	0.739	80.3	49.3
	50	3.38	134.8	1.887	49.8	125.8
	100	6.74	268.5	3.759	0	250.6

$CTDI_{vol}$, volume CT dose index; DLP, dose-length product; ED, effective dose; NLST, National Lung Screening Trial.
[a] Conversion factor of 0.014 was used to estimate ED.
[b] Dose reduction of each CT scan was calculated compared to 120 kVp and 100 mAs acquisition.
[c] Radiation dose of each CT scan was compared to the average ED of NLST, which was 1.5 mSv [4].

elements [7]. A novel IR algorithm, iterative model reconstruction (IMR) (Philips Healthcare, Cleveland, OH), was developed recently and this knowledge-based IR incorporates system optics as well as image statistics.

Patients who require sequential comparisons of nodule size with follow-up CT could potentially benefit from a novel IR algorithm in conjunction with reduced dose CT scan. A prerequisite is the preservation of diagnostic accuracy and feasibility of nodule measurements. Previous research dealt with the volumetric analysis of pulmonary nodules with respect to a reduced radiation dose [8–12], IR algorithms [13] or both [14–17] as well as reported the availability of semi-automated volumetry in the setting of low radiation dose and IR applications. However, IMR has not been investigated to date and research is limited on the effect of CT radiation dose and reconstruction algorithms for the accuracy and reproducibility of volumetric measurement. In addition, there has been no study which focused on mass measurement, a new method for monitoring subsolid nodule growth.

We hypothesized that the accuracy and reproducibility of semi-automated nodule volume and mass measurements would be potentially affected by various radiation dose settings and reconstruction algorithms such as iDose^4 (Philips Healthcare, Cleveland, OH) and IMR. Therefore, we performed modeling analysis using commercial volumetry software and an anthropomorphic chest phantom with simulated nodules.

2. Materials and methods

2.1. Phantom

To obtain CT scan images of various radiation doses, we performed a phantom study using an anthropomorphic male chest phantom (multipurpose chest phantom N1 Lungman, Kyoto Kagaku, Kyoto, Japan) with simulated pulmonary nodules. The anthropomorphic chest phantom consisted of simulated pulmonary vessels, heart, trachea, chest wall and abdomen block. The phantom was made of polyurethane (soft tissue) and epoxy resin (synthetic bone). The phantom measured 43 cm × 40 cm × 48 cm in dimension with a chest girth of 94 cm. Simulated pulmonary nodules of various diameters and attenuations (diameter 10 and 12 mm; attenuation +100, −630 and −800 HU for each diameter) were manually affixed to simulated pulmonary vessels. Nodules with +100 HU simulated solid nodules and nodules with −630 and −800 HU simulated ground-glass nodules (GGNs).

2.2. CT acquisition

CT scans were performed with a 256-section iCT machine (Philips Healthcare, Cleveland, OH). Phantom was scanned with a kilovoltage of 120 kVp and a tube current-time product of 10, 20, 50 and 100 mAs. A total of 4 radiation dose settings were used in this study (Table 1). Other acquisition parameters were as follows; detector collimation, 128 mm × 0.625 mm; gantry rotation time, 0.4 s; pitch, 0.915; FOV, 350 mm and matrix size, 512 × 512 pixels. CT raw data were reconstructed with a slice thickness of 1 mm and an increment of 0.9 mm. The phantom was scanned once with each dose setting and all CT scans were obtained sequentially on the same day without changing the positions of the phantom or the nodules within it.

2.3. Iterative reconstruction techniques (iDose^4 and IMR)

A series of CT scans with four radiation dose settings were reconstructed with FBP, iDose^4 (level 4) and IMR (level 1) algorithms. IR levels for iDose^4 and IMR were chosen empirically after preliminary review of CT images at each IR level to find a single IR level with optimum image quality. A single level was chosen for each IR as volumetry was unaffected by the IR level according to the previous researches [13,16]. Subsequently, a total of 12 CT datasets were prepared (Fig. 1). A sharp filter Y-Sharp (YA) was used for FBP and iDose^4 and a sharp plus filter, a possible YA-equivalent, was used for IMR as YA could not be applied directly to IMR. iDose^4 is a hybrid IR algorithm that incorporates statistics-model based denoising into raw and image data space [18]. IMR is a novel knowledge-based IR algorithm and is an optimization process that incorporates knowledge of data statistics, image statistics and system models [19]. The notable feature of IMR is that the characteristics of the CT system (such as detector sampling, angular sampling and system geometries) are taken into account in the optimization process [19]. The consideration of system properties allow for the design of the cost function and for IMR to effectively control image noise while maximizing spatial resolution at significantly lower radiation doses than traditionally used FBP reconstruction [19].

2.4. Radiation dose assessment

For radiation dose assessment, the volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) were recorded for the scans at each mAs. $CTDI_{vol}$ and DLP were acquired from the dose information provided by the CT scanner. Estimated effective dose (ED) was calculated from the DLP with a revised normalized effective dose constant of 0.014. Dose reduction in percentages was calculated compared to the radiation dose of a 120 kVp and 100 mAs CT scan; in addition, a radiation dose of each CT scan was compared to the average ED of 1.5 mSv in NLST [4] (Table 1).

2.5. Semi-automated nodule volumetry

Two radiologists (S.M.L. and Y.S.S.) were asked to perform two semi-automated volumetric measurements of simulated nodules on each CT scan at an interval of 4 weeks. They were blinded to the size and attenuation of the nodules. Measurements were performed independently between the readers using a commercial semi-automatic volumetry software package (LungCARE, Siemens Medical Solutions, Erlangen, Germany) (Fig. 2). The detailed working process of this software