CHEST

Dose reduction and image quality improvement of chest radiography by using bone-suppression technique and low tube voltage: a phantom study

Satoshi Takagi[1] · Tatsuya Yaegashi[2] · Masayori Ishikawa[3]

Abstract

Objective To clarify the relationship between entrance surface dose (ESD) and physical image quality of original and bone-suppressed chest radiographs acquired using high and low tube voltages.

Methods An anthropomorphic chest phantom and a 12-mm diameter spherical simulated nodule with a CT value of approximately + 100 HU were used. The lung field in the chest radiograph was divided into seven areas, and the nodule was set in a total of 66 positions. A total of 264 chest radiographs were acquired using four ESD conditions: approximately 0.3 mGy at 140 and 70 kVp and approximately 0.2 and 0.1 mGy at 70 kVp. The radiographs were processed to produce bone-suppressed images. Differences in contrast and contrast-to-noise ratio (CNR) values of the nodule between each condition and between the original and bone-suppressed images were analyzed by a two-sided Wilcoxon signed-rank test.

Results In the areas not overlapping with the ribs, both contrast and CNR values were significantly increased with the bone-suppression technique ($p < 0.01$). In the bone-suppressed images, these values of the three conditions at 70 kVp were equal to or significantly higher than those of the condition at 140 kVp. There was no apparent decrease in these values between the ESD of approximately 0.3 and 0.1 mGy at 70 kVp.

Conclusion By using the shortest exposure time and the lowest tube voltage possible not to increase in blurring artifact and image noise, it is possible to improve the image quality of bone-suppressed images and reduce the patient dose.

Key Points
• *The effectiveness of bone-suppression techniques differs in areas of lung field.*
• *Image quality of bone-suppressed chest radiographs is improved by lower tube voltage.*
• *Applying lower tube voltage to bone-suppressed chest radiographs leads to dose reduction.*

Keywords Radiography, thoracic · Solitary pulmonary nodule · Reduction dosage · Phantoms, imaging · Image processing, Computer-assisted

Abbreviations
CNR Contrast-to-noise ratio
ESD Entrance surface dose
mAs Milliampere-second
ROI Region of interest

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Introduction

Contrast in X-ray images is generally increased by lowering the tube voltage [1], and the image quality of chest radiographs was improved using this technique [2–4]. However, besides lesions, ribs are depicted with a higher contrast in chest radiographs obtained with a lower tube voltage [3]. Moreover, the diagnostic

performance in cases where pulmonary lesions overlap with ribs in chest radiographs is decreased by using a lower tube voltage [5]. Therefore, although the contrast of pulmonary lesions and soft tissues is lower, chest radiography using higher tube voltage is widely performed to reduce the contrast of ribs.

To improve diagnostic performance in cases where pulmonary lesions overlap with ribs in chest radiographs, some prior studies have reported the usefulness of the dual-energy subtraction and postprocessing bone-suppression techniques [6–11]. Compared to the dual-energy subtraction technique, the bone-suppression technique does not require any additional dose and special equipment for image acquisition, and it can process images that have been previously acquired and stored.

All of the previous studies on the usefulness of the bone-suppression technique were performed by using chest radiographs obtained with a high tube voltage [8–11]. However, if ribs are precisely suppressed by this technique at any tube voltage, it is expected that the contrast of pulmonary lesions on bone-suppressed images should be increased by using a lower tube voltage. In a study that compared bone-suppressed images obtained with various tube voltages at an equal entrance surface dose (ESD), the image quality of relatively dense simulated nodules in the bone-suppressed image improved as the tube voltage was lowered [12].

However, to perform chest radiography with an equal ESD, the exposure time has to be prolonged as the tube voltage is lowered. Prolongation of exposure time in chest radiography leads to an increase in blurring artifact due to movement of the heart. Although it is possible to shorten the exposure time by reducing the ESD, there has been no report on the effect of reducing the ESD on the image quality of the bone-suppressed images. Thus, the aim of this study was to clarify the relationship between ESD and physical image quality of original and bone-suppressed chest radiographs acquired using high and low tube voltages.

Materials and methods

Chest phantom and nodule position

This phantom study did not require institutional review board approval. This study was carried out using an anthropomorphic chest phantom (N-1; Kyoto Kagaku) and a 12-mm diameter spherical simulated nodule with a CT value of approximately + 100 Hounsfield units at 80 keV beam energy. The lung field in the chest radiograph was divided into four areas: apex, center, periphery, and overlapping with soft tissue. It has been reported that differences in the numbers of overlapping ribs in the lung field affect the effectiveness of the bone-suppression techniques [12]. Therefore, we subdivided the central lung field into three areas: not overlapping with ribs, overlapping with one rib, and overlapping with two ribs. The peripheral lung field was further divided into two areas: not overlapping with ribs and overlapping with two ribs. We defined 10 positions of the simulated nodule in these five areas. In addition, eight positions of the simulated nodule were defined in the apex and overlapping with soft tissue areas. Therefore, there were 66 total positions that were the positions of the simulated nodule on the chest radiograph (Fig. 1).

