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FULL PAPER

90-kVp low-tube-voltage CT pulmonary angiography in combination with advanced modeled iterative reconstruction algorithm: effects on radiation dose, image quality and diagnostic accuracy for the detection of pulmonary embolism

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Objective: To evaluate low-tube-voltage 90-kVp CT pulmonary angiography (CTPA) with advanced modeled iterative reconstruction algorithm (Admirer) compared to 120-kVp equivalent dual-energy (DE) acquisition with regards to radiation exposure, image quality and diagnostic accuracy for pulmonary embolism (PE) assessment.

Methods: CTPA studies of 40 patients with suspected PE (56.7 ± 16.3 years) performed on a third-generation 192-slice dual-source CT scanner were retrospectively included. 120-kVp equivalent linearly-blended (60% 90-kVp, 40% 150-kVp) and 90-kVp images were reconstructed. Attenuation and noise of the pulmonary trunk were measured to calculate contrast-to-noise ratios (CNR). Three radiologists assessed the presence of central and segmental PE and diagnostic confidence. Interobserver agreement was calculated using intraclass correlation coefficient (ICC). Radiation exposure was assessed as effective dose (ED).

Results: Pulmonary trunk CNR values were significantly increased in 90-kVp compared to linearly-blended series (15.4 ± 6.3 vs 11.3 ± 4.6 , $p < 0.001$). Diagnostic accuracy for PE assessment was similar in both series with excellent interobserver agreement ($p = 0.48$; ICC, 0.83; $p = 0.48$). Overall confidence for PE assessment was rated excellent for both series with a significant advantage for linearly-blended series ($p < 0.001$; 4.1 vs 3.8). ED was reduced by 37.2% with 90-kVp compared to 120-kVp equivalent image series (1.1 ± 0.6 vs 1.7 ± 0.7 mSv, $p < 0.001$). **Conclusion:** 90-kVp CTPA with Admirer provided increased quantitative image quality with similar diagnostic accuracy and confidence for PE assessment compared to 120-kVp equivalent acquisition, while radiation dose was reduced by 37.2%.

Advances in knowledge: 90-kVp CTPA with an advanced iterative reconstruction algorithm results in excellent image quality and reduction of radiation exposure without limiting diagnostic performance.

INTRODUCTION

CT pulmonary angiography (CTPA) is a fast, accurate and widely available imaging technique and, as such, the modality of choice for assessment of acute pulmonary embolism (PE), a major cause of morbidity, mortality and hospitalization.¹ Diagnostic accuracy of CTPA for PE detection is constantly increasing with values greater than 90%, while at the same time, there is concern over the cumulative

radiation exposure of patients.² With the introduction of new scanner generations, which allow a more precise setting of tube voltage with an increment of 10 kV and an increased tube current capacity, acquisition at lower tube voltages has become available. Low-tube-voltage acquisition results in greater attenuation of iodinated contrast medium, but also increased noise compared to standard 120-kVp acquisition, while radiation dose is reduced substantially, when

tube current is kept constant.^{3–5} Iterative reconstruction (IR) techniques reduce image noise independently of tube current and voltage settings without radiation penalty. Thus, IR allow for increased contrast combined with low-tube-voltage scans, which has been shown to improve image quality at lower radiation doses than standard 120-kVp scans.^{6–9} A new IR algorithm, advanced modeled iterative reconstruction algorithm (Admire), has shown beneficial results in several body regions, including CT angiography (CTA) of the thorax in congenital heart disease patients, and coronary CTA.^{10,11} To our knowledge, the impact of Admire on low-tube-voltage CTPA for the evaluation of PE has not been investigated so far.

Hence, the aim of our study was to evaluate the impact of low-tube-voltage 90-kVp CTPA in combination with Admire compared to 120-kVp equivalent linearly-blended image series with regards to image quality, diagnostic accuracy and confidence for PE assessment.

METHODS AND MATERIALS

Patients

This retrospective study was approved by the local institutional review board with a waiver for written consent. All studies were performed during clinical routine in patients with suspected acute PE between March and July 2016. “Triple-rule-out” studies for acute chest pain, examinations with inaccurate region of interest (ROI) placement during bolus-tracking, severe motion artifacts, a flow-rate below 5 ml s⁻¹, or extravasation during contrast injection were excluded. Thus, a total of 40 patients (19 female; mean age, 56.7 ± 16.3 years) were enrolled in this study. Mean body mass index was 25.4 ± 3.2 kg m⁻².

