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ORIGINAL PAPER

Incidental findings detection using low tube potential for CT pulmonary angiography

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Abstract While lowering the radiation dose using a reduced tube potential (kVp) strategy for CT pulmonary angiography (CTPA) maintains accuracy for pulmonary embolism detection, there is no data regarding the effect of increased noise from lower kVp on both the accuracy of lung and mediastinum lesion detection in the same patient cohort. This study compares the accuracy and diagnostic confidence of lung nodules and enlarged mediastinal lymph nodes detection between low and standard kVp CTPA. The study cohort included 272 CTPA studies acquired at low kVp and 274 studies at standard kVp. Each patient had a routine chest CT acquired within 60 days of the CTPA that served as a reference standard for lung and mediastinum lesions. In additional to the evaluation of image quality, two radiologists independently interpreted lung nodules and mediastinal lymph nodes on CTPA and recorded confidence level for each interpretation. Multivariate models assessed effect of kVp settings on diagnostic accuracy and confidence level in interpretation. Low kVp CTPAs had higher image noise. A significant decrease in the confidence levels for evaluation of mediastinal lymph nodes was observed at low kVp by one of two readers, although there was no significant correlation between accuracy of interpretation and kVp settings for lung and mediastinum lesion detection (adjusted odds ratios = 0.67–1.22, p values >0.2). While increased image noise may decrease the diagnostic confidence of the radiologist, the detection of lung nodules and enlarged mediastinal lymph nodes was not compromised. Referring clinicians can expect that lower radiation dose CTPA answers questions related to lungs and mediastinum.

Keywords Diagnostic confidence · Computed tomography · Pulmonary embolism · Lung nodules · Mediastinal lymph nodes · Radiation dose

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Introduction

Patient and overall population radiation exposure has increased significantly since multi-detector computed tomography (MDCT) has become mainstream for clinical diagnoses such as pulmonary embolism (PE). The additional radiation has provided diagnostic confidence since pulmonary artery filling defects are directly visualized, other important diagnoses (e.g. lymph node enlargement) are seen, and a clearly normal study is reassuring. However, as radiation concerns have escalated, clinicians have been charged with ordering studies only when appropriate, and radiologists have been charged with lowering the exposure for those studies that are appropriate.

This project focuses on lower radiation dose CT pulmonary angiography (CTPA) images; a highly impactful way to lower the MDCT photon flux is to decrease the X-ray CT tube potential, measured as the peak kiloVoltage (kVp) [1, 2]. This strategy has gained acceptance because while the images have more overall noise [3–5], the lower kVp does not compromise the iodine enhanced signal in the pulmonary artery and the accuracy of PE detection [1–4, 6–10]. However, the same accuracy in detecting lung nodules and mediastinal lesions, that are common findings on CTPA [11–15], using low kVp techniques, has not been systematically studied. If lower radiation dose compromises assessment of findings in lung or mediastinum, one potential implication will be the need for additional CT imaging to confirm suspected findings. Hence, the purpose of this study is to evaluate the effect of lower radiation dose CTPA images achieved by a reduced kVp on the detection and diagnostic confidence of lung nodules and enlarged mediastinal lymph nodes compared to standard dose CTPA.

Methods

Patient selection

The institutional human research committee approved this HIPAA-compliant retrospective study; informed consent was waived. Searching picture archiving communication systems (PACS) at a single, large, urban teaching hospital identified 5,816 consecutive CTPA studies performed between January 2008 and April 2010. This included patients scanned at standard radiation dose, based on higher kVp protocols (120–130 kVp) and those scanned after January 1, 2009 when the department adopted a change to weight-based low kVp techniques (80 kVp for patients weighing <80 kg and 100 or 110 kVp for those weighing ≥80 kg).