Image acquisition

For the tube voltage values, 140 kVp was adopted as the high tube voltage and 70 kVp was adopted as the low tube voltage, as this lower value was reported as having the best image quality of bone-suppressed images [12]. An ESD of 0.3 mGy or less is recommended in posteroanterior chest radiography [13]. Therefore, chest radiographs were acquired with milliampere-second (mAs) values closest to an ESD of 0.3 mGy at both 70 and 140 kVp and mAs values closest to an ESD of 0.2 and 0.1 mGy at 70 kVp. In each of
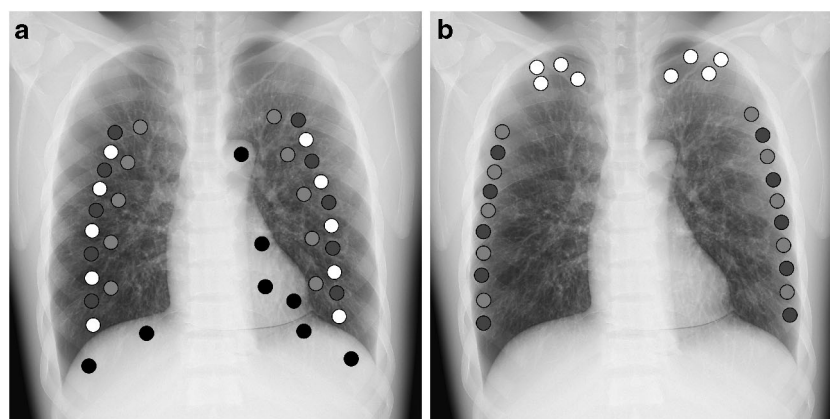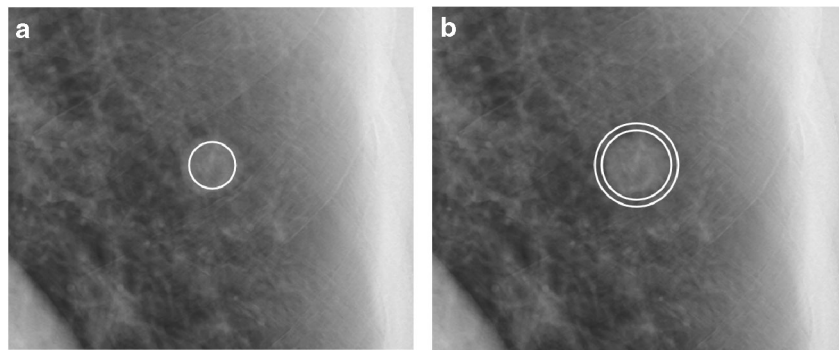

Fig. 1 Chest radiograph of 66 positions of the spherical simulated nodule. **a** Image shows 10 white spots, central area not overlapping with ribs; 10 light gray spots, central area overlapping with one rib; 10 dark gray spots, central area overlapping with two ribs; and 8 black spots, area overlapping with soft tissue. **b** Image shows 8 white spots, apex area; 10 light gray spots, peripheral area not overlapping with ribs; and 10 dark gray spots, peripheral area overlapping with two ribs

Fig. 2 Region of interest (ROI) for calculating the contrast and contrast-to-noise ratio values of the simulated nodule. **a** A circular ROI with a diameter of 10.05 mm at the center of the nodule as a signal. **b** An annular ROI with an inner diameter of 15.00 mm and an outer diameter of 16.50 mm around the nodule as a background

these four conditions, chest radiography was performed by setting the simulated nodule at each of the defined 66 positions, and a total of 264 chest radiographs were acquired. All posteroanterior chest radiographs were acquired using a cesium iodide amorphous silicon flat-panel detector (DR-ID 1200; Fujifilm Medical Systems) with an integrated 10:1 grid, 2.5 mm Al equivalent filtration, and a 2.0-m detector-to-tube distance. The detector was 35 cm × 43 cm (matrix size, 2336 × 2836; gray level, 10-bit; pixel size, 150 μm). The "Scintillation with Optical Fiber" dosimeter (MIDSOF;

AcroBio) that could confirm the measured value in real time was attached to the center of the irradiation field on the X-ray incident side of the phantom, and the ESD was confirmed for each imaging condition. When the measured value greatly differed from the target value, the obtained image was discarded, and the image was acquired again under the same conditions. The process of generating chest radiographs after exposure was unified in all images, and recommended parameters of the manufacturer were used. All chest radiographs were then processed by dedicated software

