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Noise-optimized advanced image-based virtual monoenergetic imaging for improved visualization of lung cancer: Comparison with traditional virtual monoenergetic imaging

Claudia Frellesen, Moritz Kaup, Julian L. Wichmann*, Kristina Hüsers, Jan-Erik Scholtz, Moritz H. Albrecht, Sarah C. Metzger, Ralf W. Bauer, J. Matthias Kerl, Thomas Lehnert, Thomas J. Vogl, Boris Bodelle

University Hospital Frankfurt, Department of Diagnostic and Interventional Radiology, Theodor-Stern-Kai 7, 60590 Frankfurt, Germany

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ABSTRACT

Purpose: To assess the effect of a noise-optimized image-based virtual monoenergetic imaging (VMI+) algorithm in direct comparison with the traditional VMI technique and standard linearly-blended images emulating 120-kVp acquisition (M_0.3) on image quality at dual-energy CT in patients with lung cancer.

Materials and Methods: Dual-source dual-energy CT examinations of 48 patients with biopsy-proven primary ($n = 31$) or recurrent ($n = 20$) lung cancer were evaluated. Images were reconstructed as M_0.3, and VMI+ and traditional VMI series at 40, 55, and 70 keV. Attenuation of tumor, descending aorta, pulmonary trunk, latissimus muscle, and noise were measured. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated. Five-point scales were used by three observers to subjectively evaluate general image impression, tumor delineation, image sharpness, and image noise.

Results: Background noise was consistently lower with VMI+ compared to VMI at all keV levels (all $p < 0.0001$) and M_0.3 (all $p \leq 0.0004$). Tumor SNR and CNR peaked in the 40 keV VMI+ series, significantly higher compared to all VMI and M_0.3 series (all $p < 0.0008$). Observers preferred the 55 keV VMI+ series regarding general image impression and tumor delineation compared to all other series (all $p < 0.0001$). Image sharpness and image noise ratings were highest in the 55 keV VMI+ and 70 keV VMI and VMI+ reconstructions.

Conclusions: Tumor CNR peaked at 40 keV VMI+ while observers preferred 55 keV VMI+ series overall other series for dual-energy CT of lung cancer. The noise-optimized VMI+ technique showed significantly lower background noise and higher SNR and CNR compared to the traditional VMI technique at matching keV levels.

1. Introduction

Computed tomography (CT) is considered a standard technique for early detection, staging and follow-up evaluation of small cell (SCLC) and non-small cell (NSCLC) lung cancer and consecutive metastases [1,2]. The role of chest CT has been emphasized with the ongoing discussion on the recommendation for lung cancer screening using low-dose unenhanced chest CT [3].

However, current conventional CT techniques lack potential for quantitative imaging to improve characterization especially of mediastinal masses and facilitate nodal staging compared to other imaging modalities such as positon emission tomography (PET) [4]. Dual-energy CT allows for tissue characterization and can be performed for imaging of the chest without dose penalty compared to standard single-energy CT [5,6]. Thus, the dual-energy CT technique has been applied to chest imaging for improved assessment of lung perfusion in pulmonary embolism [7], evaluation of pulmonary nodules [8], ventilation mapping [9], and other lung diseases [10,11].

However, experience with dual-energy CT in imaging of lung cancer is scarce [12,13]. Besides its potential for quantitative imaging, dual-energy CT can also be used to enhance image quality using dedicated post-processing. Virtual monoenergetic imaging (VMI) allows for simulated extrapolation of photon energies to a desired kiloelectron volt (keV) level [14]. This technique has shown promising results to improve image quality of soft tissue tumors

* Corresponding author. Fax: +49 69 6301 7258.
E-mail address: docwichmann@gmail.com (J.L. Wichmann).

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in contrast-enhanced dual-energy CT [15,16]. However, the established traditional VMI algorithm suffered from severe image noise at low keV levels which provided the strongest contrast enhancement [15,17]. Recently, an advanced image-based VMI algorithm (VMI+) with optimized noise reduction was introduced and has shown superior objective and image quality especially at low keV levels (40–60 keV) compared to the traditional VMI technique [18–20]. However, the VMI+ algorithm has not been evaluated for imaging of the chest so far.

Thus, the purpose of our study was to assess the effect of this noise-optimized image-based VMI+ algorithm in direct comparison with the traditional VMI technique and standard linearly blended images emulating 120-kVp acquisition on image quality at dual-energy CT in patients with lung cancer.

2. Materials and methods

2.1. Patient selection

This retrospective study was approved by the ethics committee of our hospital with a waiver of written informed consent. We included a total of 51 patients with positive findings of SCLC ($n = 17$) or NSCLC ($n = 34$) with a minimum lesions size of 10 mm detected on clinically-indicated contrast-enhanced chest dual-energy CT examinations performed between October 2013 and December 2014. All cases were confirmed by histopathology, further divided into biopsy-proven untreated primary ($n = 31$) or recurrent ($n = 20$) lung cancer. Exclusion criteria were examinations with severe motion or beam-hardening artifacts and scans with unsuccessful contrast material administration due to extravasation or other technical issues.

