Optimizing Contrast Resolution in Digital Chest Radiography by Varying Copper Filtration and kVp

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Purpose To measure the effect of increasing kilovoltage peak (kVp) and copper filtration thickness on entrance skin exposure and contrast resolution for chest radiography performed using digital flat-panel detectors.

Methods A phantom-based experiment was conducted in which 24 radiographs of a quality control chest phantom were obtained at varying kVp levels and copper filtration thicknesses. The entrance skin exposure was measured and analyzed for each exposure. All radiographs were analyzed based on measured pixel values and contrast:noise ratio (CNR) and using subjective analysis, which focused on contrast resolution assessment performed by 4 radiologists.

Results The results from the subjective image analysis showed that increasing copper filtration in increments of 0.1 mm resulted in less of a decrease in contrast resolution compared with increasing the kVp by 10 kVp, and that contrast resolution is more dependent on energy level than on filtration. The results from objective image analysis indicated that CNR decreased when kVp increased at all filtration thicknesses, but consistent dependency between CNR and filtration was not evident. Exposure data analysis showed an average 46% decrease in entrance skin exposure for each increase of 0.1 mm in copper filtration thickness.

Discussion Although subjective and objective data analysis results indicated that increases of copper filtration are more beneficial to maintaining contrast resolution and reducing entrance skin exposure compared with increases of kVp, objective image data analysis showed a greater reduction in contrast resolution when kVp is increased. These results validate previous research that concluded that copper filtration should be considered as a dose-reduction and image-optimization strategy in digital radiography departments.

Conclusion Although entrance skin exposure reduction can be accomplished using higher kVp and copper filtration, increasing copper filtration thickness could be considered to minimize the loss of contrast resolution for routine chest imaging when digital flat-panel detectors are used.

Keywords | *entrance skin exposure, copper filtration, kilovoltage peak, contrast resolution*

Most diagnostic radiography departments use aluminum as the primary added filtration material although other materials, such as copper, might be more efficient.[1] Increasing copper filtration thinness has been made easier with modern radiography systems, which offer additional filtration selection buttons on the collimator or automatic selection with an anatomically programmed technique.[2] However, before copper is adopted as the added filtration material, its effect on entrance skin exposure and contrast resolution should be studied.

Contrast resolution describes how well an object can be differentiated from its background and is an important diagnostic feature of medical imaging because it affects the quality and interpretive value of radiographs.[3] This image-quality feature measures how small changes in exposure level are displayed as a distinct shade of gray on the final image with distinct pixel values.[2,4] In the 1970s, the medical profession began to realize the value of contrast resolution with the development of computed tomography (CT) scanning and xeroradiography.[5] With CT, more tissue interfaces could be seen and quantified in the form of CT numbers,[6] and xeroradiography was able to enhance small contrast differences in soft tissues with the use of an amorphous selenium detector material.[7] Because xeroradiography requires high doses, it became an increasingly unpopular choice, and eventually, was replaced by improved film-screen imaging technology.[5] The lasting effect, however, was the need for improved contrast resolution and visualization of more tissues that could indicate suspected pathologies.[2,5] Newer digital image receptors, whether direct or indirect, have enhanced sensitivity at a wider range of x-ray energies.[5] In addition, their spectral response is affected by the inherent, heterogenous x-ray beam composition, and in particular, the average K-edge.[5] However, as the medical imaging profession continues to use and develop digital detector technologies, the detector's effect on contrast resolution and its ability to resolve small changes in attenuation and display them as distinct shades of gray on an image must be considered.

