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Impact of increasing tube potential and additional filtration on image quality and radiation dose for digital chest radiography

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ABSTRACT

Background: Chest radiography is one of the most commonly performed examinations as routine check-ups in radiology departments. Radiographers should be concerned with minimizing patient radiation dose while maintaining high diagnostic image quality.

Objective: This study aimed to investigate the effect of increasing tube potential (kV) and adding filtration on image quality and radiation dose for posteroanterior (PA) chest radiography using a digital radiography (DR) system.

Materials and methods: Eighty-five kV with no filter was used as the reference exposure technique. Subsequently, the kV was increased to 96, 117, and 133, and additional filtrations of 2 mm Al, 1 mm Al+0.1 mm Cu, and 1 mm Al+0.2 mm Cu were applied. A total of sixteen images were produced. The entrance surface air kerma (ESAK) was measured and evaluated. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were accessed for objective image quality. Five independent radiographers assessed a subjective image quality (IQ) score using two alternative forced choices (2AFC).

Results: Increasing kV and adding filtration reduced the ESAK while enhancing the SNR and CNR. However, the IQ score declined relative to the reference image when higher kV and additional filtration were applied except 85 kV. The IQ score indicated that an image acquired at 85 kV with 1 mm Al+0.2 mm Cu showed superior quality compared to the reference image. Notably, the SNR for this image was significantly higher ($p<0.05$). Additionally, this image resulted in a lower radiation dose (13.44 mGy) compared to the reference image (24.97 mGy). Furthermore, the image quality (IQ) score was higher than the reference images.

Conclusion: This study's findings indicate that using an 85 kV with 1 mm Al+0.2 mm Cu additional filtration for digital PA chest radiography can reduce the radiation dose while improving image quality. However, this study used an anthropomorphic chest phantom; further clinical research is recommended.

Introduction

Diagnostic medical imaging procedures and technologies have increased over the past decade,[1] raising concerns regarding patient radiation doses.[2,3] Chest radiography is one of the most common examinations in the radiology department, typically in routine check-ups. It is approximately 30-40% of all radiographic procedures performed.[4] A single chest radiograph delivers an ionizing radiation dose equivalent to three days of natural environmental exposure, which is minimal. However, the cumulative dose from repeated imaging can be significant.[5]

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Atiyyah TAE-R *et al*. indicates that cumulative exposure from diagnostic imaging, including PA chest radiography, may not cause acute toxicity but could increase long-term malignancy risk due to chronic exposure. Despite the relatively low radiation dose associated with chest radiography, approximately 0.07 mSv[2], there is still a potential for biological effects through a stochastic effect, particularly cancer.[6] The probability of this effect is directly related to the increase in radiation dose, and it is essential to note that there is no threshold dose for this effect.[7]

In recent years, optimizing radiation dose has become a considerable challenge, particularly since the introduction of digital radiography. Digital image receptors have a wider dynamic range than traditional radiographic film, which can lead to a phenomenon called "dose creep," where excess radiation is used without awareness. Radiation dose optimization is one of the fundamental principles for radiation protection established by the International Commission on Radiological Protection (ICRP), which states that all exposures should be maintained at a level as low as reasonably achievable (ALARA) without compromising the diagnostic quality of the examination.[7]

One strategy for optimizing radiation dose is X-ray beam hardening. This technique influences photon interactions, particularly photoelectric absorption. Increasing kVp and adding filtration can increase the effective photon energy and reduce the patient's radiation dose.[8-10] However, it is crucial to consider that these adjustments may also impact image quality.

Radiographers should carefully consider specific exposure parameters for each patient. Furthermore, appropriate technical exposure factors must be established to ensure the production of images that meet diagnostic purposes.

