The use of 80 kV versus 100 kV in pulmonary CT angiography: an evaluation of the impact on radiation dose and image quality on two CT scanners

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ABSTRACT

Introduction: Use of CT in the investigation of pulmonary embolism in radiosensitive patients such as pregnant and young female patients entails the need for protocol optimization. The aim of this study was to analyze the dose reduction and image quality achieved by using 80 kV instead of 100 kV in CT pulmonary angiography protocols.

Methods: 80 examinations of non-obese patients were analyzed (40 consecutive patients for each protocol, equally distributed on two CT scanners). Objective image quality was assessed by measurements of HU values (average and standard deviation) in five ROIs in pulmonary arteries and calculations of signal-to-noise (SNR) and contrast-to-noise ratios (CNR). Subjective image quality was independently evaluated by two radiologists in terms of perceived noise, sharp reproduction of pulmonary arteries and overall diagnostic quality. Radiation dose parameters ($CTDI_{vol}$, DLP, SSDE and effective dose) and effective risk were compared. Differences in radiation dose and objective measures of image quality for the two protocols were assessed using the independent t test; comparison of subjective grading of image quality was performed with the Mann-Whitney U test.

Results: Use of 80 kV significantly increased both arterial contrast enhancement and image noise. Differences in SNR and CNR between protocols were not statistically significant. Achieved dose reduction by using 80kV was significant on both scanners (SSDE reduction 35% and 46%, $p<0.001$; effective dose reduction 40% and 53%, $p<0.001$).

Conclusion: Use of 80 kV protocols for CT examinations of pulmonary arteries in non-obese patients with bodyweight below 80kg results in significant reduction of radiation doses without compromising image quality.

Introduction

Pulmonary embolism (PE) is the third most common cause of death amongst cardiovascular diseases after myocardial infarction and stroke[1, 2]. Reported mortality associated with untreated PE is 30%[3]. Sudden death occurs in up to 10% of acute PE patients and two thirds of those patients die in the first two hours after onset of symptoms.[4] Clinical signs and symptoms of PE, such as chest pain and shortness of breath, are unspecific, as they also occur in other pulmonary and cardiac diseases. Thus, there is a great need for accurate and rapid diagnosis[3, 5]. CT pulmonary angiography (CTPA) has become the first-choice method for diagnosing PE due to accessibility, accuracy and cost-effectiveness[6]. One challenge is the high radiation sensitivity of the breast tissue[7], and women in childbearing age represent a special patient group due to the higher risk of PE associated with oral contraceptives, pre- and post-partum pregnancy[4]. Pregnancy requires special attention due to scattered radiation to the fetus and increased radiation sensitivity in the breast tissue[8]. Nuclear medicine (NM) has the advantage of lower dose to breast tissue and the disadvantage of higher fetal doses[9] due to pooling of radionuclide in the maternal bladder. The diagnostic accuracy is comparable[7] but CTPA is more easily available and allows investigation of eventual alternate pathologies. Due to the high mortality and unspecific symptoms, the threshold for referral to CTPA for suspected PE is low. This entails the need for careful protocol optimization with a focus on radiation dose reduction[5]. Reducing tube voltage is suggested as an effective dose reduction strategy for CT angiography.[10,11] Reduced kV increases attenuation in contrast agent filled arteries and increases contrast difference between vessels and other tissues which may compensate for increased image noise[12].

Despite several previously published studies proving the feasibility of reducing kV in CTPA, the use of 100 and even 120kV is still widespread. Based on reports with only positive effects of reducing voltage in CTPA protocols[13-19], an 80kV protocol was introduced. The aim of this study was to strengthen the arguments of previous studies by adding information of the effect of kV reduction on SSDE (which give a better estimate of the organ doses than $CTDI_{vol}$[20]) and effective risk which would be a more suitable parameter for the target group (young female patients). A novel approach in our study is also the use of an additional criterion of subjective image quality assessment “sharp reproduction of the pulmonary arteries” as the pulmonary arteries are the organ of interest in CTPA studies.