Radiographs consist of many shades of gray representing varying degrees of differential absorption as x-ray photons penetrate tissues. The visibility of these gray shades is critical, and more shades of gray are preferred.[5] Although the human eye is inherently attracted to high-contrast images, radiologists are trained to see the value in longer contrast scales and the information contained in these subtle gray shades.[5] For example, on a chest radiograph, broncho-pulmonary markings and the asymmetry of aeration between lung tissues are best visualized with longer scales of contrast.[8]

Furthermore, radiography is limited to 5 radiographic densities: air (gas), adipose tissue (fat), water, mineral, and metal.[8,9] A principle of radiograph interpretation revolves around an understanding of these 5 radiographic densities and how they are seen on radiographs.[9] Materials of different radiographic densities that come in physical contact with each other will contrast each other on a radiograph, whereas those with similar densities will not contrast each other.[9] Of particular diagnostic value to radiologists with selected radiographic studies is the visualization of tissues composed primarily of water and those made of adipose tissue. The effective atomic number of water is 7.42 with a tissue density of 1.0 g/cm^3. Adipose tissue has a slightly lower atomic number of 5.92 and tissue density of 0.91 g/cm^3.[5,10] The distinction between water and adipose tissue is minimal, and therefore, the ability of the detector to resolve the small differences in attenuation and display them as distinct shades of gray requires high-contrast resolution.[11] This distinction, however small, is relied on to assess certain tissue conditions such as edema and inflammation[11] and illustrates the need for improved contrast resolution.

According to the ALARA (as low as reasonably achievable) principle, radiation exposure should be minimized while maintaining image quality, making the choice of radiographic technique a compromise between image quality and patient exposure.[5] The inherent characteristics of digital radiography systems can be leveraged in this compromise because digital flat-panel detectors have an increased exposure latitude and dynamic range.[3] In addition, higher detective quantum efficiency of these digital image receptors leads to an increase in detector sensitivity to radiation. These characteristics allow the radiographer to modify exposure factors in a way that might reduce patient exposure.[12] An important consideration in setting a radiographic technique for digital systems is to find a balance in the selection of kilovoltage peak (kVp), which needs to be high enough to penetrate the anatomy of interest, and milliampere seconds (mAs) that provide an adequate signal:noise ratio.[4,5] Proper technique selection results in no visible quantum mottle or a diagnostically acceptable level of quantum mottle, providing a threshold level of subject contrasts in the remnant beam such that the final displayed image is of diagnostic quality.[5] The benefits of using a high kVp technique with corresponding lower mAs are well known and include appropriate penetration and reduced patient exposure, which occur as a result of the x-ray beam hardening.[2] Furthermore, high kVp techniques have been embraced by the profession as evidenced by the recommendations of the American Society of Radiologic Technologists in their white paper on best practices in digital radiography and the Image Wisely and Image Gently initiatives.[13,14] However, radiographers must consider the effect that high kVp techniques have on subject contrast[15] because kVp is the primary controller of subject contrast[5] and thus affects contrast resolution.[4] With digital imaging systems, excessive increases in kVp reduce differential absorption leading to a narrower range of image receptor exposure.[4,5] Furthermore, the available data needed for histogram equalization and rescaling is reduced when excessive kVp is used.[5]

In addition to using a high kVp technique, additional filtration can be used to harden the beam and, therefore, reduce patient exposure,[2] but this is at the expense of subject contrast.[15] Subject contrast can be restored by decreasing kVp, which partially reverses the exposure-reduction effects of additional filtration.[5,15] To mitigate this tradeoff, the use of copper filters has been suggested for digital image receptors. Although original research related to copper filters dates to 1959,[5] there has been a renewed interest in copper because of the use of higher kVp with digital image receptors.[15] Recent research indicates that increased levels of copper filtration can decrease entrance skin exposure by 25% to 44%.[16]

Although the radiology profession has focused on reducing radiation exposure for all types of radiography examinations, plain chest radiography has not received as much attention in that effort, mostly because of the differential attenuation and superimposition of thoracic structures; superimposition of thoracic structures adds anatomical noise.[17] With plain chest radiography constituting a substantial percentage of all referrals,[18] research focusing on reducing patient exposure during chest radiography is beneficial. More specifically, research that investigates how the benefits of increasing kVp and copper filtration can be leveraged to maximize exposure reduction and image quality during plain chest radiography deserves attention. The results of such research are important to the entire radiology profession, including radiographers, radiologists, department managers, and physicists. One such study investigated optimal beam quality for chest imaging using a flat-panel detector to obtain radiographs of a chest phantom at various kVp levels (90-140 kVp), with and without copper filtration. The study concluded that images obtained using 90 kVp with copper filtration were superior in quality to images acquired using the traditional 120 kVp without copper filtration with respect to the visibility of anatomical structures at identical entrance skin exposure.[19] Another study that focused on assessing the effect of increased copper filtration on chest image quality reported achieving a balance between radiation exposure and image quality at 0.3 mm of copper filtration and 120 kVp, with a 37% reduction in patient exposure.[17] A different study analyzed the relationship between dose reduction and copper filtration in digital radiography chest imaging using up to 0.3 mm of copper filtration as the independent variable, while studying dose and image quality as the dependent variables. This study found that the entrance skin exposure was reduced by approximately 33%, and image quality was equivalent to that of the standard kVp when copper filtration was used.[20]