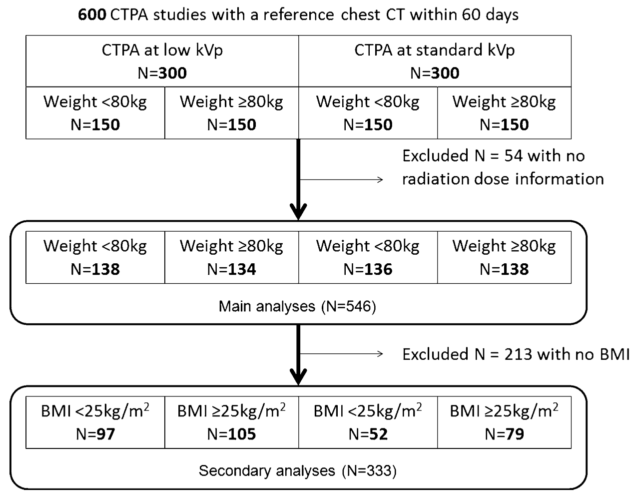

Fig. 1 Patient selection flow chart. *CTPA* computed tomography pulmonary angiography, *BMI* body mass index

A total of 600 CTPA studies (300 low kVp plus 300 standard kVp, both of which were equally divided ($n = 150$) into <80 and ≥80 kg weight groups (Fig. 1) were randomly assembled from the 5,816 CTPA studies based on the criteria that cohort patients underwent additional chest CT imaging that was not a CTPA within 60 days of the CTPA. As detailed below, each of these studies was independently re-read for all imaging findings and served as a reference standard for the lung and mediastinum findings detected by CTPA studies. Fifty-four of the 600 patients were excluded from the analysis because the radiation dose could not be confirmed from the radiology records. Thus, the final population included 546 CTPA examinations stratified into four subpopulations.

CT acquisition

All 546 CTPA examinations used 16-, 64- and 128 slice scanners of the same manufacture (Emotion, Definition/Sensation 64/Definition AS/Definition AS+, Siemens Healthcare, Erlangen. Germany) [16, 17] with standard imaging protocols ("Appendix"). The Dose Length Product (DLP) and average volume CT dose index ($CTDI_{vol}$) were recorded from each CT scanner's output as indexes of radiation exposure.

Clinically indicated non-CTPA chest CT scans evaluated as a reference for the findings detected by CTPA examinations included 517 studies (201 non-contrast and 316 contrast-enhanced chest CT scans); 25 chest CT studies were used as reference for 2 or more CTPA examinations. Details of the chest CT acquisition are described in the "Appendix".

CTPA subjective image quality analysis

All images were anonymized and evaluated on a PACS workstation (Centricity, GE Healthcare, IL) identical to those used for clinical interpretation. Two thoracic radiologists with 8 and 6 years experience in thoracic imaging independently reviewed all 546 CTPA examinations without knowledge of the CT parameters. To simulate routine clinical interpretation, each reader individually adjusted window width/level to optimize the image quality for each study. Image quality was assessed using a 4-point scale in two areas: quality of contrast opacification (1-non diagnostic, 2-limited, only diagnostic in central pulmonary arteries, 3-grainy but no difficulty with diagnosis at all levels of the pulmonary arteries, and 4-excellent contrast opacification with no limitations) and image noise (1-non diagnostic, 2-interpretation possible, 3-minimal noise but diagnosis confident, and 4-no noise).

CTPA findings

The same two readers independently interpreted clinical findings on CTPA studies: presence of PE, presence of solid lung nodule/mass >5 mm in diameter, solid lung nodules ≤5 mm in diameter, ground glass nodules, and mediastinal lymph nodes >1 cm in short-axis diameter. Readers also recorded their confidence level for each interpretation using a 3-point scale (1-not confident, 2-fairly confident but some ambivalence, and 3-very confident).

Evaluation of reference chest CT examinations

Reference chest CT studies were reviewed by a third thoracic radiologist with 20 years of experience in thoracic imaging and without knowledge of the findings of the CTPA evaluations. Studies were evaluated for presence of solid lung nodule/mass >5 mm in diameter, solid lung nodules ≤5 mm in diameter, ground glass nodules, and mediastinal lymph nodes >1 cm in short-axis diameter. A forth radiologist with 6 years of experience reviewed official CT reports to determine findings at time of clinical interpretation. Final interpretation of each reference chest CT examination was determined after adjudication, and these data were used as a reference standard of each lung finding and enlarged mediastinal lymph node detected on the CTPA images.