Methods

The study is comparative, non-randomized and analyzes radiation doses and image quality in 80 examinations of non-obese patients with a body weight under 80 kg (40 consecutive patients for each protocol, equally distributed on two CT scanners). The sample size was decided based on ICRP[21] recommendation for data collection for establishing DRL’s. A post-hoc power analysis confirmed that the sample size was appropriate to detect differences in dose and image quality with a power of 80%.

The CT scanners used in this study were Somatom Definition AS + (128 slice) and Somatom Sensation 64 (Siemens Medical Solutions, Forchheim, Germany), later referred to as scanner 1 and 2, respectively. Both CT scanners had regular quality control and the results fell within expected tolerance. The only difference between the old protocol and the new one was the adjustment from 100 kV to 80 kV. Automated tube current modulation (CareDose4D, Siemens) was used inn all examinations. There was used filtered back projection reconstruction algorithm with the same kernel in all patients. All patients received 80 ml contrast agent 350 mg/ml, followed by 30 ml saline administrated with a flow rate of 5 ml/s through an 18-gauge cannula placed in an antecubital vein. Scan timing was individualized using bolus-tracking with a threshold of 120 Hounsfield units (HU) in a region of interest (ROI) in the pulmonary trunk (no difference in the contrast regime between 100 and 80 kV protocols).

Table 1. Scan parameters.

	scanner 1		scanner 2	
	Old protocol	New protocol	Old protocol	New protocol
Tube voltage (kV)	100	80	100	80
Ref. mAs	150	150	135	135
Rotation time(s)	0,3	0,3	0,3	0,3
Total collimation (mm)	128 x 0,6	128 x 0,6	64 x 0,6	64 x 0,6
Reconstructed slice thickness (mm)	1,5	1,5	1,5	1,5
Kernel	B20f	B20f	B20f	B20f
Pitch	0,8	0,8	0,9	0,9
$CTDI_{vol}$ (mGy)	5,91	2,79	6,0	2,74

Subjective assessment of image quality

The images were evaluated by two radiologists (with 25 and 5 years experience in thoracic radiology) using a five-point Likert scale for subjective image noise (5 = very low, 4 = low, 3 = medium, 2 = high, 1 = very high) and sharp reproduction of the pulmonary arteries (5 = very good, 4 = good, 3 = medium, 2 = bad, 1 = very bad). In addition, a total assessment of diagnostic image quality was given (5 = very good, 4 = good, 3 = sufficient, 2 = bad, 1 = very bad).

The two radiologists received randomized lists with identification numbers and searched for the examinations in PACS (Picture Archiving and Communicating System) themselves. A Sectra IDS7, (Linköping, Sweden) PACS workstation with two diagnostic Eizo Radiforce MX241W monitors (Cypress, CA, USA) was used for image evaluation. The radiologists evaluated the images independently, blinded to specific patient identification and exposure parameters and without knowledge of the results of the physical measurements performed on the images. Radiologists were free to use all the tools available in PACS that are commonly used for clinical images (adjustment of window/level, magnification, etc.).

Objective assessment of image quality

Attenuation (quantified as average HU) and noise (quantified as standard deviation HU) were measured in ROIs placed in the lumen of the pulmonary trunk, right and left pulmonary arteries, and right and left lower lobar arteries. When PE was present we avoided incorporating the embolus in the ROI. These measurements were then combined to calculate average attenuation and noise for the pulmonary arteries. Attenuation in pulmonary arteries is referred to as fundamental in the diagnosis of PE.[1,5] Attenuation and noise was also recorded in a paravertebral muscle at the level of the pulmonary trunk (figure 1). All measurements were performed in a homogeneous area with a CT angiography window setting (width 600 HU, center 100 HU).

The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) have been suggested as the most appropriate parameters to objectively quantify the quality of clinical images[22], with CNR as the key indicator for pulmonary embolism detectability[18]. In our study, the SNR was calculated as ratio of average HU and noise in pulmonary arteries.

CNR was calculated using average attenuation in the pulmonary arteries (HU_{PA}) and paravertebral muscle (HU_{PM}) and noise in the paravertebral muscle (SD_{PM}), according to the formula[23]: $CNR= (HU_{PA} – HU_{PM})/SD_{PM}$.