This study aims to validate previous research that focused on how to best achieve a balance between radiation exposure and contrast resolution using copper filtration and to provide guidelines for radiographers on how to translate this research into clinical practice. The effect of increased copper filtration on contrast resolution and entrance skin exposure was investigated. The guiding research question for this study was: How do contrast resolution and entrance skin exposure change with increasing copper filtration and varying kVp for routine chest imaging performed using digital flat-panel detectors?

Methods

This study was designed as a phantom-based experiment; institutional review board approval was not required. Data were collected in 2 phases: image acquisition (July 2021) and image analysis (August 2021). Exposure data from image acquisition was analyzed. Subjective and objective image analyses also were performed, as recommended in the literature.[21]

Image Acquisition

The image acquisition phase included obtaining radiographs of a quality control phantom (model 07-646, Nuclear Associates), also called the *Duke phantom*. There are 3 test objects (lung, heart, and abdomen) in the chest phantom (see **Figure 1**). Each test object contains a contrast detail test pattern consisting of a 5-by-5 matrix of copper disks of different diameters and thicknesses. The disks in each column have the same thickness and decreasing diameter,

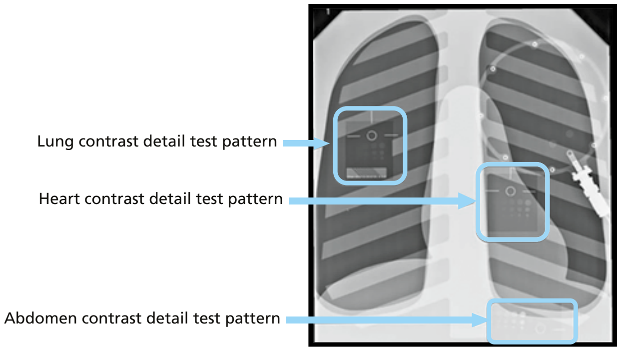

Figure 1. *Phantom with the 3 contrast detail test patterns: lung, heart, and abdomen. Image courtesy of the authors.*

which ranges from 6 to 0.5 mm. Each row contains disks that have the same diameter but vary in thickness.

Images were obtained at 6 different energy levels for 4 copper filtration conditions. Entrance skin exposure was measured for each exposure using a dosimeter. The mAs were selected using automatic exposure control to stay near a target exposure index value of 1400 for a digital flat-panel detector (Carestream Health) and to maintain the image receptor exposure for all conditions.

Independent variables were the 6 energy levels (70, 81, 90, 99, 109, 121 kVp) and 4 copper filtration conditions (0, 0.1, 0.2, 0.3 mm). Controlled variables were:

- acquisition – Carestream digital radiography (DR) system (target exposure index value = 1400)
- dosimeter – Fluke model 1350005000
- exposure field – fixed for all exposures
- focal spot size – large (1.0 mm)
- generator – 80 kW Siemens high frequency generator
- grid – 12:1
- half-value layer – 2.75 mm aluminum
- source-to-image receptor distance – 40 in

Exposure Data Analysis

Exposure data from image acquisition were analyzed at each kVp level by calculating the percent change in mAs required to maintain image receptor exposure as a function of the increase in copper filtration thickness. In addition, entrance skin exposure was measured at each kVp level and copper filtration thickness while image receptor exposure was maintained.