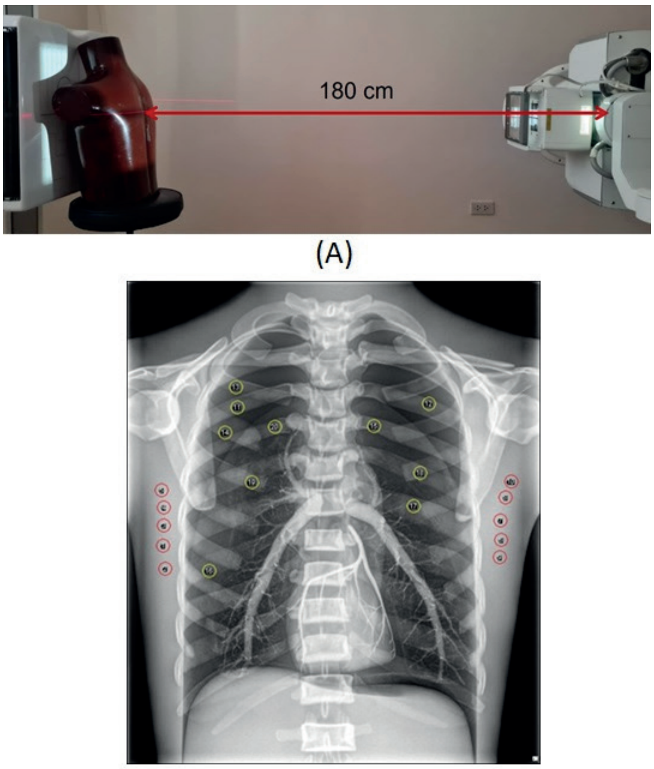
This study investigated the effect of high kV with additional filtration on the radiation dose and image quality for digital chest radiography. Moreover, the study aimed to identify the optimal exposure parameter, providing essential guidance in digital chest X-ray examinations.

Materials and methods

Radiographic equipment and data acquisition

This study was performed using a flat plate detector (Digital GOS (Gadox); Philips Healthcare) operating with a Digital Diagnost X-ray machine (Philips Healthcare). The quality controls of the X-ray unit, including kV and time accuracy and precision, radiation output reproducibility and linearity, and collimator and beam alignment, were within acceptable limitations.

An anthropomorphic chest phantom (RS-330, Radiology Support Devices, Inc., USA) was radiographed in the posteroanterior (PA) position using a large focal spot with a 180 cm source-to-image distance (SID) (Figure 1A). Two outer AEC chambers with an anti-scatter grid (85 lines per centimeter, 10:1 ratio) were used. Tube potentials increased from 85 to 133 kV, with approximate 15% kV rule increments.[11] The image with 85 kV was used as a reference image calculated by kV = (thickness*2) + 40.[12,13] The additional filtrations built in the X-ray machine were: no filtration, 2 mm Al, 1 mm Al+0.1 mm Cu, and 1 mm Al+0.2 mm Cu. Sixteen images were produced.



(B)

Figure 1*. A simulation of phantom's chest radiography setup. A: ROIs on the phantom image using the ImageJ software, B: the yellow circle is the object, the red circle is the background.*

Radiation dose measurement

The entrance surface air kerma (ESAK) is defined as the kerma to air measured on the central beam axis at the position of the phantom, including the backscattered radiation. The ESAK is a dosimetry quantity recommended for use as a patient dose by IAEA. The ESAK was calculated by multiplying an incident air kerma with an appropriate backscatter factor for each HVL according to TRS No. 457.[14] An ionization dosimeter (Radcal ionization chamber, model 10X5-6 with Radcal electrometer, model 9010, Radcal Corporation, Monrovia, CA, USA) was used to measure the incident air kerma (IAK).

$$K_e = K_i \times B \qquad \text{Equation 1}$$

When K_e : entrance surface air kerma (ESAK)
K_i : incident air kerma
B : backscatter factor (BSF) for selected field size