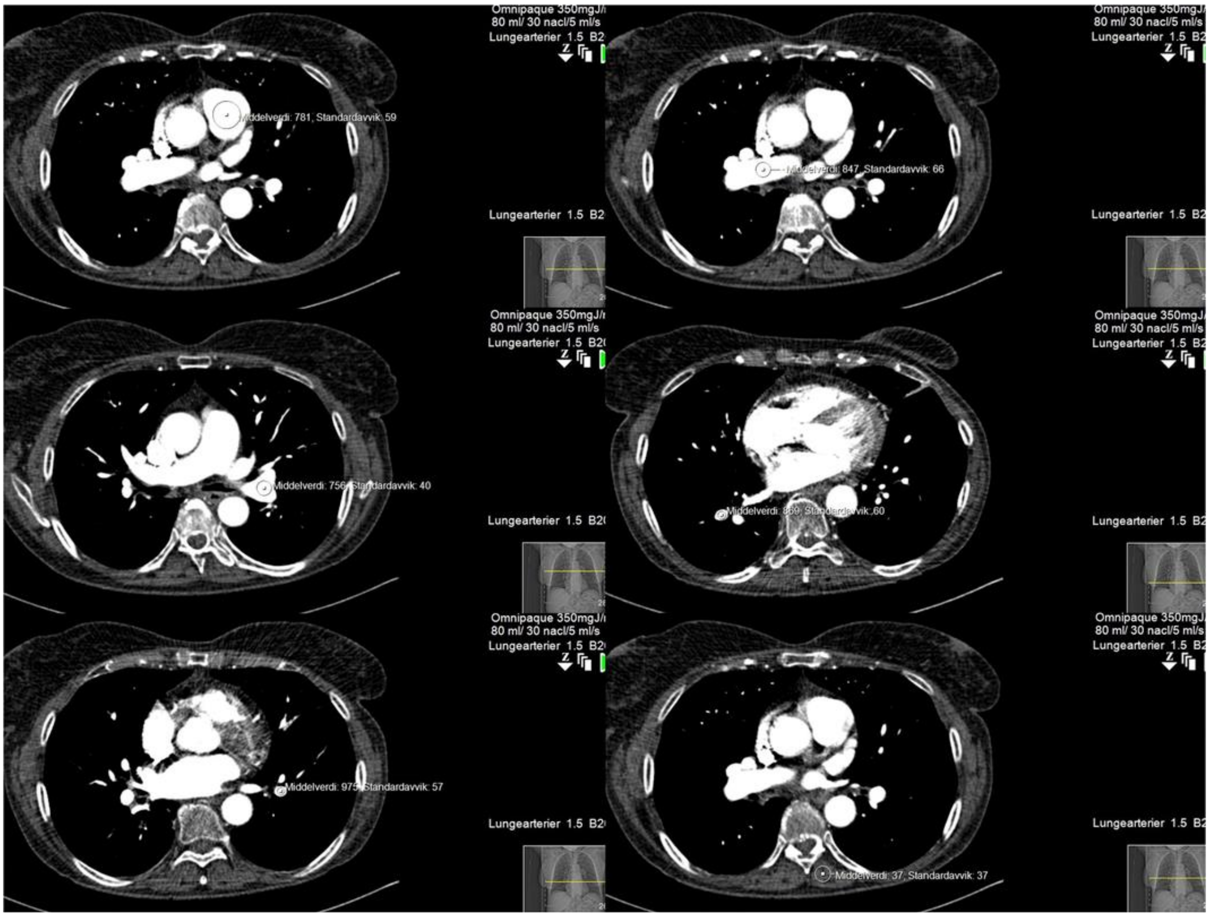

Figure 1. ROIs for the objective measurements of attenuation (quantified as average HU) and noise (quantified as standard deviation HU) placed in the lumen of the pulmonary trunk, right and left pulmonary arteries, right and left lower lobar arteries and paravertebral muscle.

Radiation doses and risk estimates for women of various age

CT dose index ($CTDI_{vol}$) and dose length product (DLP) were recorded from the examination reports transferred from the CT scanner to PACS. Effective doses were calculated as a product of DLP and a conversion factor of 0.014 for thorax[24]. Size specific dose estimate (SSDE) was calculated as a product of $CTDI_{vol}$ and the correction factor (f_{size}) proposed by AAPM[20] based on the patient's effective diameter (calculated as the geometric mean of the anteroposterior and lateral diameter measured at the level of the pulmonary trunk).