Subjective Image Data Analysis

Subjective image analysis focusing on contrast resolution assessment was performed by 4 board-certified radiologists from different geographical locations who were not affiliated with the same institution or each other and were blinded to the image acquisition protocol. The researchers used convenience sampling to recruit radiologists they currently or formerly worked with. The radiologists' years of experience and specialty reading areas varied. Radiologist 1 had 24 years of experience in diagnostic radiology and in nuclear medicine. Radiologist 2 had been board certified as a diagnostic radiologist for 18 years and completed fellowship in magnetic resonance (MR) imaging, with an emphasis on body and musculoskeletal MR imaging. Radiologist 3 had 30 years of experience as a general radiologist with additional education in musculoskeletal imaging, which they routinely read. Radiologist 4 had 12 years of experience in diagnostic radiology and 6 years of experience in cardiothoracic imaging, including fellowship.

The radiologists were asked to review 24 images and record the number of disks they could resolve in the lung contrast detail test pattern of the chest phantom. All 4 radiologists were provided with written instructions to guide them through the image analysis process. They were asked to zoom in on the lung contrast detail test pattern and to count disks as resolved if they could visualize at least 50% of the disk. The authors termed this metric as *disks resolved* and used it as a measure of contrast resolution.[22] The radiologists also were instructed not to modify the window width or window level from the default values. The radiologists were asked to record the amount of time spent reviewing and scoring the images.

Data collected from the subjective image analysis performed by the radiologists was analyzed using descriptive and inferential statistics. For the radiologists' assessment, the number of disks resolved was analyzed as a function of energy level (kVp) and the thickness of copper filtration (mm). Linear regression of the data from the 6 energy levels for each filtration thickness was used to calculate the slope and correlation coefficients, expressed as Pearson correlation coefficient (r),[23] for each radiologist's data set to determine the dependence of the number of disks resolved on kVp. All calculations were performed using Excel (Microsoft). In addition, linear regression of the data from the 4 filtration conditions at each energy level was used to calculate the slope and correlation coefficients for each radiologist data set to determine dependence on copper filtration. Rather than expressing the slope in terms of disks resolved per 1 kVp and disks resolved per 1 mm of copper, the slopes were scaled to the more clinically relevant values of disks resolved per 10 kVp and disks resolved per 0.1 mm of copper.

Objective Image Data Analysis

Objective image analysis was performed by a researcher who did not participate in the image acquisition phase. This phase of image analysis was based on the measured pixel values and focused on the contrast:noise ratio (CNR), which also is a measure of contrast resolution. Pixel values were measured from the thickest, largest uniform disk and the background in the lung contrast detail test pattern using the region of interest tool in Horos (iCat Solutions Inc), a free, open-source medical image viewer application.

The CNR was calculated based on the signal and noise of the region of interest (ROI), measuring the thickest, largest diameter disk (ROI_1) along with the background (ROI_2) divided by standard deviation (σ):

$$CNR = \frac{|(ROI_1 - ROI_2)|}{\sigma}$$

ROI_1 refers to the mean signal from the ROI located on the disk, and ROI_2 refers to the mean signal from the ROI located in the background (see **Figure 2**).[24,25] The following equation was used to estimate standard deviation (σ)

$$\sigma = \sqrt{\frac{(SD_1)^2+(SD_2)^2}{2}}$$

SD_1 is the standard deviation for ROI_1 (disk), and SD_2 is the standard deviation of ROI_2 (background).[24,25]

The slope and correlation coefficients also were calculated for the objective data using the same approach as outlined for the subjective data.

Data Collection Validity and Reliability

To ensure data collection validity and reliability, 2 researchers participated in image acquisition. The radiologists participating in the subjective image data analysis were blinded to the image acquisition parameters. Furthermore, all radiologists received the same instructions regarding image scoring. Objective measurement of CNR was used to compare data collected from the subjective image analysis with data collected from the objective image analysis.

Results

Results were obtained from analyses of exposure data of image acquisition, subjective image data, and objective image data.

Exposure Data Analysis

The data collection conditions of image acquisition and resulting entrance skin exposure values are shown in **Table 1**. With each increase in the thickness of copper filtration, the mAs required to maintain image receptor exposure increased (see **Table 2**). The average increase in mAs for each 0.1 mm increase of copper filtration was 30% for the kVp range used. However, as kVp increased, the mAs required to maintain image receptor exposure decreased due to the increased output and beam penetration.