Table 1 Median contrast values of the simulated nodule

Lung field	BS	Tube voltage and ESD			
		70 kVp			140 kVp
		0.307 mGy	0.191 mGy	0.099 mGy	0.282 mGy
Apex	(−)	77 (39–92)*	80 (38–91)*	77 (37–96)*	67 (42–81)
	(+)	90 (44–99)	87 (44–100)	93 (52–105)	92 (49–106)
Center					
Not overlapping with ribs	(−)	79 (54–115)	80 (53–112)	78 (52–109)*	81 (57–114)
	(+)	100 (78–147)*, §	100 (79–144)§	97 (71–140)§	97 (82–140)§
Overlapping with one rib	(−)	119 (84–141)†	120 (84–141)†	118 (77–140)†	106 (76–127)
	(+)	95 (68–124)†, §	92 (69–123)†, §	85 (64–125)*, §	84 (63–112)§
Overlapping with two ribs	(−)	128 (105–156)†	129 (106–156)†	129 (106–159)†	113 (94–141)
	(+)	92 (62–117)†, §	92 (64–115)†, §	91 (66–116)†, §	84 (64–107)§
Periphery					
Not overlapping with ribs	(−)	16 (−26–62)*	17 (−25–63)*	14 (−28–64)*	26 (−4–58)
	(+)	60 (55–84)*, §	63 (55–87)†, §	68 (51–89)*, §	60 (49–72)§
Overlapping with two ribs	(−)	104 (84–135)†	106 (83–134)†	105 (86–137)†	92 (68–111)
	(+)	40 (26–75)§	38 (30–75)§	41 (23–74)§	42 (35–68)§
Overlapping with soft tissue	(−)	63 (50–99)*	63 (50–101)*	64 (50–102)*	55 (42–87)
	(+)	48 (30–89)*, ‡	49 (33–89)*, ‡	48 (29–90)*, ‡	40 (23–80)‡

Values represent median (minimum–maximum) in each defined area. P values were calculated by a two-sided Wilcoxon signed-rank test

BS, bone suppression; *ESD*, entrance surface dose

* Significant difference ($p < 0.05$) compared to 140 kVp

† Significant difference ($p < 0.01$) compared to 140 kVp

‡ Significant difference ($p < 0.05$) compared to nonsuppression

§ Significant difference ($p < 0.01$) compared to nonsuppression

Table 2 Median CNR values of the simulated nodule

Lung field	BS	Tube voltage and ESD			
		70 kVp			140 kVp
		0.307 mGy	0.191 mGy	0.099 mGy	0.282 mGy
Apex	(−)	1.25 (0.62–2.18)	1.23 (0.60–2.14)	1.21 (0.57–1.93)	1.26 (0.76–2.04)
	(+)	1.42 (0.99–3.81)	1.42 (0.95–3.75)	1.40 (1.08–3.79)	1.48 (1.10–3.32)
Center					
Not overlapping with ribs	(−)	2.23 (0.84–3.37)	2.28 (0.81–3.39)	2.23 (0.81–3.42)	2.32 (1.07–4.03)
	(+)	2.92 (1.98–3.98)[§]	2.88 (2.00–3.88)[§]	2.82 (2.02–3.89)[§]	2.61 (1.73–4.48)[§]
Overlapping with one rib	(−)	2.48 (1.76–3.56)	2.46 (1.74–3.57)	2.52 (1.75–3.60)	2.56 (1.55–3.50)
	(+)	2.71 (1.38–3.76)	2.66 (1.39–3.76)	2.75 (1.39–3.77)	2.70 (1.23–3.53)
Overlapping with two ribs	(−)	2.54 (1.79–3.31)[*]	2.57 (1.84–3.29)[†]	2.64 (1.89–3.29)[*]	2.39 (1.77–3.01)
	(+)	2.48 (1.94–3.46)[†]	2.47 (2.01–3.52)[†]	2.40 (2.20–3.52)[†]	2.30 (1.81–3.20)
Periphery					
Not overlapping with ribs	(−)	0.17 (−0.15–0.77)[†]	0.18 (−0.14–0.78)[†]	0.15 (−0.16–0.76)[†]	0.31 (−0.03–0.76)
	(+)	0.71 (0.38–1.09)[*, §]	0.72 (0.40–1.13)[*, §]	0.69 (0.38–1.09)[§]	0.72 (0.36–1.02)[§]
Overlapping with two ribs	(−)	0.94 (0.79–1.54)[†]	0.95 (0.79–1.54)[†]	0.93 (0.79–1.52)[†]	0.84 (0.69–1.35)
	(+)	0.38 (0.22–1.29)[§]	0.36 (0.25–1.25)[§]	0.38 (0.20–1.27)[§]	0.43 (0.32–1.16)[§]
Overlapping with soft tissue	(−)	1.03 (0.88–2.32)[*]	1.04 (0.88–2.27)[*]	1.00 (0.79–2.04)	0.98 (0.82–2.17)
	(+)	0.79 (0.69–2.15)[*, ‡]	0.80 (0.70–2.21)[‡]	0.74 (0.70–2.09)[‡]	0.75 (0.61–2.00)[‡]

Values represent median (minimum–maximum) in each defined area. P values were calculated by a two-sided Wilcoxon signed-rank test

BS, bone suppression; *ESD*, entrance surface dose; *CNR*, contrast-to-noise ratio

[*] Significant difference ($p < 0.05$) compared to 140 kVp

[†] Significant difference ($p < 0.01$) compared to 140 kVp

[‡] Significant difference ($p < 0.05$) compared to nonsuppression

[§] Significant difference ($p < 0.01$) compared to nonsuppression

(ClearRead BS 3.6.1; Riverain Technologies), and a total of 264 bone-suppressed images were produced.