Objective image quality analysis

The forth radiologist measured the vascular attenuation and image noise on CTPA: mean hounsfield unite (HU) values within a circular region of interest (ROI) were recorded from the left pulmonary arterial tree or on the right if obstructive PE or atelectasis in left lung. Background noise was defined as the standard deviation (SD) of the CT density HU in air. Background signal was measured using the pectoral muscle. The signal-to-noise ratio (SNR) was calculated as mean HU in the pulmonary artery divided by background noise, and CNR was calculated as mean HU in the pulmonary artery minus background signal, divided by the background noise.

Statistical analysis

Characteristics between different kVp groups were compared using unpaired Student's *t* test, Chi square test, and Wilcoxon rank-sum test, as appropriate. Inter-observer agreement was assessed by Kappa test. Accuracy (the fraction of true positive and true negative cases) of each reader's interpretation of the CTPA study was calculated using the findings from the chest CT as reference standard. Accuracy of interpretation and confidence level was compared between low and standard kVp settings using Chi square test.

Multivariate logistic/ordered logistic regression models were fitted to evaluate the effect of the kVp settings on the accuracy of interpretation and confidence level, while controlling for age, gender, body weight, time difference between the CTPA and reference chest CT, contrast versus non-contrast enhanced reference chest CT, tube current, and five different types of scanner (Emotion/Definition/Sensation 64/Definition AS/Definition AS+, Siemens Healthcare, Erlangen, Germany, details in Appendix) used for the CTPA study.

Subgroup/sensitivity analyses

Because accuracy of the detection of enlarged mediastinal lymph nodes can be significantly affected by the use of iodinated contrast media, we added the subgroup analysis using CTPA studies for which the reference chest CT was contrast-enhanced ($n = 316$).

Of the 546 patients, body mass index (BMI) was available in 333 and in this sub-cohort (Fig. 1), the secondary analyses were performed to evaluate the feasibility of BMI-based low kVp protocol with a cutoff of 25 kg/m^2 (i.e., 80 kVp for patients with <25 kg/m^2 and 100/110 kVp for those with ≥25 kg/m^2). The secondary analyses used the same methods as the index study where the patients were separated according to body weight.

For sensitivity analysis, we included the three different scanner types regarding the number of detectors (16, 64, or 128 detectors) as a covariate in the regression model, instead of the five scanner categories. All statistical

Table 1 Clinical factors and characteristics of CTPA and reference chest CT studies

	Weight <80 kg			Weight ≥80 kg		
	Low kVp $n = 138$	Standard kVp $n = 136$	*p* value	Low kVp $n = 134$	Standard kVp $n = 138$	*p* value
Clinical factors						
Age (years)	58.0 ± 15.3	58.8 ± 15.5	0.687	58.7 ± 13.7	58.5 ± 12.3	0.927
Gender (% of Male)	30.4 %	36.0 %	0.326	68.7 %	65.9 %	0.633
Body weight (kg)	62.9 ± 10.0	64.9 ± 8.9	0.110	94.5 ± 13.2	94.6 ± 19.0	0.435
CTPA analysis						
Presence of PE	14.5 %	17.0 %	0.564	14.2 %	13.0 %	0.785
Background noise (HU)	31.4 ± 12.2	21.1 ± 5.4	<0.001	24.6 ± 7.2	23.7 ± 5.9	0.288
CT number in main PA (HU)	519.6 ± 192.4	352.5 ± 130.3	<0.001	291.0 ± 92.2	283.8 ± 103.4	0.546
Main PA SNR	18.4 ± 9.0	17.7 ± 7.7	0.496	12.9 ± 5.6	12.9 ± 6.2	0.999
Lobar PA SNR	18.6 ± 9.2	17.8 ± 7.9	0.480	12.5 ± 5.8	12.6 ± 6.0	0.844
Segmental PA SNR	19.3 ± 10.3	18.7 ± 9.3	0.674	12.4 ± 6.0	13.7 ± 6.8	0.096
Main PA CNR	16.6 ± 8.6	15.4 ± 7.5	0.227	10.7 ± 5.3	10.7 ± 5.9	0.970
Lobar PA CNR	16.8 ± 8.9	15.5 ± 7.7	0.220	10.3 ± 5.5	10.4 ± 5.7	0.874
Segmental PA CNR	17.5 ± 9.9	16.5 ± 9.1	0.398	10.2 ± 5.8	11.5 ± 6.5	0.093
DLP (Gy/cm)	146.2 ± 52.0	480.6 ± 128.0	<0.001	424.6 ± 102.4	653.7 ± 169.9	<0.001
CTDIvol (mGy)	4.9 ± 1.9	16.1 ± 3.9	<0.001	15.3 ± 9.2	21.8 ± 5.5	<0.001
Subjective noise score	3.22 ± 0.57	3.69 ± 0.46	<0.001	3.32 ± 0.54	3.61 ± 0.52	<0.001
Subjective image quality score	3.81 ± 0.33	3.71 ± 0.53	0.346	3.51 ± 0.55	3.54 ± 0.68	0.149
Reference chest CT studies						
Day difference from CTPA	14.3	18.1	0.320	11.5	14.2	0.320
% of prior CT	60.9 %	58.1 %	0.639	62.7 %	57.2 %	0.639
Contrast use	60.9 %	64.7 %	0.511	49.3 %	56.5 %	0.230
Solid lung nodules >5 mm	31.2 %	37.0 %	0.306	30.1 %	28.3 %	0.742
Solid lung nodules ≤5 mm	29.0 %	25.9 %	0.571	20.3 %	21.7 %	0.771
Ground glass nodules	7.2 %	8.9 %	0.618	7.5 %	5.8 %	0.569
Mediastinal lymph nodes >1 cm	41.3 %	50.4 %	0.133	31.6 %	38.4 %	0.239