Within the kVp range used, an average 46% decrease in entrance skin exposure was observed for each increase of 0.1 mm in copper filtration (see **Table 3**). This is because copper absorbs less of

Figure 2. *Lung contrast detail test pattern with the thickest, largest diameter disk (region of interest [ROI]₁) outlined in light blue and background (ROI₂) outlined in dark blue. Image courtesy of the authors.*

Table 1

Data Collection Conditions and Resulting ESE Per Radiograph

Radiograph	kVp	Copper filtration, mm	mAs	EI	ESE, mR
1	70	0.0	17.80	1436	124.3
2	70	0.1	21.70	1447	71.86
3	70	0.2	25.60	1454	54.54
4	70	0.3	30.30	1461	44.34
5	81	0.0	7.01	1444	63.48
6	81	0.1	8.21	1456	39.03
7	81	0.2	9.50	1438	30.99
8	81	0.3	10.90	1449	26.27
9	90	0.0	3.99	1439	43.02
10	90	0.1	4.62	1449	27.91
11	90	0.2	5.22	1469	22.61
12	90	0.3	5.90	1477	19.48
13	99	0.0	2.54	1440	33.09
14	99	0.1	2.90	1457	21.27
15	99	0.2	3.22	1469	17.49
16	99	0.3	3.60	1488	15.43
17	109	0.0	1.79	1449	25.26
18	109	0.1	1.99	1463	17.44
19	109	0.2	2.20	1477	14.87
20	109	0.3	2.42	1493	13.42
21	121	0.0	1.36	1441	21.09
22	121	0.1	1.47	1450	15.58
23	121	0.2	1.56	1451	12.08
24	121	0.3	1.68	1394	10.75

Abbreviations: EI, exposure index; ESE, entrance skin exposure; mAs, milliampere seconds; mR, milliroentgen; kVp, kilovoltage peak.

the beam at the higher energy level; therefore, mAs do not have to be increased as much to maintain image receptor exposure.

Subjective Image Data Analysis

Although results from the subjective image data analysis were not consistent among all 4 radiologists, 3 of the 4 radiologists' results showed a substantial decrease in disks resolved as kVp increased, with high correlation at all filtration thicknesses (see **Table 4**). Analyses by radiologists 1, 3, and 4 showed that the number of disks resolved was dependent on kVp, which is evident in the slopes (−1.31, −1.54, −1.24, respectively) and the correlation coefficients (−0.93, −0.96, −0.86, respectively). Results from radiologist 2 were not consistent with the results from the other 3 radiologists; results did not show that the number of disks resolved decreased as kVp increased as shown in the

Table 2

Percent Increase of mAs Required to Maintain Image Receptor Exposure as a Function of Copper Filtration

	Increase of mAs, %					
Copper filtration, mm	70 kVp	81 kVp	90 kVp	99 kVp	109 kVp	121 kVp
0.0	0	0	0	0	0	0
0.1	22	17	16	14	11	8
0.2	44	36	31	27	23	15
0.3	70	55	48	42	35	24
Average increase in mAs per 0.1 mm of copper	45	36	31	28	23	15

Table 3

Percent Decrease of ESE as a Function of Copper Filtration While Maintaining Image Receptor Exposure

	Decrease in ESE, %					
Copper filtration, mm	70 kVp	81 kVp	90 kVp	99 kVp	109 kVp	121 kVp
0.0	0	0	0	0	0	0
0.1	42	39	35	36	31	26
0.2	56	51	47	47	41	43
0.3	54	59	55	52	47	49
Average decrease in ESE per 0.1 mm of copper	54	49	46	45	40	39

Table 4

Number of Disks Resolved per Radiologist in The Lung Contrast Detail Test Pattern of the Radiographs