Physical evaluation

A total of 528 images from 264 original chest radiographs and bone-suppressed images were analyzed. For all the images, by using image processing software (ImageJ 1.52e, National Institutes of Health), a circular region of interest (ROI) with a diameter of 10.05 mm was set as the signal at the center of the simulated nodule. In addition, an annular ROI with an inner diameter of 15.00 mm and an outer diameter of 16.50 mm was set as the background to surround the simulated nodule (Fig. 2). Then, the contrast and contrast-to-noise ratio (CNR) values of each simulated nodule were calculated using the following equations:

$$\text{contrast} = M_{\text{obj}} - M_{\text{bkg}},$$

$$\text{CNR} = \frac{\text{contrast}}{\sigma_{\text{bkg}}},$$

where M_{obj} is the mean pixel value of the signal circular ROI, and M_{bkg} and σ_{bkg} are the mean pixel value and the standard deviation of the background annular ROI in the same image.

Statistical analysis

For each defined area, we applied the two-sided Wilcoxon signed-rank test to analyze the differences in the contrast and CNR values between all pairs of the four conditions for each image and between the original chest radiographs and bone-suppressed images for the same condition. SPSS version 22 (IBM Corporation) was used to perform all statistical analyses; $p < 0.05$ was considered an indicator of statistically significant differences.

Results

The mean ± standard deviation for the measured value of the ESD at 140 kVp was 0.282 ± 0.010 mGy (tube current, 100 mA; exposure time, 18 ms; mAs value, 1.8). At 70 kVp, these values were 0.307 ± 0.008 (tube current, 250 mA;

Table 3 *p* values of the contrast compared between three conditions at 70 kVp using a two-sided Wilcoxon signed-rank test

Lung field	BS	Pair of ESD (mGy)		
		0.307 vs. 0.191	0.307 vs. 0.099	0.191 vs. 0.099
Apex	(−)	0.23	0.06	0.20
	(+)	0.28	0.02*	0.43
Center				
Not overlapping with ribs	(−)	0.11	< 0.01†	< 0.01†
	(+)	0.04*	0.01*	0.02*
Overlapping with one rib	(−)	0.34	0.03*	0.05
	(+)	0.72	0.10	0.10
Overlapping with two ribs	(−)	0.63	0.86	0.86
	(+)	0.86	0.88	0.51
Periphery				
Not overlapping with ribs	(−)	0.16	0.67	0.26
	(+)	0.03*	0.77	0.64
Overlapping with two ribs	(−)	0.26	< 0.01†	0.04*
	(+)	0.90	0.40	0.48
Overlapping with soft tissue	(−)	0.07	0.08	0.61
	(+)	0.17	0.20	0.89

BS, bone suppression; *ESD*, entrance surface dose

* $p < 0.05$

† $p < 0.01$

exposure time, 32 ms; mAs value, 8.0), 0.191 ± 0.006 (tube current, 250 mA; exposure time, 20 ms; mAs value, 5.0), and 0.099 ± 0.004 mGy (tube current, 160 mA; exposure time, 16 ms; mAs value, 2.56). The median values of the contrast and CNR in each defined area are summarized in Tables 1 and 2, and the minimum and maximum values are shown in parentheses. The results of statistical analyses for the differences between each of the three conditions at 70 kVp and the condition at 140 kVp and between the original and bone-suppressed images are also shown. The results of the statistical analyses for the differences between the three conditions at 70 kVp are shown in Tables 3 and 4.

Apex area

Compared to the condition at 140 kVp, the contrast values of all three conditions at 70 kVp in the original chest radiographs were significantly higher ($p < 0.05$). A comparison between the three conditions at 70 kVp showed that the contrast values at approximately 0.1 mGy in the bone-suppressed images were significantly higher than those at approximately 0.3 mGy ($p = 0.02$). Although the minimum, median, and maximum values of both the contrast and CNR values increased with the bone-suppression technique, in some images, this technique caused a decrease in these values. Therefore, there were no significant differences between the original and bone-suppressed images.

Central area not overlapping with ribs

Compared to the condition at 140 kVp, the contrast values of approximately 0.1 mGy at 70 kVp in the original chest radiographs were significantly lower ($p < 0.05$) and those of approximately 0.3 mGy at 70 kVp in the bone-suppressed images were significantly higher ($p < 0.05$). A comparison between the three conditions at 70 kVp showed that the contrast values in both the original and bone-suppressed images were significantly higher as the ESD increased. Both the contrast and CNR values under all four conditions significantly increased with the bone-suppression technique ($p < 0.01$).