CT protocol

All CTPA studies were performed on a 192-slice third-generation dual-source CT scanner (Somatom Force, Siemens Healthcare, Forchheim, Germany). The scanner operated in dual-energy (DE) mode providing 90-kVp (95 ref. mAs) and 150-kVp (59 ref. mAs). The second X-ray tube was equipped with a tin filter (Selective Photon Shield II, Siemens Healthcare). Patients received commands for slight inspiratory breath-hold, before acquisition started in craniocaudal direction with a pitch of 0.7 and collimation of 192 × 0.6. Automatic tube current modulation (Caredose 4D, Siemens Healthcare) was activated in all scans.

A total of 0.9 ml kg⁻¹ body weight with a maximum of 90 ml of non-ionic contrast agent (Ultravist, Iopromide 300 mg iodine/ml, Bayer Healthcare, Berlin, Germany) was i.v. injected at a flow-rate of 5 ml s⁻¹ via an antecubital vein, followed by a 50 ml saline chaser. Bolus-tracking technique triggered the scan, with a ROI in the pulmonary trunk, threshold of 120 HU and delay of 7 s.

Data reconstruction

CTPA data were reconstructed as 120-kVp equivalent linearly-blended M_{0.6} image series, combining 60% of the 90-kVp and 40% of the 150-kVp spectrum, and as 90-kVp series. All data were reconstructed as axial and coronal images with a section

thickness and increment of 2 mm using Admire (Siemens Healthcare) at a strength level of 3 of 5.

Radiation dose

Cumulative radiation doses expressed as dose-length-product (DLP) and CT dose index (CTDI_{vol}) were recorded from the patient's protocol saved in the patient achieving and communication system. Radiation doses of the 90-kVp acquisition were extracted by a validated software. To calculate effective dose (ED), DLP was multiplied with the International Commission on Radiological Protection conversion factor for thorax CT (0.014 mSv mGy⁻¹cm⁻¹). Radiation doses of the 90-kVp acquisition were extracted from the dataset by previously used and validated software which has been developed inhouse in cooperation with Fraunhofer Institute Darmstadt, Germany.¹²

Quantitative image analysis

Quantitative analysis was performed by a radiologist with three years of experience in chest imaging using a commercially available PACS (picture archiving and communication system) workstation (Centricity 4.2, General Electric Healthcare, Milwaukee, WI). Circular ROIs were placed in the pulmonary trunk and erector spinae muscle to measure attenuation and standard deviation in HU). ROIs were drawn as large as possible, but avoiding surrounding anatomical structures. Standard deviation of subcutaneous pectoral fat was recorded to quantify image noise. To ensure data consistency, all measurements were performed three times and results were averaged. The following formulas for calculating quantitative image quality based on contrast-to-noise ratio (CNR) and signal-to-noise ratio (SNR) were used: CNR = (HU_{artery} - HU_{muscle})/noise, and SNR = HU_{artery}/noise.

Qualitative image analysis

To provide a reference standard for the diagnosis of PE, a consensus reading was performed by two board-certified radiologists with more than 8 years of experience using all available image series and follow-up examinations. The reference standard for our study was based on the same CTPA acquisition.

Four blinded radiologists with 3–6 years of experience in CTPA (two residents, two consultants) independently assessed linearly-blended 120-kVp and 90-kVp image series for the presence of central and segmental PE with 1 = PE certainly absent, 2 = PE possibly absent, 3 = indeterminate, 4 = PE possibly present and 5 = PE definitely present. Central PE was defined as endoluminal clots in the pulmonary trunk or main pulmonary arteries. Additionally, radiologists rated their overall diagnostic confidence in the assessment of PE, as well as for the evaluation of central and segmental pulmonary arteries, ranging from 1 = poor to 5 = excellent diagnostic confidence. Preset window settings (width, 800 HU; level, 300 HU) could be freely modified. To reduce the risk of recall bias, only a single imaging protocol was evaluated during each session, with a minimum of 2 weeks between readings.

Statistical analysis

Statistical analysis was performed using dedicated software (Medcalc 12.7.2; Medcalc Software bvba, Ostend, Belgium). The

Kolmogorov-Smirnov test was applied to evaluate normality of data distribution. Normally distributed data was analyzed using the paired Student t-test, while unequal variances were analyzed using the Wilcoxon signed-rank test. The non-parametric Friedman test with post-hoc test was used to evaluate qualitative image quality.

Ratings were dichotomized, and scores of 1 and 2 were regarded as negative, while 3 to 5 were considered positive for PE to calculate sensitivity, specificity, negative predictive value (NPV), positive predictive value (PPV), diagnostic accuracy and 95% confidence intervals. Additionally, Receiver operating characteristic (ROC) analysis was performed to compare area under the curve (AUC) values.