The effective risk (R) for a 20, 30 and 40 years old female patient was estimated by using Brenner’s equation[25].

$R = \sum r_T H_T$

where r_T is the lifetime tissue-specific cancer risk per unit equivalent dose to that tissue, and H_T is the equivalent dose for tissue T. We calculated the average organ doses (H_T) for breast tissue, lungs, thyroid, stomach and liver based on the average $CTDI_{vol}$ values by using ratios of organ dose to $CTDI_{vol}$ (f_{organ})[26]. The r_T values proposed by Brenner were used[25].

Statistical analysis

Statistical analyses were conducted using SPSS for Windows version 24 (IBM Inc, Armonk, NY).. Three factors related to the distribution of data were highlighted: average, standard deviation, and lowest and highest value. The Shapiro-Wilk test was used to determine that the data were normally distributed. A t-test was used to investigate whether there were differences in the distribution of age, weight, BMI, effective diameter, thickness of extra thoracic tissues between the groups. Differences in physical image quality parameters and radiation dose between the groups were evaluated using the t-test. Differences in scores for subjective image quality were assessed with the Mann Whitney test. P values of less than 0.05 were considered to be statistically significant. Inter-rater agreement was assessed using Cohen's kappa test with following interpretation of agreement: 0.00-0.20 slight, 0.21-0.40 fair, 0.41-0.60 moderate, 0.61-0.80 substantial, 0.81-1.00 almost perfect[27]. Detailed analyses of percentage agreement were used additionally.

Ethical considerations

This project was approved by the local research ethics committee and also the Regional Committee for Medical and Health Research Ethics. All image evaluations were undertaken on anonymized images. Previous studies have reported no consensus on the body weight threshold for using 80 kV protocols. Within our work we opted to use an 80 kg threshold in view of the potential risk of repeating examinations due to unsatisfactory image quality in larger patients.

Results

Patient characteristics

There was no statistically significant difference in distribution of patient characteristics parameters between the groups except for gender (table 2). Nine of the female patients were under 40 years old. None of them were pregnant, only one post-partum patient was included (in the group examine with 80kV protocol on scanner 2).

Table 2. Patient data presented as average ± standard deviation (minimum - maximum)

	scanner 1		scanner 2	
	100 kV	80 kV	100 kV	80 kV
Age (years)	68,9±12,3 (39-89)	63,7±16,8 (30-95)	63,8±17,5 (21-88)	61,9±20,7 (17-92)
Weight (kg)	63±8,6 (51-80)	65,7±11,2 (48-79)	66,5±11,3 (50-80)	60,7±10,5 (41-78)
BMI	22,8±2,6 (18,5-27,6)	22,6±2,7 (17-28)	22,1±3 (17,2-28,7)	21,9±3,2 (16,6-30,5)
Effective diameter (mm)	290,5±31,5 (237,5-386,5)	280,3±25 (239-345,4)	277,5±27,6 (216,9-314,3)	260,2±20,6 (229,8-304,4)
Gender(male/female)	10/10	8/12	5/15	5/15

PE positive	3	3	4	3

Subjective image quality

Subjectively assessed noise was significantly higher on the images acquired with the 80 kV protocols. The scores for sharp reproduction of pulmonary arteries were lower for 80 kV protocols, but the difference was not significant for any of the scanners (table 3).

Overall rating of diagnostic image quality provided lower scores for 80 kV performed on both scanners with more accentuated difference on scanner 2. The post-partum patient received a score of 3 for total assessment of diagnostic image quality.