CTPA computed tomography pulmonary angiography, *PE* pulmonary embolism, *HU* hounsfield unite, *PA* pulmonary artery, *SNR* signal to noise ratio, *CNR* contrast to noise ratio, *DLP* dose length product, $CTDI_{vol}$ volume CT dose index

analyses were performed on STATA version 11.2 (Stata Corp., College Station, TX).

Results

Patient demographics did not significantly differ between low and standard kVp groups, for both weight cohorts. Both DLP and $CTDI_{vol}$ were significantly higher for those patients imaged at the standard kVp (Table 1).

CTPA subjective image quality analysis

At both weight groups, inter-reader agreements were moderate to good for both contrast opacification (kappa = 0.59–0.66) and image noise (kappa = 0.57–0.69). There was no significant difference in contrast opacification scores between low and standard kVp groups, whereas low kVp images had significantly inferior image noise scores) (Table 1).

CTPA image findings

Among the 546 CTPA examinations, 80 studies (14.7 %) were positive for PE, with a similar positivity rate between low and standard radiation dose groups (Table 1). Inter-reader agreement of confidence level of CTPA interpretation was low (kappa = 0.00–0.26) and thus the analysis of confidence level was performed separately for reader 1 and 2. Images acquired at the standard kVp tended to have higher mean scores for the confidence level (i.e., more confident in interpretation) compared to the low kVp; this tendency was more obvious for reader 2 and in the patients <80 kg (Table 2). Multivariate ordered logistic regression showed a significant decrease in confidence level at low kVp for enlarged mediastinal lymph nodes interpreted by

Table 2 Comparisons of confidence level of interpretation between low and standard kVp settings

	Reader 1			Reader 2		
	Low kVp	Standard kVp	*p* value	Low kVp	Standard kVp	*p*value
Weight <80 kg						
Pulmonary embolism	2.82 ± 0.40	2.84 ± 0.46	0.059	2.74 ± 0.49	2.85 ± 0.45	0.002
Solid lung nodules >5 mm	3 ± 0	2.97 ± 0.17	0.122	2.86 ± 0.47	2.91 ± 0.38	0.771
Solid lung nodules ≤5 mm	2.97 ± 0.17	2.99 ± 0.09	0.371	2.73 ± 0.60	2.90 ± 0.39	0.028
Ground glass nodules	2.97 ± 0.15	3 ± 0	0.247	2.70 ± 0.66	2.89 ± 0.40	0.014
Mediastinal lymph nodes >1 cm	2.95 ± 0.22	2.99 ± 0.09	0.066	2.06 ± 0.59	2.89 ± 0.32	<0.001
Weight ≥80 kg						
Pulmonary embolism	2.80 ± 0.42	2.80 ± 0.45	0.480	2.75 ± 0.54	2.72 ± 0.62	0.375
Solid lung nodules >5 mm	2.99 ± 0.09	2.99 ± 0.09	NS	2.90 ± 0.39	2.96 ± 0.22	0.199
Solid lung nodules ≤5 mm	2.97 ± 0.17	2.98 ± 0.15	0.720	2.75 ± 0.56	2.92 ± 0.32	0.008
Ground glass nodules	2.97 ± 0.17	2.99 ± 0.09	0.209	2.74 ± 0.61	2.91 ± 0.35	0.017
Mediastinal lymph nodes >1 cm	2.99 ± 0.09	2.99 ± 0.12	0.999	2.66 ± 0.50	2.85 ± 0.42	<0.001