Inter and intrareader agreement was assessed using Intraclass Correlation Coefficient (ICC) in a two-way mixed-effects model and interpreted as follows: ICC 0–0.20, slight; 0.21–0.40, fair; ICC 0.41–0.60, moderate; ICC 0.61–0.80, substantial; and ICC 0.81–1, almost perfect agreement.

A p -value ≤ 0.05 was considered a significant result.

RESULTS

Radiation dose

Mean ED for extracted 90-kVp and linearly-blended 120-kVp image series were 1.1 ± 0.6 mSv and 1.7 ± 0.7 mSv, respectively (DLP, 77.5 ± 44 mGy*cm and 123.4 ± 51.1 mGy*cm; CTDI_{vol}, 2.6 ± 1.7 mGy and 4.1 ± 2.0 mGy). Thus, 90-kVp CTPA acquisition resulted in a significant radiation dose reduction of 37% (all $p < 0.001$).

Quantitative image analysis

90-kVp image series showed significantly higher attenuation in the pulmonary trunk compared to linearly-blended M_{0.6} series (mean attenuation, 373 ± 103.22 vs 285.47 ± 76.6 HU, $p < 0.001$) with simultaneously increased image noise (mean noise, 21.03 ± 3.3 vs 20.31 ± 2.89 HU, $p < 0.001$), resulting in significantly higher CNR and SNR values (mean CNR, 15.38 ± 6.26 vs 11.3 ± 4.6 ; mean SNR, 17.85 ± 6.41 vs 13.93 ± 4.75 , all $p < 0.001$). Results of quantitative image analysis are displayed in Figure 1.

Figure 1. Mean CNR and SNR of the pulmonary trunk for linearly-blended and 90-kVp image series. CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio.

Figure 2. Axial reformatted, 120-kVp equivalent linearly-blended M_{0.6} (a) and 90-kVp (b) CTPA images of a 45-year-old male patient with bilateral central and segmental PE (arrows). 90-kVp provided higher vessel contrast and slightly increased noise compared to 120-kVp equivalent (M_{0.6}) series. While the suitability for artery assessment of both images is similar, radiation dose was reduced by 37.2% using 90-kVp acquisition (ED, 1.1 ± 0.6 vs 1.7 ± 0.7 mSv, $p < 0.001$). Window settings in both reconstructions were: level, 100 HU; width, 400 HU. CTPA, CT pulmonary angiography; HU, Hounsfield units; PE, pulmonary embolism.

Diagnostic accuracy

According to the initial consensus reading, 9 of 40 patients (22.5%) were positive for central and segmental PE, while another 9 patients showed segmental PE only.

Results were comparable regarding diagnostic accuracy for central PE between both image series, with a diagnostic accuracy of 0.98 and AUC of 0.996 for 90 kVp images, while linearly-blended 120-kVp series showed a diagnostic accuracy of 0.98 and AUC of 0.995 ($p = 0.48$) (Figure 2). Diagnostic accuracy of 1.0 (AUC, 1.0) for the detection of segmental PE were similar excellent for both image series. Sensitivity, specificity, NPV and PPV are displayed in Table 1.

Qualitative image analysis

Diagnostic confidence scores for overall PE assessment were good for both image series, but showed significantly higher confidence for linearly-blended images compared to 90-kVp images (4.1 ± 0.5 vs 3.8 ± 0.6 , $p < 0.001$). Results for diagnostic confidence for central and segmental PE assessment comparing linearly-blended and 90-kVp series did not reach significance (central, 4.0 ± 0.4 vs 4.2 ± 0.4 , $p = 0.308$; segmental, 3.8 ± 0.6 vs 3.5 ± 0.6 , $p = 0.063$). Detailed results for qualitative image analysis are summarized in Table 2.

Table 1. Diagnostic accuracy for the evaluation of PE

Parameter	Central PE	Segmental PE
Sensitivity	1.0	1.0
Specificity	0.98	1.0
PPV	0.98	1.0
NPV	1.0	1.0

NPV, negative predictive value; PE, pulmonary embolism; PPV, positive predictive value.

Table 2. Diagnostic confidence in the assessment of PE

Parameter	120-kVp equivalent	90-kVp	<i>p</i> -value
Overall confidence	4.1 ± 0.5	3.8 ± 0.6	<0.001
Confidence central PE	4.0 ± 0.4	4.2 ± 0.4	0.308
Confidence segmental PE	3.8 ± 0.6	3.5 ± 0.6	0.063

PE, pulmonary embolism.