Central area overlapping with one rib

Compared to the condition at 140 kVp, the contrast values of all three conditions at 70 kVp in both the original and bone-suppressed images were significantly higher ($p < 0.05$, Fig. 3). A comparison between the three conditions at 70 kVp showed that although the contrast values at approximately 0.3 mGy in the original chest radiographs were significantly higher than those at 0.1 mGy ($p = 0.03$), the CNR values in both the original and bone-suppressed images were significantly higher at approximately 0.1 mGy ($p < 0.01$). The contrast values significantly decreased with the bone-suppression technique under all four conditions ($p < 0.01$).

Table 4 *p* values of CNR compared between three conditions at 70 kVp using a two-sided Wilcoxon signed-rank test

Lung field	BS	Pair of ESD [mGy]		
		0.307 vs. 0.191	0.307 vs. 0.099	0.191 vs. 0.099
Apex	(−)	0.39	0.13	0.17
	(+)	0.60	0.40	0.48
Center				
Not overlapping with ribs	(−)	0.34	0.61	0.78
	(+)	0.73	0.88	0.81
Overlapping with one rib	(−)	0.20	< 0.01[†]	0.03[*]
	(+)	0.16	< 0.01[†]	0.09
Overlapping with two ribs	(−)	0.09	0.14	0.24
	(+)	0.24	0.44	0.55
Periphery				
Not overlapping with ribs	(−)	0.41	0.10	0.06
	(+)	0.06	0.35	0.06
Overlapping with two ribs	(−)	0.65	0.01[*]	0.01[*]
	(+)	0.67	0.89	0.68
Overlapping with soft tissue	(−)	0.17	0.03[*]	0.05
	(+)	0.35	0.06	0.03[*]

BS, bone suppression; *ESD*, entrance surface dose; *CNR*, contrast-to-noise ratio

[*] $p < 0.05$

[†] $p < 0.01$

Central area overlapping with two ribs