Data presented as mean ± standard deviation

reader 2, while reader 1 had no significant association between the confidence level and kVp settings, for each finding (Table 3).

Evaluation of reference chest CT examinations

Median time difference between the CTPA examination and reference chest CT was 14.8 days (interquartile range: 7–29 days); 59.7 % of the reference chest CTs were performed before CTPAs (Table 1).

In univariate analysis, low kVp tended to result in lower accuracy for reader 2 regarding small (≤5 mm) solid lung nodule detection in the <80 kg group and ground glass nodule detection in the ≥80 kg group (Table 4). However, the multivariate analysis did not show a significant association between low kVp and a lower diagnostic accuracy for either reader (Table 3).

Objective image quality analysis

The image noise was higher at low kVp settings for both weight groups, but the difference was statistically significant in only the low weight group (Table 1). The SNR and CNR did not significantly differ between low and standard kVp groups for both weight groups.

Subgroup/sensitivity analyses

The subgroup analysis using CTPA studies with a contrast-enhanced reference chest CT showed the same results as those from the main analyses; a significant decrease in confidence level at low kVp for mediastinal lymph nodal detection was observed at the multivariate analyses for the reader 2 (coefficient = −2.91, $p < 0.001$), while reader 1 had no significant association between the confidence level and kVp settings. Accuracy of mediastinal lymph nodal detection was not affected by the kVp settings (adjusted odds ratios = 0.85, $p = 0.628$ for reader 1 and 0.99, $p = 0.969$ for reader 2).

Analysis using BMI < 25 kg/m^2 as a cutoff (Fig. 1) between 80 kVp and 100/110 kVp showed qualitatively the same results as those using an 80 kg cutoff; reader 2 had a significantly decreased confidence for enlarged mediastinal lymph node detection (coefficient = −1.97, $p < 0.001$); the multivariate analyses did not prove an association between low kVp and lower accuracy of interpretation; lower kVp increased the background noise (32.0 ± 13.2 HU vs. 20.6 ± 6.3 HU, $p < 0.001$) and CT number in the main pulmonary artery (532.0 ± 194.2 HU vs. 361.3 ± 127.8 HU, $p < 0.001$) only for patients with a BMI < 25 kg/m^2 patient group; there was no significant difference in SNR and in CNR for both BMI groups.

The sensitivity analysis including the three different scanner types in the multivariate models also showed the same results as those from the main analyses; a significant decrease in confidence level at low kVp for mediastinal lymph nodal detection was observed for reader 2 (coefficient = −2.33, $p < 0.001$).

Discussion

Diagnostic errors are an important cause of preventable adverse events which can directly cause patient morbidity and mortality, and include both missed and delayed diagnosis. Schiff et al. [18] analyzed 583 physician reported errors; two of the top three most common missed or delayed diagnoses included PE and lung cancer, both of

Table 3 Multivariate regression analyses for the confidence level and accuracy of interpretation when using low kVp

Confidence level	Reader 1			Reader 2		
	Coefficient	95 % CI	*p* value	Coefficient	95 % CI	*p* value
Pulmonary embolism	0.402	−0.18 to 0.99	0.177	−0.06	−0.62 to 0.50	0.849
Solid lung nodules >5 mm	−1.41	−3.61 to 0.78	0.207	0.20	−0.67 to 1.07	0.658
Solid lung nodules ≤5 mm	0.32	−1.12 to 1.76	0.665	−0.54	−1.21 to 0.13	0.115
Ground glass nodules	−0.89	−3.23 to 1.44	0.453	−0.51	−1.17 to 0.15	0.131
Mediastinal lymph nodes >1 cm	0.37	−1.24 to 1.97	0.653	−2.35	−2.89 to −1.82	<0.001
Accuracy of interpretation	Adjusted OR	95 % CI	*p* value	Adjusted OR	95 % CI	*p* value
Solid lung nodules >5 mm	1.17	0.65–2.09	0.601	1.15	0.65–2.03	0.641
Solid lung nodules ≤5 mm	1.22	0.73–2.05	0.452	0.72	0.43–1.20	0.205
Ground glass nodules	0.68	0.32–1.46	0.321	0.67	0.36–1.25	0.211
Mediastinal lymph nodes >1 cm	0.88	0.54–1.43	0.607	0.86	0.54–1.36	0.519