Objective assessment of image quality

To calculate the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR), twenty regions of interest (ROIs) were drawn by an experienced radiographer: 10 ROIs in the ribs and lungs (object) and 10 ROIs in the soft tissue (background) as shown in Figure 1B. The size and location of ROIs were kept constant for all images using ImageJ software (National Institutes of Health, Bethesda, MD). The SNR and CNR were calculated using the following Equation 2[15] and 3.[15, 16]

$$SNR_i = \frac{PV_i}{\sigma_i} \qquad \text{Equation 2}$$

$$CNR = \frac{PV_i - PV_{bg}}{\sigma_{bg}} \qquad \text{Equation 3}$$

When PV_i and σ_i : mean pixel value and the standard deviation of ROI , respectively.
PV_{bg} : mean pixel value of the ROI background
σ_{bg} : standard deviation of the ROI background.

Subjective assessment of image quality

Visual grading analysis (VGA) was performed using two alternative forced choices (2AFC). 2AFC assesses the responses of the observers who are presented with two separate images displayed side by side.[17] Images were displayed on two Coronis 5MP monitors (Barco MDCG-5121, Kortrijk, Belgium; 2048 by 2560 pixels). The reference image (85 kV with no added filtration) was permanently displayed on one monitor, and the experimental images were shown in random order on the other monitor to be scored against the reference image.

Five radiographers with at least 5 years of clinical experience evaluated the image using a 5-point Likert scale. The image quality (IQ) criteria were adapted from the European Guidelines on Quality Criteria for Diagnostic Radiographic Images,[18] shown in Table 1.

Radiographers were not permitted to manipulate the windowing and magnification of the image. The overall score for each image was calculated by adding the scores from all six IQ criteria. The final IQ score for each image was determined by taking the average IQ score from the five radiographers.

The intra-class correlation coefficient (ICC) and its 95% Confidence level (CI) were used to assess the reliability based on a single measurement, absolute agreement, and two-way mixed-effects model. The ICC value was interpreted as follows: poor (<0.5), moderate (0.5 to <0.75), good (0.75 to 0.9), and excellent (>0.9) reliability.[19-21]

Table 1. Criteria evaluation tool for the visual grading analysis.

No.	Criteria	Image Score
1	Visually sharp reproduction of the vascular pattern in the whole lung, particularly the peripheral vessels	5 = much better than
2	Visually sharp reproduction of the trachea and proximal bronchi	4 = slightly better than
3	Visually sharp reproduction of the borders of the heart and aorta	3 = equal to
4	Visually sharp reproduction of the diaphragm and lateral costophrenic angles	
5	Visualization of the retrocardiac lung and the mediastinum	2 = slightly worse than
6	Visualization of the spine through the heart shadow	1 = much worse than

Statistical analysis

All results are presented as means±standard deviation (SD). Tests showed that DAP and IQ were normally distributed. The data were compared using an ANOVA-like test. The inter-observer correlation was also evaluated by the intra-class correlation coefficient (ICC), and the result was considered significant at the 95% confidence level by using. Differences were considered to be statistically significant at $p<0.05$.

Results

Radiation dose

When using the AEC, the results indicated that with both increasing in kV and adding filtrations, there was a gradual reduction in ESAK (Figure 2). The most significant decrease in ESAK (60.76%) was found at 133 kV with a 1 mm Al+0.2 mm Cu filter compared to the reference image at 85 kV without filtration. In contrast, the minimum reduction of 21.10% occurred at 96 kV without filtration. Furthermore, the ESAK at 117 kV and 133 kV, both with and without additional filtration, showed similarities (Figure 2).

Objective image quality

With an increase in kV and adding filtration, both SNR and CNR increased. When compared with the reference image, it was found that there were statistically significant increases in SNR and CNR ($p<0.05$) except 85 kV with 2 mm Al, 85 kV with 1 mm Al+0.2 mm Cu, and 96 kV without filtration (Figure 3). The highest SNR and CNR, achieved from 133 kV combined with 1 mm Al+0.2 mm Cu, were 12.52±1.12 and 14.85±0.66, respectively.