Radiograph	kVp	Copper filtration, mm	No. of disks resolved			
			Rad 1	Rad 2	Rad 3	Rad 4
1	70	0.00	17	12	16	20
2	70	0.10	17	15	14	21
3	70	0.20	16	11	16	20
4	70	0.30	16	11	15	20
5	81	0.00	13	11	12	22
6	81	0.10	14	10	14	19
7	81	0.20	13	12	13	19
8	81	0.30	14	9	16	19
9	90	0.00	13	12	13	18
10	90	0.10	14	12	13	20
11	90	0.20	14	12	13	17
12	90	0.30	12	10	13	18
13	99	0.00	11	12	11	17
14	99	0.10	13	12	11	16
15	99	0.20	13	9	12	19
16	99	0.30	12	9	12	20
17	109	0.00	13	8	10	18
18	109	0.10	11	13	10	14
19	109	0.20	11	12	10	15
20	109	0.30	10	14	9	15
21	121	0.00	10	14	7	14
22	121	0.10	9	12	8	14
23	121	0.20	9	11	7	15
24	121	0.30	8	13	7	14

Abbreviation: rad, radiologist.

slope being close to 0 and a correlation coefficient of 0.08. Results from all 4 radiologists indicated that the number of disks resolved were more dependent on energy level than on filtration. In all cases, the correlation of disks resolved as a function of filtration was much weaker than as a function of energy level.

The average of the slopes for the data from radiologist 1 was 1.31 fewer disks resolved for every increase of 10 kVp with a very high negative correlation ($r = -0.93$), and 0.28 fewer disks resolved for every 0.1 mm increase of copper filtration with a low negative correlation ($r = -0.39$) (see **Table 5**). The average of the slopes for the data from radiologist 2 was 0.12 more disks resolved for every increase of 10 kVp with negligible correlation ($r = 0.08$), and a decrease of 0.27 disks resolved for every 0.1 mm increase of copper filtration with a low negative correlation ($r = -0.35$). Conversely, the average of the slopes for the data from radiologist 3 was 1.54 fewer disks resolved for every increase of 10 kVp with a very high negative correlation ($r = -0.96$), and an increase of 0.17 disks resolved for every 0.1 mm increase of copper filtration with a negligible positive correlation ($r = 0.09$). The data from radiologist 4 showed 1.24 fewer disks resolved for every increase of 10 kVp with a very high negative correlation ($r = -0.87$), and a decrease of 0.13 disks resolved for every 0.1 mm increase of copper filtration with a negligible negative correlation ($r = -0.14$).

Objective Image Data Analysis

Means and standard deviations based on pixel values for ROI_1 (disk) and ROI_2 (background) were used to calculate the CNR for each radiograph (see **Table 6**). The average of the slopes from the CNR was a decrease of 0.71 per 10 kVp with a very high negative correlation (−0.93) and a decrease of 0.07 for every 0.1 mm of copper filtration with low negative correlation (−0.30). Similar to the average change in disks resolved in the results from subjective image data analysis, the CNR decreases as energy increases with high correlation at all filtration thicknesses. However, a consistent dependency between CNR and the filtration level was not evident (see **Table 7**).

Discussion

The purpose of this research was to measure the effect of kVp and copper filtration thickness on entrance skin exposure and contrast resolution for routine chest imaging performed using digital flat-panel detectors. Because contrast resolution describes how well an object can be differentiated from its

Table 5

Average Change in Number of Disks Resolved per Radiologist for Each Increase in kVp and Copper Filtration

Radiologist	10 kVp increase	*r*	0.1 mm copper filtration increase	*r*
1	−1.31	−0.93	−0.28	−0.39
2	0.12	0.08	−0.27	−0.35
3	−1.54	−0.96	0.17	0.09
4	−1.24	−0.87	−0.13	−0.14
Average	−0.99	−0.67	−0.13	−0.20

Table 6

CNR for Each Radiograph Calculated Using Means and Standard Deviations Based on Pixel Values