Multivariate ordered logistic (confidence level) and logistic (accuracy) model includes kVp, age, gender, weight, time difference between the CTPA and reference chest CT, contrast versus non-contrast enhanced reference chest CT, tube current, and the type of scanner used for the CTPA study

CI confidence interval, *OR* odds ratio

Table 4 Accuracy of each reader's interpretation for lung and mediastinal findings

	Reader 1			Reader 2		
	Low kVp	Standard kVp	*p* value	Low kVp	Standard kVp	*p* value
Weight <80 kg						
Solid lung nodules >5 mm	86.2 % (80.4–92.1 %)	80.9 % (74.2–87.6 %)	0.232	83.3 % (77.0–89.6 %)	80.9 % (74.2–87.6 %)	0.597
Solid lung nodules ≤5 mm	75.4 % (68.1–82.6 %)	71.3 % (63.6–79.0 %)	0.450	73.9 % (66.5–81.3 %)	82.4 % (75.9–88.8 %)	0.091
Ground glass nodules	89.9 % (84.8–95.0 %)	91.2 % (86.3–96.0 %)	0.709	84.1 % (77.9–90.2 %)	86.0 % (80.1–91.9 %)	0.647
Mediastinal lymph nodes >1 cm	69.6 % (61.8–77.3 %)	76.5 % (69.3–83.7 %)	0.198	62.3 % (54.1–70.5 %)	67.6 % (59.7–75.6 %)	0.355
Weight ≥80 kg						
Solid lung nodules >5 mm	82.7 % (76.2–89.2 %)	84.8 % (78.7–90.9 %)	0.643	85.7 % (79.7–91.7 %)	80.4 % (73.7–87.1 %)	0.247
Solid lung nodules ≤5 mm	84.2 % (77.9–90.5 %)	79.0 % (72.1–85.9 %)	0.268	77.4 % (70.2–84.6 %)	79.0 % (72.1–85.9 %)	0.758
Ground glass nodules	91.0 % (86.0–95.9 %)	92.8 % (88.4–97.1 %)	0.593	82.7 % (76.2–89.2 %)	90.6 % (85.6–95.5 %)	0.056
Mediastinal lymph nodes >1 cm	75.2 % (67.8–82.6 %)	74.6 % (67.3–82.0 %)	0.917	72.2 % (64.5–79.9 %)	70.3 % (62.6–78.0 %)	0.731

Numbers in parentheses are 95 % confidence intervals

which can be detected on CTPA images. Lowering the radiation dose using a reduced kVp strategy is validated for pulmonary arty filling defects [7, 19] and allows a reduction in the injected iodine mass [6] that is desired for patients who may require repeat studies who have multiple comorbidities such as cardiac and renal dysfunction. These benefits have generated enthusiasm for lowering the kVp of CTPA images, but for the transition to be clinically viable, data is needed to confirm that images acquired at a low kVp CTPA meet the overall clinical need in patient assessment. Hall et al. [11] reported that clinically relevant non-PE findings were identified in 24 % (136/589) of CTPA studies, a 2.5-fold increase when compared with the detection rate of PE (9 %). While previous non-CTPA studies showed an uncompromised accuracy of lung nodule detection on low-dose CT images [20, 21], findings were not confirmed on low kVp CTPA images. Moreover, no data is available regarding the detectability of mediastinal findings on a low-dose CT. While subjective image quality scores for mediastinum on 100 kVp CTPA images have been reported as comparative to the scores on 140 kVp CTPA images [4], this study provides the initial data regarding the diagnostic accuracy of mediastinal findings based on a reference standard imaging. The prevalence of malignancy is known to be high among those who have acute PE [22], and thus accurate diagnosis of lung nodules and/or mediastinal lymph nodes is critical to patient care. The current population had a prevalence of PE, lung nodules, and lymph nodes that is similar to previous reports [11, 23–25]. Our results suggest that the detection of lung nodules and enlarged mediastinal lymph nodes was not significantly compromised when lowering the radiation exposure with lower kVp settings: 80 kVp for small patients (<80 kg or BMI < 25 kg/m^2) and 100/110 kVp for large patients ($\geq$80 kg or BMI ≥ 25 kg/m^2).