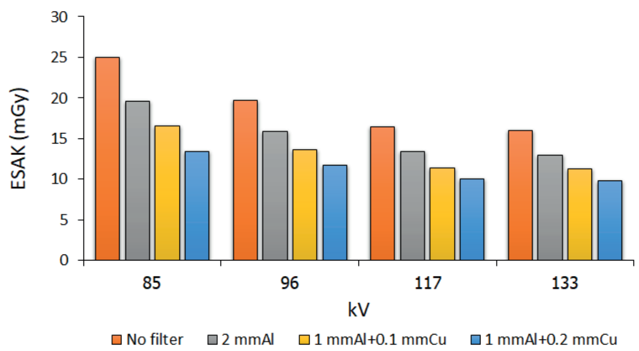


***Figure 2**. Decrease in ESAK as kV increases and filtration added.*

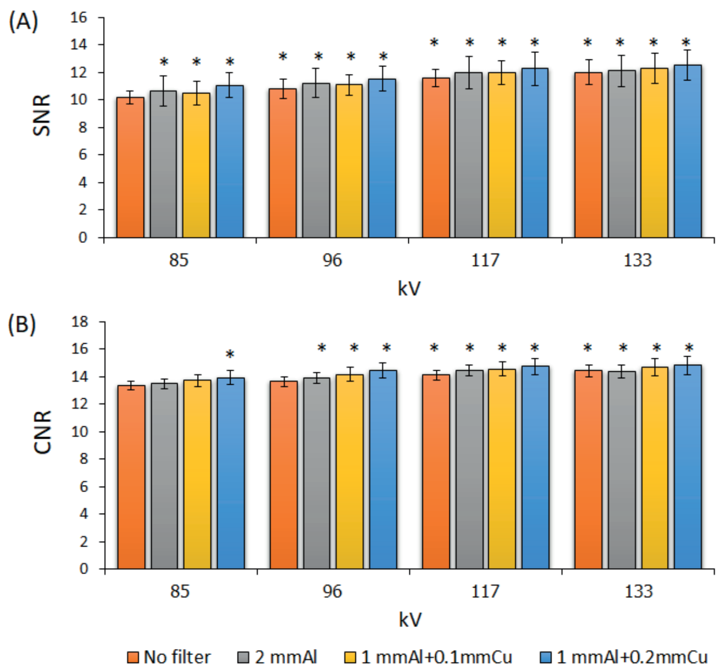


***Figure 3**. Objective image quality assessment as kV increases and filtration was added. A: SNR increase, B: CNR increase (*p<0.05).*

Subjective image quality

The average subjective image quality scores compared to the reference image are shown in Table 2 (>3: higher subjective image quality than the reference image, 3: the same subjective image quality as the reference image, <3: lower subjective image quality than the reference image). According to the data, the images obtained from 85 kV with 2 mm Al, 85 kV with 1 mm Al+0.1 mm Cu, 85 kV with 1 mm Al+0.2 mm Cu, and 96 kV with 2 mm Al showed more excellent IQ scores than the reference image. The highest IQ score was 3.60±0.81 from 85 kV with 2 mm Al. The reliability of the observer was good (ICC was 0.78) (p<0.05).