Table 3. Average scores for the four patient groups (mean ± standard deviation) with the lowest of the two scores given by the radiologists in parenthesis (mean), and p-values for significance assessment of the differences between the 100 and 80 kV protocols, calculated for each scanner

	scanner 1			scanner 2		
	100 kV	80 kV	p value	100 kV	80 kV	p value
Subjective noise	4,2±0,4 (4)	3,8±0,8 (3,55)	0,06	4,15±0,7 (3,9)	3,45±0,7 (3,05)	<0,001
sharp reproduction of pulmonary arteries	4,15±0,7 (3,85)	4,1±0,6 (3,9)	0,659	4,07±0,6 (3,85)	3,9±0,6 (3,65)	0,327
total assessment of diagnostic image quality	4,18±0,6 (4,0)	4,1±0,7 (3,9)	0,718	4,23±0,5 (4,1)	3,83±0,6 (3,45)	0,033

Interobserver variation

Interobserver variation between radiologists analyzed by Cohen's kappa test gave the following results: k = 0,23 for noise, k = 0.24 for sharp reproduction of pulmonary arteries and k = 0.37 for total image quality. This corresponds to a fair agreement. When analyzing percentage agreement, the difference between the scores given by the two radiologists was maximum one point in 95% of the cases for noise, 98,8% for sharp reproduction of pulmonary arteries and 97,5% for total image quality.

Objective image quality

Attenuation (HU) in lung arteries was significantly higher for 80 kV protocols (table 4). Large variation in attenuation in the lung arteries was also recorded within all the groups (i.e. for examinations performed on the same CT machine and with the same protocol).

Noise measured in lung arteries was significantly higher for 80 kV protocols on both scanners (higher difference on scanner 2). Noise measured in paravertebral muscle was also higher for 80 kV protocols but statistically significant only for scanner 2.

Slight and not statistically significant differences in both SNR and CNR between 80 kV and 100 kV protocols were recorded on both scanners.

Table 4. Average values and standard deviations for image quality parameters measured for the four patient groups and p-values for significance assessment of the differences between the 100 and 80 kV protocols, separately calculated for each scanner.

	scanner 1			scanner 2		
	100 kV	80 kV	p value	100 kV	100 kV	p value
Average attenuation (HU) in pulmonary arteries	458±115	655±193	<0.001	571±145	741±247	0,01
Average noise (SD in HU) in pulmonary arteries	25±5	34±9	<0.001	29±9	42±16	0,001
Attenuation (HU) in paravertebral muscle	40±6	47±11	0,026	49±9	53±15	0,25
Noise (SD in HU) in paravertebral muscle	24±7	28±6	0,035	24±7	32±9	0,001
SNR	18,8±4,9	20,3±6,7	0,52	20,3±6,1	19±6,5	0,478
CNR	19,2±7,9	23,2±10,1	0,201	23,4±9,7	23±10,3	0,779

Radiation dose

Based on the protocol's CTDI$_{vol}$ (CTDI$_{vol}$ values provided by the CT machine before scan start based on reference mAs), an expected dose reduction of approximately 50% was estimated on both scanners (table 1).

The actual dose reduction based on values which take into account the effect of tube current modulation (table 5) was significant in terms of both CTDI$_{vol}$, DLP, SSDE, and effective dose on both scanners (p<0,001 for all parameters). Higher dose reduction on scanner 2 was recorded.

Table 5. Radiation doses expressed as mean ± standard deviation (minimum - maximum) and percentual dose reduction for the two scanners and effective risk (number of cases per 10^6) for a 20, 30 and 40 years old female patient.

	scanner 1	scanner 2

	100 kV	80 kV	dose reduction (%)	100 kV	80 kV	dose reduction (%)
CTDI$_{vol}$ (mGy)	4,7±1,2 (2,3-7,4)	3,0 ±1 (1,5-5,9)	36	4,6±1,1 (2,2-6)	2,4±0,4 (1,61-3,1)	48
DLP (mGy ·cm)	149,7±50,4 (76-284)	90±41,5 (48-228)	40	148,3±31,9 (94-204)	69,7±19 (40-99)	53
SSDE (mGy)	6±1,2 (3,5-7,9)	3,9±1,1 (2,2-7,5)	35	6,1±1,4 (2,7-8,1)	3,3±0,4 (2,6-4,2)	46
Effective dose (mSv)	2,1±0,7 (1,1-4)	1,2±0,6 (0,67-3,19)	40	2,1±0,4 (1,3-2,9)	1±0,3 (0,56-1,4)	53
Effective risk 20 y	52,19	33,31	32	51,08	26,65	47
Effective risk 30 y	31,87	20,32	36	31,59	16,28	48
Effective risk 40 y	24,44	15,60	30	23,92	12,48	49