While the detection accuracy was similar between the different radiation exposure protocols, the confidence level decreased when the kVp was lowered, especially for enlarged mediastinal lymph nodal detection. We also observed the large inter-reader variability in confidence that could be due to differences in radiologists' interpretation experience for images with increased image noise. Increased image noise is known to affect the low-contrast resolution (mediastinal window) [26, 27] but has little impact on the high-contrast resolution (lung window) [28]; this may reduce confidence in interpretation of the mediastinum while lung nodule detection confidence was maintained. Decreased confidence may result in increased rate of recommendation for additional imaging [29]. Since benefits of lower radiation exposure from low kVp protocols are likely to be significant, additional time and training may be needed to reduce the variability and increase the confidence level when reading low kVp studies with increased noise. It is also important to carefully consider the risk–benefit balance depending on the clinical scenario. Older patients with high risks of malignancy may sometimes need standard kVp settings for confidently identifying mediastinal abnormalities. We recommend vigilance and communication among both referring clinicians and radiologists as lower kVp CTPA images become routine at many institutions.

There are several additional strategies that can lower the radiation dose in CTPA images. Lowering tube current also decreases photon flux and lowers the radiation exposure, and important component of radiation dose reduction. For all CTPA studies in our cohort, we implemented tube current modulation that is readily available at the majority of recent CT scanners to avoid overexposure [30–32]. Iterative image reconstruction algorithms reduce noise, and this benefit is typically used to lower radiation exposure [33]. While the current data was acquired before these methods became available clinically, iterative methods should be incorporated when available.

We acknowledge study trade-offs and limitations. First, while prospective studies incorporating reference standard imaging would mitigate the heterogeneity of the data, completion of a large trial would be difficult since patients would require additional scanning. As the benefit from lowering radiation exposure is huge, lower radiation dose CT protocols are often incorporated to clinical practice without prospective studies. Our retrospective data uses multiple CT scanners and parameters that were slightly different among scanners and influenced image noise; newer scanners in the standard kVp group with body weight $\geq$80 kg achieved superior objective image quality ("Appendix"). However the current data argue that despite this, the lower kVp images achieved comparable diagnostic accuracy to that from the standard kVp group. Second, we acknowledge that the reference chest CT scans included both non-contrast and contrast-enhanced CT studies, and attempted adjustments in the multivariate analysis as well as performed the subgroup analysis. Third, we note that among the two readers, we did not test for a possible learning curve. Future work should investigate the level of confidence after training with more than two readers. Fourth, we acknowledge that a number of body size metrics have been employed when tailoring kVp settings. We used body weight because it is easily obtainable at the time of CT scan and body weight-based kVp protocols are the routine clinical practice at our institution. BMI is another well-established metric of body habitus, but in this population, BMI was available only in 333 out of 546 patients. In the secondary analysis, we confirmed that the BMI cutoff and body weight cutoff give similar results. Finally, while the study design benefits from objective data regarding image quality, this approach by necessity used data from the pulmonary arteries, not the lungs and mediastinum. Objective image quality for subtle abnormalities such as small ground glass lesions is not reproducible. Thus, our approach was considered the best alternative for objective data [1, 6–8] since there would have been enormous variability from volume averaging among lesions that do not have distinct borders.

In conclusion, while increased image noise may decrease the diagnostic confidence of image interpretation by the radiologist, there was no compromise in accuracy for the detection of lung nodules and enlarged mediastinal lymph nodes using low radiation dose CTPA with low kVp settings. Hence, referring clinicians can expect that a single CTPA study can answer questions related to lung and mediastinum findings.

Conflict of interest None.