Compared to the condition at 140 kVp, both the contrast and CNR values of all three conditions at 70 kVp in both the original and bone-suppressed images were significantly higher ($p < 0.05$). There were no significant differences in any pairs of the three conditions at 70 kVp. The contrast values significantly decreased with the use of the bone-suppression technique under all four conditions ($p < 0.01$).

Fig. 3 The simulated nodule at a position overlapping with one rib in the right central lung field in the original chest radiograph (**a**–**c**) and bone-suppressed image (**d**–**f**). **a** Tube voltage, 70 kVp; entrance surface dose (ESD), 0.307 mGy; contrast, 124; contrast-to-noise ratio (CNR), 2.48. **b** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 125; CNR, 2.52. **c** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 113; CNR, 2.56. **d** Tube voltage, 70 kVp; ESD, 0.307 mGy; contrast, 85; CNR, 2.62. **e** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 85; CNR, 2.63. **f** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 82; CNR, 2.70
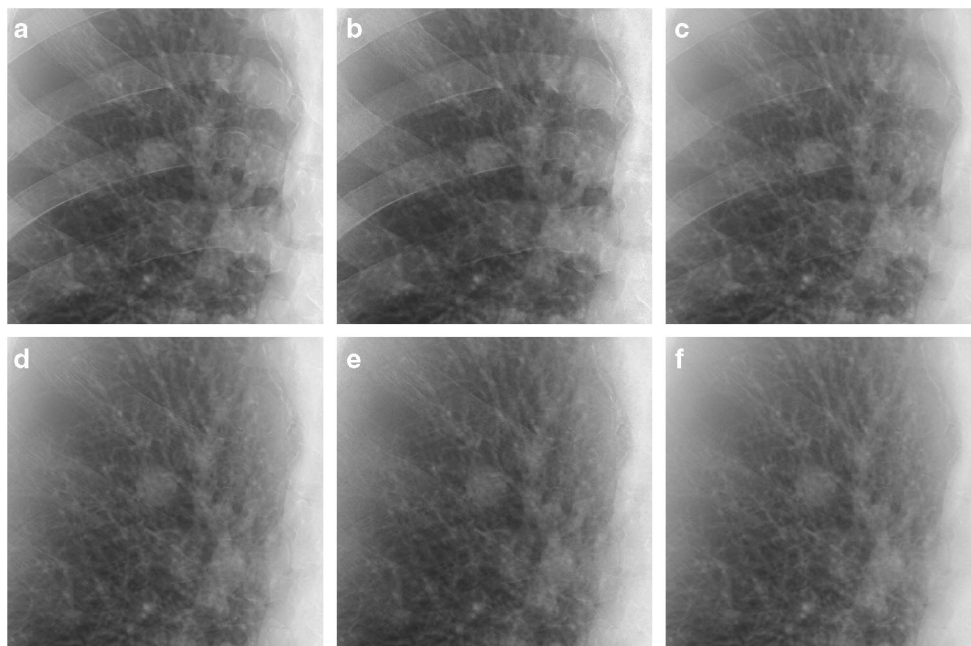
Fig. 4 The simulated nodule at a position not overlapping with ribs in the right peripheral lung field in the original chest radiograph (**a**–**c**) and bone-suppressed image (**d**–**f**). **a** Tube voltage, 70 kVp; entrance surface dose (ESD), 0.307 mGy; contrast, − 26; contrast-to-noise ratio (CNR), − 0.15. **b** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, − 28; CNR, − 0.16. **c** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, − 4; CNR, − 0.03. **d** Tube voltage, 70 kVp; ESD, 0.307 mGy; contrast, 55; CNR, 0.38. **e** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 55; CNR, 0.38. **f** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 50; CNR, 0.36
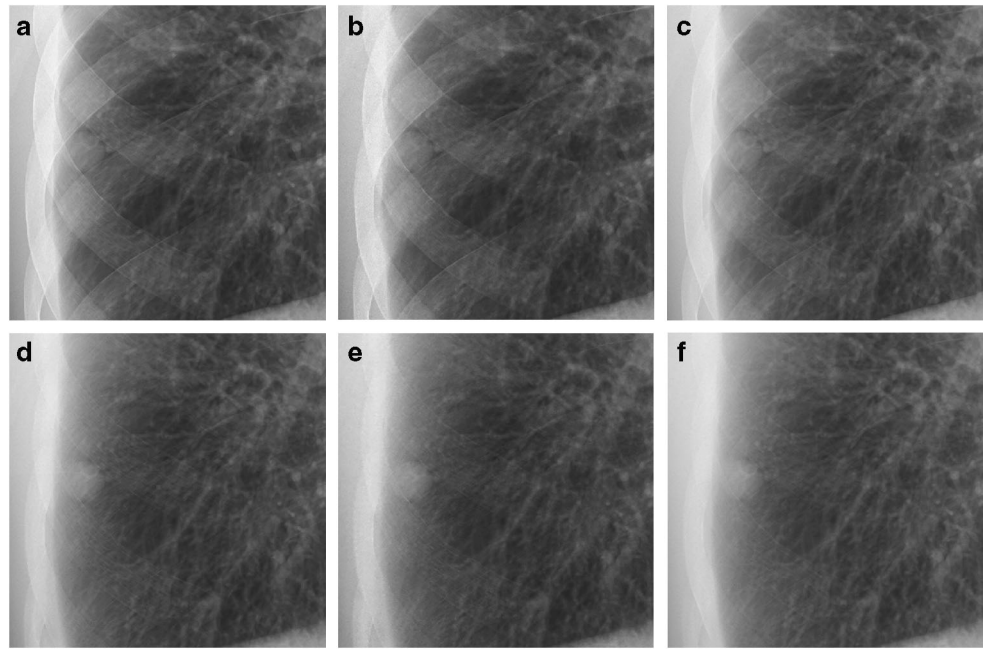
Peripheral area not overlapping with ribs