* Note: All differences were statistically significant ($p<0.001$)

Discussion

As expected, subjectively perceived noise is substantially higher on the images acquired with the 80 kV protocols in accordance with higher measured noise. No statistically significant difference in scores for sharp reproduction of pulmonary arteries between the 100 kV and 80 kV protocols for any of the scanners confirms previous results[14]. Overall rating of diagnostic image quality gave lower scores for 80 kV protocols on both scanners. There was very little difference in average values for scanner 2, which is consistent with other studies[14,18-19].

Cohen’s kappa test showed a fair agreement in all analyzed aspects of subjective image quality. A low k coefficient may be due to the use of a five-point Likert scale. When observers are required to make finer discriminations, identical scores are more difficult to obtain[28]. Cohen’s kappa only takes into account whether or not the observers give the same score and does not discern between different ranges of disagreement (four-points and one-points differences in scores are treated equally). Other causes of inter-observer variation may be differences in how radiologists examined the images (different use of viewing tools) or subjective preferences regarding image’s appearance. Comparable k values were also found in similar studies[13]. At the same time, if the observers are well trained and the probability of scoring based on guessing is very low, Cohen’s kappa may underestimate agreement significantly, and other statistical methods can safely be trusted[28]. The proportion of specific agreement, rather than Cohen’s kappa, was proposed as an informative agreement measure for clinicians[29]. Both radiologists have extensive experience in interpreting CT images and therefore the score differences which were a maximum of one point difference were 95% of the cases for noise, 99% for sharp reproduction of pulmonary arteries and 98% for total image quality might provide a better description of inter-observer variation in our study.

Significantly higher attenuation in the pulmonary arteries for the 80 kV protocols compared to the 100 kV protocols for both CT scanners confirms the expectations. Reducing voltage to 80kV brings the average energy of the photons closer to the K-edge of iodine and increases attenuation in contrast enhanced vessels. Variation in attenuation in pulmonary arteries within the groups can be a consequence of use of the same amount of contrast agent in all patients without adjusting for patient size.

As expected based on results presented in other studies[13,19], no statistically significant difference in SNR was noted between the 80 kV and 100 kV protocols on both scanners. CNR increased slightly using 80 kV protocol but the difference was not significant. This confirms the expectation that the significant attenuation increase caused by reducing kV could compensate for the noise increase. Previous studies do not indicate any significant difference in CNR between 100 kV and 80 kV protocols[13,30], not even between 100 kV and 70 kV protocols[31].

The protocol specific $\mathrm{CTDI_{vol}}$ values predicted a dose reduction of approximately 50% on both scanners (table 1). As expected, the actually achieved dose reduction in terms of $\mathrm{CTDI_{vol}}$, DLP, SSDE, and effective dose in the study was statistically significant and confirms previous evidence[13,16-18]. However, different percent dose reduction on the two scanners (36 % vs 48% $\mathrm{CTDI_{vol}}$ reduction) showed that the scanners reacted differently to the kV decrease when scanning patients and using tube current modulation. A thinner beam width might allow a more fine-tuned mA adjustment between rotations when using tube current modulation and that might explain the higher dose reduction on scanner 2 which caused higher noise increase on that scanner. Slight differences in both dose and image quality were expected due to differences in technical details between scanners[32]. The effective risk decreased considerably (table 5). However, our effective risk assessments give only a rough estimate as they are based on the mean doses for the groups. Separate calculations for every patient wouldn't be so relevant given the limited number of young female patients included. Considering that our calculations did not take into account for higher breast sensitivity in pregnant and post-partum patients, the effective risk for those patients might be higher than our estimations.

We recognize that there are some limitations to our study, one of which is that we did not investigate directly the effect of lower tube voltage on the efficiency of detecting PE. However, maintained CNR and subjective diagnostic image quality suggest that it would not cause a negative impact (fig. 2). A further limitation is that we did not assess image quality for lung or mediastinum window settings used for the examination of incidental findings. One of the patients examined with 80 kV protocol had a combined HRCT for interstitial lung disease and PE study. In this case the high-resolution reconstruction for assessment of lung findings was very poor due to excessive noise.