Appendix

CT pulmonary angiography acquisition

All 546 CTPA examinations used 16-, 64- and 128 slice scanners of the same manufacture (Emotion, Definition/

Sensation 64/Definition AS/Definition AS+, Siemens Healthcare, Erlangen. Germany). Details of the CTPA parameters are described in the Table below. All patients received 75 ml iodinated contrast media intravenously (370 mg iodine per mL) at a rate of 3.5–4 mL/second without a saline chaser. The acquisition was timed using bolus tracking at the main pulmonary artery with a CT density threshold of 80 Hounsfield Units (HU). Axial images were reconstructed with 1 mm thickness with a 0.5 mm increment using standard soft tissue kernel for evaluation of PE, and contiguous 5 mm-thick slices in a high resolution algorithm for evaluation of the lung parenchyma.

	Emotion 16	Definition AS	Definition	Definition AS+	*p* value
Lower kVp (Weight <80 kg, $n = 138$)					
Number of patients	92	8	18	20	–
Number of detector row	16	64	64	128	–
Tube voltage	80	80	80	80	–
Reference mAs for tube current modulation	150	180	200	200	–
Gantry rotation time (s)	0.6	0.5	0.5	0.5	–
Collimation (mm)	0.6	0.6	0.6	0.6	–
Helical pitch factor	1	0.9	1	0.75	–
Mean SNR at left main PA	17.7	19.0	20.8	17.8	0.556
Mean CNR at left main PA	16.0	17.3	18.9	15.8	0.559
Lower kVp (Weight ≥80 kg, $n = 134$)					
Number of patients	75	9	16	16	–
Number of detector row	16	64	64	128	–
Tube voltage	110	100	100	100	–
Reference mAs for tube current modulation	150	180	200	200	–
Gantry rotation time (s)	0.6	0.5	0.5	0.5	–
Collimation (mm)	0.6	0.6	0.6	0.6	–
Helical pitch factor	1	0.9	1	0.75	–
Mean SNR at left main PA	13.2	11.7	12.2	13.3	0.814
Mean CNR at left main PA	11	9.7	10.4	11.3	0.801

	Emotion 16	Definition	Sensation 64	Definition AS+	*p* value
Standard kVp (Weight <80 kg, $n = 136$)					
Number of patients	16	8	104	8	–
Number of detector row	16	64	64	128	–
Tube voltage	130	120	120	120	–
Reference mAs for tube current modulation	150	200	200	200	–
Gantry rotation time (s)	0.6	0.5	0.5	0.5	–
Collimation (mm)	0.6	0.6	0.6	0.6	–
Helical pitch factor	1	1	1	0.75	–
Mean SNR at left main PA	15.9	15.5	18.1	17	0.636
Mean CNR at left main PA	13.2	13.3	15.9	14.7	0.512
Standard kVp (Weight ≥80 kg, $n = 138$)					
Number of patients	18	7	84	29	–
Number of detector row	16	64	64	128	–
Tube voltage	130	120	120	120	–
Reference mAs for tube current modulation	150	200	200	200	–
Gantry rotation time (sec)	0.6	0.5	0.5	0.5	–
Collimation (mm)	0.6	0.6	0.6	0.6	–
Helical pitch factor	1	1	1	0.35–0.75*	–
Mean SNR at left main PA	10.4	10.4	12.3	16.7§	0.001
Mean CNR at left main PA	8.4	8.3	10.3	14.2§	0.004

All CT scanners were from Siemens Healthcare, Forchheim, Germany

p values are from one-way ANOVA for the analysis of differences between different CT scanners

SNR signal to noise ratio, *CNR* contrast to noise ratio, *PA* pulmonary artery

* The pitch factor was adjusted based on the patient body habitus to achieve the higher mAs in larger patients

§ Significantly higher than other three scanners by the post hoc pair-wise multiple comparisons after one-way ANOVA

Reference chest CT acquisition

Acquisition parameters were optimized with tube voltage of 120–140 kVp and the tube current was determined using manufacturer automated software with a range between 100 and 500 mA. Reconstructions included contiguous 5 mm thick slices in both high resolution and soft tissue algorithms for evaluation of the lung parenchyma and mediastinum respectively. Thin section high resolution 1–1.25 mm thick slices were also obtained at 10 mm intervals.

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