Compared to the condition at 140 kVp, both the contrast and CNR values of all three conditions at 70 kVp in the original chest radiographs were significantly lower ($p < 0.05$, Fig. 4). However, these values were significantly increased with the use of the bone-suppression technique under all four conditions ($p < 0.01$). These values of all three conditions at 70 kVp in the bone-suppressed images were significantly higher ($p < 0.05$), except for the CNR values at approximately 0.1 mGy. A comparison between the three conditions at

70 kVp showed that the contrast values at approximately 0.2 mGy in the bone-suppressed images were significantly higher than those at approximately 0.3 mGy ($p = 0.03$).

Peripheral area overlapping with two ribs

Compared to the condition at 140 kVp, both the contrast and CNR values of all three conditions at 70 kVp in the original chest radiographs were significantly higher ($p < 0.01$, Fig. 5). A comparison between the three conditions at 70 kVp showed that the contrast values were significantly higher ($p < 0.05$),

Fig. 5 The simulated nodule at a position overlapping with two ribs in the left peripheral lung field in the original chest radiograph (**a**–**c**) and bone-suppressed image (**d**–**f**). **a** Tube voltage, 70 kVp; entrance surface dose (ESD), 0.307 mGy; contrast, 90; contrast-to-noise ratio (CNR), 0.89. **b** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 94; CNR, 0.86. **c** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 71; CNR, 0.74. **d** Tube voltage, 70 kVp; ESD, 0.307 mGy; contrast, 40; CNR, 0.38. **e** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 41; CNR, 0.38. **f** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 35; CNR, 0.35
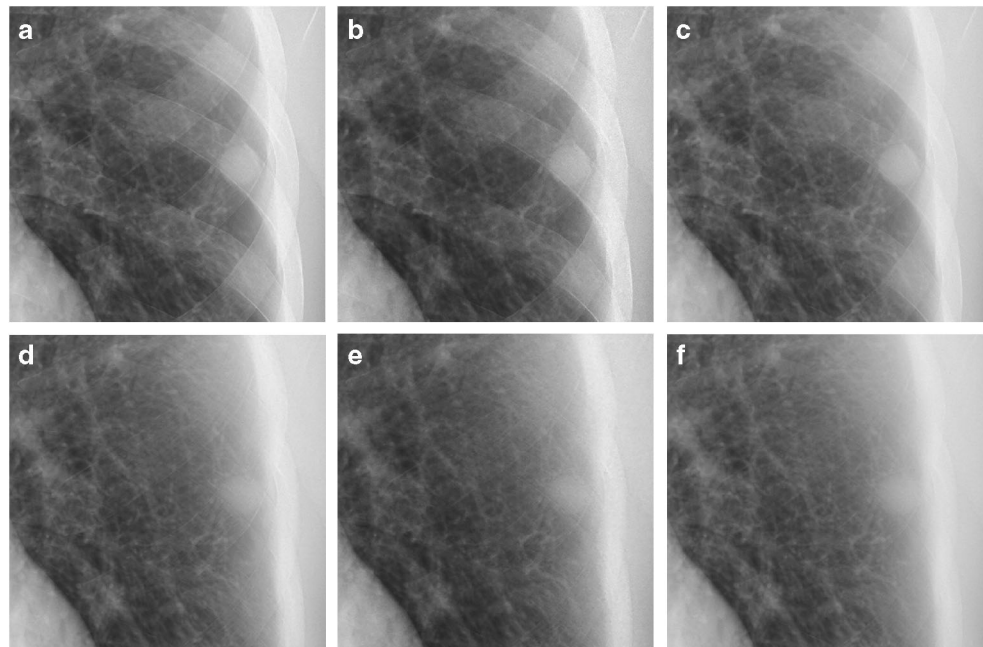
Fig. 6 The simulated nodule at a position overlapping with soft tissue in the original chest radiograph (**a**–**c**) and bone-suppressed image (**d**–**f**). **a** Tube voltage, 70 kVp; entrance surface dose (ESD), 0.307 mGy; contrast, 74; contrast-to-noise ratio (CNR), 1.01. **b** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 81; CNR, 1.00. **c** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 66; CNR, 0.98. **d** Tube voltage, 70 kVp; ESD, 0.307 mGy; contrast, 69; CNR, 0.97. **e** Tube voltage, 70 kVp; ESD, 0.099 mGy; contrast, 74; CNR, 0.95. **f** Tube voltage, 140 kVp; ESD, 0.282 mGy; contrast, 64; CNR, 0.99
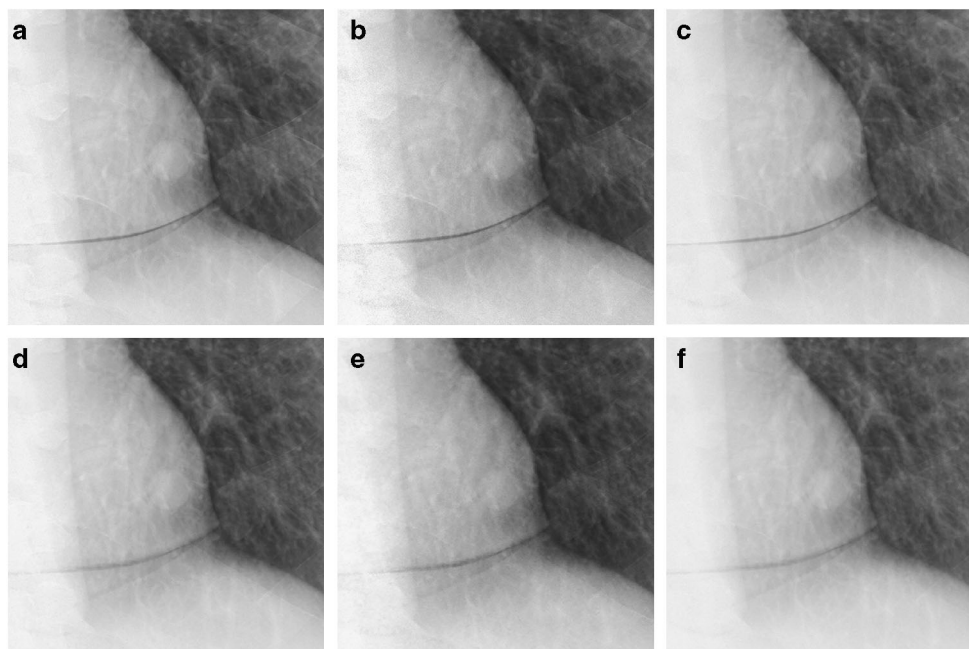
but the CNR values were significantly lower ($p < 0.01$) at approximately 0.1 mGy in the original chest radiographs. Both the contrast and CNR values significantly decreased with the use of the bone-suppression technique under all four conditions ($p < 0.01$).

Area overlapping with soft tissue

Compared to the condition at 140 kVp, the contrast values of all three conditions at 70 kVp in both the original and bone-suppressed images were significantly higher ($p < 0.05$, Fig. 6). Furthermore, the CNR values were significantly higher at approximately 0.3 mGy in both the original and bone-suppressed images ($p < 0.05$) and at approximately 0.2 mGy in the original chest radiographs ($p < 0.05$). A comparison between the three conditions at 70 kVp showed that the CNR values at approximately 0.1 mGy were significantly lower than those at approximately 0.3 mGy in the original chest radiographs ($p = 0.03$) and those at approximately 0.2 mGy in the bone-suppressed images ($p = 0.03$). Both the contrast and CNR values significantly decreased with the use of the bone-suppression technique under all four conditions ($p < 0.05$).