Contraindications for DECT were age less than 18 years, known reactions to iodinated contrast material, impaired renal function (glomerular filtration rate below 45 mL/min) or pregnancy.

2.2. Dual-energy CT protocol

Dual-energy CT examinations in this study were performed on a second-generation 128-slice dual-source CT in dual-energy mode (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany). Both X-ray tubes were operated at different tube potentials. Exact examination parameters were as follows: tube A: 80 kVp, reference current-time product of 186 mAs per rotation; tube B: Sn140 kVp with tin filter, 79 mAs per rotation; rotation time 0.5 s; pitch 0.55; collimation $2 \times 64 \times 0.6$ mm. Real-time automatic attenuation-based tube-current modulation software (CareDose4D, Siemens) was activated in all scans. Images were acquired in craniocaudal direction in inspiratory breath hold with the patient in a supine position. Dual-energy CT imaging was initiated 50 s after intravenous administration of 60 mL of nonionic iodinated contrast agent (iopamidol, Imeron 400, Bracco, Konstanz, Germany) through an antecubital vein at a flow rate of 2 mL/sec.

2.3. Dual-energy CT dataset post-processing

First, a standard linearly blended image series was automatically reconstructed by the scanner software based on the acquired dual-energy CT raw data using a standard dual-energy CT blending factor (M_0.3) merging 30% of the 80 kVp spectrum and 70% of the 140 kVp data spectrum as commonly performed in dual-energy CT of the chest [21]. This image series is routinely created and is supposed to emulate the image impression of a single-energy 120-kVp acquisition and was therefore considered the standard image series in our study.

Further post-processing was performed on a commercially-available 3D workstation (syngo. via, version VA11A, Siemens Healthcare) using the dedicated dual-energy monoenergetic application. In our study, three image series with different photon energies (40, 55, and 75 keV) were reconstructed with both the VMI and the VMI+ algorithm. These keV levels have been recommended in prior studies [18,19]. Images with higher energy levels were not reconstructed since the iodine signal detectable in soft tissue can be expected to appear too faint [15].

All images were reconstructed with a dedicated dual-energy medium-soft convolution kernel (D30f) and advanced modeled iterative reconstruction (ADMIRE, Siemens Healthcare) using a strength level of 3. All image series were exported as axial images with a slice thickness of 2.0 mm and an interslice gap of 1.0 mm. Thus, in each patient a total of seven image series were reconstructed and evaluated: (1) standard linearly blended; (2–4) 40, 55, and 70 keV traditional VMI; (5–7) 40, 55, and 70 keV noise-optimized VMI+.

2.4. Quantitative image analysis

All image series were evaluated on the same workstation for objective image analysis. A radiologist with 4 years of experience in chest CT performed quantitative analysis. Signal attenuation was measured in mean Hounsfield (HU) units by placing a region of interest (ROI) centrally in the tumor lesion (average size, 175 mm^2), ipsilateral latissimus muscle (average size, 300 mm^2), descending aorta (average size, 175 mm^2) and the pulmonary trunk (average size, 150 mm^2). All ROIs were drawn as large as possible while carefully avoiding inclusion of adjacent anatomic structures which may influence attenuation values. Regions with focal inhomogeneity or necrosis were avoided if possible.

Image background noise was measured as the standard deviation (SD) in a circular ROI (average size, 175 mm^2) drawn in the fat tissue of the ipsilateral axilla in all cases. All measurements were performed three times and average values were calculated to ensure data consistency.

Lesion signal-to-noise ratio (SNR) was calculated as follows:

$$\mathrm{SNR} = \mathrm{HUlesion} - \mathrm{SDlesion}$$

Lesion contrast-to-noise ratio (CNR) was calculated using the following formula:

$$\mathrm{CNR} = \frac{\mathrm{HUlesion} - \mathrm{HUlatissimus}}{\mathrm{background\ noise}}$$

2.5. Qualitative image analysis

All image series were subsequently evaluated independently by three radiologists with two, four, and five years of experience in chest CT. All image annotations, ROI makers, and indicators of post-processing algorithm were removed prior to evaluation. To avoid potential recall bias, assessment of image series was performed in random order with a time interval of at least one week between evaluation of image series. Thus, there were a total of seven readout sessions for each observer but the type of image series (standard linearly blended, VMI, or VMI+) was randomized. Reviewers were blinded to the used image reconstruction method. Observers were instructed that all patients had been diagnosed with biopsy-proven primary or recurrent SCLC or NSCLC. However, patients were blinded to prior treatment, imaging reports, and previous imaging studies. Window settings were automatically set to predetermined standard values for evaluation of soft tissue (width: 400HU; level: 80HU) but readers were allowed to freely adjust these values to improve tumor visualization according to their personal preference. Readers were allowed to scroll through the complete stack of CT images.