We used body weight as the only selection criteria. 80 kV protocols might not be an optimal choice for obese patients even if they have a body weight under 80 kg. One might use additional criteria such as BMI or chest diameter although that would increase the examination time. A less time-consuming alternative would be the exclusion of clearly obese patients based on the radiographers' subjective assessment. Considering an average gestational weight gain of 13,5 kg[33] some of the pregnant patients will exceed the 80 kg weight limit. A pre-gestational weight under 80 kg might be used as a criterion for use of 80kV protocols in pregnant patients, as only a low proportion of the gestational weight gain is caused by breast enlargement or fat deposit on the upper body[34].

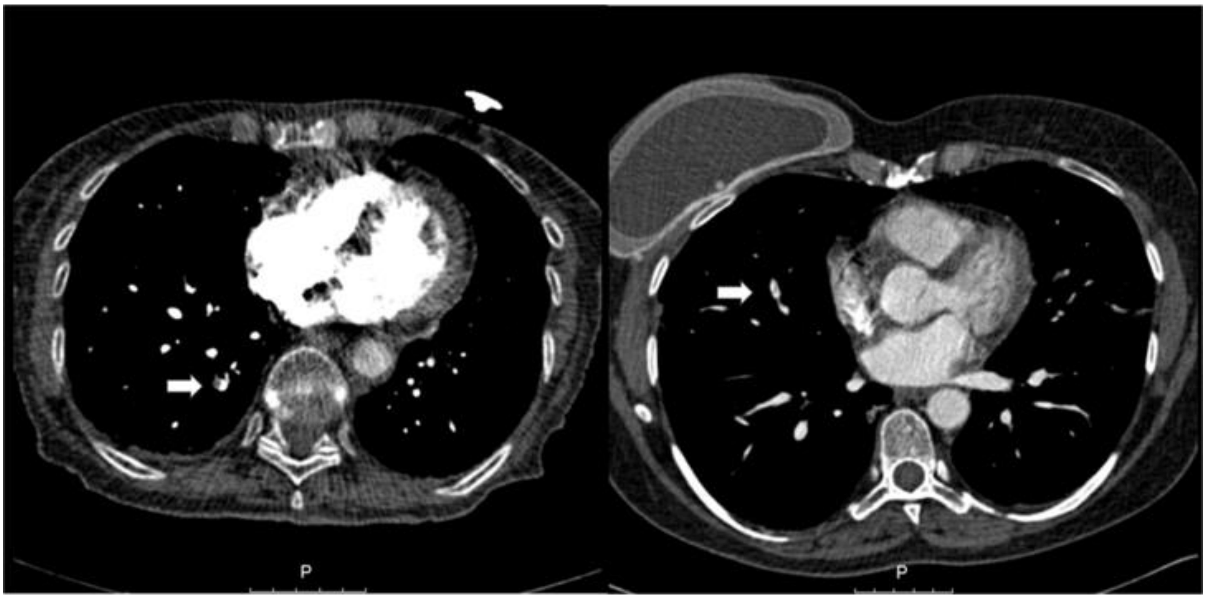

Figure 2. Pulmonary embolism in patients scanned with 80 kV protocol (right) and 100 kV protocol (left). The score for total assessment of diagnostic image quality was 4 for both examinations.

Conclusion

Optimization of CTPA protocols should be prioritized due to higher risk of PE in radiation-sensitive patient groups such as pregnant patients and contraceptive users.

The most important outcome of the study is verification of the hypothesis that reduction of kilovoltage from 100 to 80 in CTPA protocols results in significant reduction of patient doses without compromising diagnostic image quality in patients with body weight less than 80 kg.

As our results suggest, the same change in the protocol might have slightly different effects on the image quality on different scanners. It cannot be concluded that a reduction of kilovoltage to 80 without the adjustment of other scanning parameters at other protocols and/or other types of CT scanners would give exactly the same results as ours, but our results support introduction of 80 kV in CTPA protocols in non-obese patients.

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