Discussion

This study used a relatively dense simulated nodule to clarify the relationship among the ESD, tube voltage, and physical image quality in original and bone-suppressed chest radiographs. In the original chest radiographs, both the contrast and CNR values of all three conditions at 70 kVp in the peripheral area not overlapping with ribs and the contrast values of approximately 0.1 mGy at 70 kVp in the central area not overlapping with ribs were significantly lower than those of the condition at 140 kVp. However, both the contrast and CNR values significantly increased with the use of the bone-suppression technique. These values of the three conditions at 70 kVp in the bone-suppressed images were equal to or significantly higher than those of the condition at 140 kVp in all of the areas. The contrast values in the central areas overlapping with one and two ribs and both the contrast and CNR values in the peripheral area overlapping with two ribs and the area overlapping with soft tissue were significantly decreased by the bone-suppression technique under all four conditions. There was no apparent decrease in both the contrast and CNR values despite the variations in ESD of approximately 0.3 to 0.1 mGy at 70 kVp.

In studies that examined the utility of 70 kVp in chest radiographs with simulated lesions and visual assessment, it has been reported that lower tube voltage did not improve diagnostic performance [14, 15]. The reason is presumed to be an increase in the contrast of the ribs around the lesions, which is presumably resolved by the bone-suppression technique. In the areas overlapping with one or two ribs, the physical image quality of bone-suppressed images was significantly decreased because the bone-suppression technique suppressed not only the ribs but also the lesions. However, in these areas, the usefulness of the bone-suppression technique has been reported in studies that performed visual evaluations [8–11]. Therefore, in order to improve the diagnostic performance in these areas, reduction in the contrast of the ribs would be more important than improving physical image quality. In the area overlapping with soft tissue, the physical

image quality was significantly decreased with the bone-suppression technique. However, this is not considered to be a problem because bone-suppressed images are evaluated together with the original chest radiographs. When tube voltages are equal, the physical image quality generally improves as the mAs value increases. However, in this study, we noticed that the physical image quality was significantly higher at a low mAs value. This was believed to be the influence of image processing in image generation and bone suppression.

In posteroanterior chest radiography, exposure times of less than 20 ms and nominal focal spot value of 1.3 or less are recommended [13]. In this study, because we used a tube current of 250 mA or less to adjust the nominal focal spot value to 0.6 under all four conditions, the exposure time closest to 0.3 and 0.2 mGy at 70 kVp was 20 ms or more. By using a higher tube current with nominal focal spot value that does not exceed 1.3, it is possible to have an exposure time of less than 20 ms even at 70 kVp. Under the same exposure conditions, there is a decrease in the transmitted dose and an increase in the image noise when the patient's physical size increases. Therefore, it might be inappropriate to use 70 kVp for larger patients. On the other hand, it has been reported that the lower the tube voltage, the lower the effective dose equivalent when the ESD is equal at different tube voltages [15]. Although ESD is a criterion for radiation dose to the patient [13], the effective dose is regarded as a more appropriate indicator of stochastic risk [16]. Therefore, it is considered desirable to use the lowest tube voltage possible and the bone-suppression technique for reduction of effective dose equivalent and improvement of image quality.

This study had some limitations. First, this study was carried out using only one pair of digital systems. Because the parameters of image processing differ depending on the system, the image quality in other digital systems may be different from this study. Second, the effect of the additional filter was not investigated. Improvement of image quality and reduction of the ESD in chest radiography have been reported with the addition of copper filtration [2, 17, 18]. Therefore, it is necessary to consider optimal filtering in bone-suppressed chest radiographs using low tube voltage. Third, we used a relatively dense simulated nodule to obtain higher contrast and CNR values. These values become lower in low-density lesions such as ground-glass opacity, and different results would be expected from this study. Furthermore, pulmonary lesions are often depicted across several of the areas defined in this study. It is necessary to carry out an evaluation on clinical images of diseased cases. Finally, only a physical evaluation was performed. The result of the physical evaluation does not necessarily agree with the visual evaluation results. Therefore, it is necessary to conduct a visual evaluation to determine the usefulness of using low tube voltage and a bone-suppression technique.

In conclusion, although there were areas where the image quality was decreased with 70 kVp compared to 140 kVp, the image quality was significantly improved by the bone-suppression technique. In the bone-suppressed images, the contrast and CNR values of a relatively dense pulmonary nodule at 70 kVp were equal to or significantly higher than those at 140 kVp, even when the ESD was reduced to about one third. The problem in applying low tube voltage to chest radiography is the increased exposure time. Therefore, by using an exposure time that does not cause artifacts due to movement of the heart and by using the lowest tube voltage possible without causing a significant increase in image noise, it is possible to improve the image quality of bone-suppressed images and reduce the patient dose.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Satoshi Takagi.

Conflict of interest The authors declare that they have no conflict of interest.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was not required because this was a phantom study.

Ethical approval This phantom study did not require institutional review board approval.

Methodology
• Experimental
• Performed at one institution

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