DISCUSSION

Our study showed that low-tube-voltage 90-kVp CTPA in combination with a recently introduced IR algorithm provides increased objective image quality resulting in similar excellent diagnostic accuracy and confidence for PE assessment compared to 120-kVp equivalent linearly-blended image series at significant lower radiation doses.

Dual-source CT scanners allow simultaneous acquisition of two image series at different tube voltage settings (DE mode). These datasets are mainly used for post-processing.^{13–15} One of these post-processing techniques is virtual monoenergetic imaging, which provides image series at virtual, low energy levels that have shown incremental image quality in CTA scans due to increased contrast with improved diagnostic accuracy of vascular pathologies.^{16,17} A similar effect of increased contrast of iodinated structures can be reached by reducing tube voltage. Two technical developments overcame the limitation of increased image noise when scanning at lower tube voltages: increased tube capacity and further improvement of IR algorithms. When using IR techniques, low-tube-voltage CTA have shown similar good subjective image quality than standard 120-kVp images.^{18–21} A single vendor's equipment was used for this study, however, CT scanners from other vendors provide similar IR software. In comparison to DE acquisitions which are usually performed with similar radiation doses as 120-kVp scans,²² reduced tube voltage lowers radiation exposure, while contrast is beneficially increased (Figure 3). The main drawback of scanning at lower tube voltages is the missing option for

further post-processing provided by DE datasets. Thus, accurate contrast bolus is crucial with respect to varying factors such as CT scanner, contrast bolus and patient.

In contrast to cancer staging and follow-up scans, CT-based assessment of PE is mostly performed in an acute setting, and often no follow-up CT study is available to perform a direct comparison between those images. For the present study, an intra-individual comparison of single-source 90-kVp and DE-based 120-kVp equivalent CTPA seemed to be a justified approach, as several confounders to image quality, such as different timing of contrast bolus, could be excluded. Bauer *et al* showed that linearly-blended DE image series based on merging 80-kVp and Sn-140-kVp acquisition of a second-generation dual-source CT scanner have similar image quality than 64-slice single-source 120-kVp image series.²³

Viteri-Ramirez *et al* compared two low-kVp CTPA protocols in patients with up to 80 kg (176 lbs) body weight with reported ED values of 0.9 ± 0.6 mSv for the 80-kVp protocol and 2.3 ± 1 mSv for the 100-kVp protocol.²⁴ Tube voltage selection in steps of 10 kV allows 90-kVp acquisition, which may be beneficial to body-weight depending selection between 80-kVp and 100-kVp protocols in clinical routine. However, further tube voltage reduction is possible with CTPA scans as low as 70-kVp in high-pitch mode with a radiation exposure as low as 0.92 mSv and a contrast bolus of only 15 ml.²⁵ High-pitch mode uses both X-ray tubes simultaneously with similar tube voltage settings. This technique is favorable in patients unable to follow breathing instructions. However, high-pitch mode requires dual-source technique which is, so far, not widely available due to high cost. As most available CT scanners use single-source CT technique, research of low-tube-voltage techniques benefits a broader number of sites. Thus, CT settings for this study were set more conservative to provide a safe protocol for emergent CT imaging. Our results could show that 90-kVp CTPA scans in a non-selective patient cohort showed improved objective image quality compared to 120-kVp equivalent image series.

Figure 3. Axial reformatted, 120-kVp equivalent M_{0.6} (a) and 90-kVp (b) CTPA images of a 59-year-old male patient with bilateral central and segmental PE (arrows). 90-kVp images show greater attenuation of iodinated vessels and slightly increased noise, while the visualization of pulmonary arteries and, as such, diagnostic value of both image series remains similar. Window settings in both reconstructions were: level, 100 HU; width, 400 HU. CTPA, CT pulmonary angiography; HU, Hounsfield units.

This study has some limitations apart from its vendor-specific nature and retrospective study design which need to be addressed. First, to allow an intra-individual comparison we did not use true 120-kVp datasets, but 120-kVp equivalent linearly-blended DE image series. This allowed us to reconstruct low-tube-voltage image series from the same acquisition for an intra-individual comparison independent from potential interfering factors such as variability in contrast medium bolus, body habitus, patient position, or scan settings. Second, our results were based on a small cohort of only 40 patients, which is acceptable for preliminary results, while further research in a larger patient cohort

is necessary. Third, the reference standard of the study was not independent, as it was based on the same CTPA study.

In conclusion, 90-kVp CTPA in combination with Admire provides excellent suitability and similarly good diagnostic accuracy for the assessment of PE than 120-kVp equivalent linearly-blended image series, while lowering radiation dose by 37%.

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