Table 2. Average subjective image quality score (IQ score) by 5 radiographers.

kV	Filter	mAs	IQ score
85	No filter	5.36	Reference image
	2 mm Al	6.38	3.60±0.81
	1 mm Al+0.1 mm Cu	7.09	3.07±0.87
	1 mm Al+0.2 mm Cu	8.14	3.13±0.73
96	No filter	3.38	2.77±0.50
	2 mm Al	3.98	3.13±0.57
	1 mm Al+0.1 mm Cu	4.34	2.73±0.45
	1 mm Al+0.2 mm Cu	4.97	2.93±0.74
117	No filter	2.03	2.43±0.50
	2 mm Al	2.24	2.63±0.61
	1 mm Al+0.1 mm Cu	2.38	2.20±0.76
	1 mm Al+0.2 mm Cu	2.63	2.30±0.60
133	No filter	1.63	2.37±0.49
	2 mm Al	1.77	2.37±0.56
	1 mm Al+0.1 mm Cu	1.85	2.17±0.75
	1 mm Al+0.2 mm Cu	1.97	2.30±0.53

Discussion

The findings of this study indicate that increasing kV and adding filtration is a feasible radiation dose-optimization tool for digital chest radiography. In this study, the kV was adjusted following the 15% rule,[22] starting from an initial value of 85 kV and increasing to 96, 117, and 133 kV. Various filtration combinations were used, including no filtration, 2 mm Al, 1 mm of Al plus 0.1 mm Cu, and 1 mm of Al+0.2 mm of Cu. As the kV increased and filtration was added, the radiation dose (ESAK) decreased (Figure 1). These results support the findings from earlier studies.[16,23-26] Except for the increase from 117 kV to 133 kV, comparable ESAK values were recorded with the same levels of filtration. This similarity is attributed to the sufficient photon energy penetrating the chest phantom.

The variation in kV impacts both the quantity and quality of X-rays. Higher kV produces more X-ray photons with higher X-ray energy. However, adding filtration into the X-ray beam reduces the quantity of X-rays across all energy levels, resulting in a hardened X-ray energy through the absorption of low-energy X-ray photons over high-energy X-ray photons.[27]

Both kV and filtration significantly affect both patient dose and image quality. This study found that increasing the kV and adding filtration substantially reduces the ESAK while notably enhancing both the SNR and the CNR. Higher kV and added filtration produce X-rays with greater energy, which improves the beam's penetration through the patient. This enhanced penetration results in a lower patient dose (ESAK). In terms of image quality, the increased energy allows a greater number of X-ray photons to reach the image receptor, thereby improving both the SNR and CNR of the image.

However, the subjective image quality indicates that increased kVp combined with the same additional filtration results in a decreased IQ score. The results also show that using 85 kV with all filter combinations and 96 kV with 2 mm Al results in a higher IQ score than the reference image. Notably, among these techniques, the 85 kV with 1 mm Al+0.2 mm Cu provides the lowest ESAK with a reduction of 46.18%.

This study has several limitations. Firstly, it was conducted using an anthropomorphic phantom, meaning the results may not accurately reflect actual human anatomy. Secondly, the investigation was based on a single X-ray machine coupled with one image receptor, indicating the necessity for additional research involving other systems. Lastly, the subjective image quality scores were assessed by experienced radiographers who have worked in the diagnostic radiology department for over five years. Further study should include real human subjects, different X-ray systems, and a wider range of radiographers to confirm the findings and ensure they apply to various settings. It should also evaluate the diagnostic accuracy of images produced with the proposed technique. In clinical practice, the results could guide the development of updated radiography protocols, routine equipment calibration, and specialized radiographer training to optimize radiation dose and image quality, improving patient safety and diagnostic outcomes across diverse patient populations.

Conclusion

The ESAK decreases as the kV increases and with the addition of filtration. Regarding objective image quality, both the SNR and the CNR improve with higher kV and additional filtration. The IQ score suggests that an image taken at 85 kV with 1 mm Al+0.2 mm Cu has better image quality than the reference image, achieving a radiation dose reduction of 46.18%. Additionally, this image demonstrates significantly better SNR than the reference image (p<0.05).

Conflict of interest

The authors declare no conflict of interest.

Ethical approval

This study, which involved human participants, complied with the ethical principles of the Declaration of Helsinki. The research protocol was reviewed and approved by the Ethics Committee of Naresuan University, with the approval number COA No. 211/2020.

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