Radiograph	kVp	Copper filtration, mm	ESE, mR	ROI_1 M (SD)	ROI_2 M (SD)	CNR
1	70	0.00	124.30	1345 (29)	1077 (24)	7.12
2	70	0.10	71.86	1381 (28)	1114 (22)	7.50
3	70	0.20	54.54	1373 (29)	1112 (24)	6.93
4	70	0.30	44.34	1378 (30)	1114 (24)	6.87
5	81	0.00	63.48	1348 (36)	1131 (24)	5.02
6	81	0.10	39.03	1336 (30)	1125 (26)	5.32
7	81	0.20	30.99	1361 (28)	1140 (23)	6.10
8	81	0.30	26.27	1360 (32)	1146 (23)	5.43
9	90	0.00	43.02	1468 (36)	1272 (27)	4.36
10	90	0.10	27.91	1468 (30)	1261 (26)	5.21
11	90	0.20	22.61	1488 (28)	1293 (30)	4.75
12	90	0.30	19.48	1482 (32)	1290 (28)	4.52
13	99	0.00	33.09	1570 (34)	1390 (33)	3.80
14	99	0.10	21.27	1575 (32)	1395 (28)	4.23
15	99	0.20	17.49	1587 (33)	1394 (26)	4.59
16	99	0.30	15.43	1597 (36)	1426 (31)	3.60
17	109	0.00	25.26	1663 (32)	1478 (29)	4.28
18	109	0.10	17.44	1671 (35)	1495 (31)	3.76
19	109	0.20	14.87	1675 (37)	1506 (34)	3.36
20	109	0.30	13.42	1665 (32)	1500 (34)	3.53
21	121	0.00	21.09	1745 (33)	1581 (34)	3.46
22	121	0.10	15.58	1749 (34)	1580 (33)	3.57
23	121	0.20	12.08	1756 (36)	1593 (34)	3.29
24	121	0.30	10.75	1730 (32)	1601 (32)	2.85

Abbreviations: CNR, contrast:noise ratio; ROI, region of interest.

background,[3] the more disks the radiologists can resolve, the higher the contrast resolution. When a disk lacks brightness (low signal) due to low attenuation or when the variation in the gray levels of the background due to noise is greater than the disk brightness, the disk cannot be resolved against the background, resulting in low CNR.

Subjective Image Data Analysis

Subjective image data analysis shows substantial agreement of 3 of the 4 radiologists regarding the change in disks resolved as a function of kVp. Results from 3 of the 4 radiologists—all except radiologist 2—showed a very high correlation between disks resolved and kVp, and a similar decrease in disks resolved for a 10 kVp increase in energy. A possible cause for this discrepancy could be that radiologist 2 did not spend as much time scoring the 24 radiographs (15 min) as radiologist 1 (45 min), radiologist 3 (20 min), and radiologist 4 (20 min). In addition, the subjective nature of image analysis might have affected the results. Variation in ambient lighting, monitor quality, the human factor of interpreting instructions and making judgments, and visual acuity are factors that could have caused the discrepancy in the results.

Despite this discrepancy, based on the results from the subjective image data analysis, a 10 kVp increase in kVp

Table 7

Change in CNR as a Function of Increases in Copper Filtration and kVp

Copper filtration, mm	70 kVp	81 kVp	90 kVp	99 kVp	109 kVp	121 kVp	10 × slope[a]	*r*
0	7.12	5.02	4.36	3.80	4.28	3.46	−0.60	−0.86
0.1	7.50	5.32	5.21	4.23	3.76	3.57	−0.72	−0.93
0.2	6.93	6.10	4.75	4.59	3.36	3.29	−0.76	−0.97
0.3	6.87	5.43	4.52	3.60	3.53	2.85	−0.76	−0.96
Slope/10[b]	−0.13	0.20	0.00	−0.02	−0.27	−0.21		
r	−0.60	0.57	0.01	−0.07	−0.85	−0.86		

[a] *Represents the change in CNR per 10 kVp increase.*
[b] *Represents the change in CNR per 0.1 mm increase of copper filtration.*

decreases contrast much more than does a 0.1 mm increase in copper filtration. Increasing the kVp by 10 kVp reduces the number of disks resolved almost 8 times more (−0.99/−0.13 = 7.6) than a 0.1 mm increase in copper filtration (see Table 5). Therefore, adding 0.1 mm of copper filtration would result in an equivalent reduction of number of disks resolved as decreasing kVp by 1.3 kVp (10 kVp/7.6 = 1.3).

Increasing copper filtration thickness is more effective at reducing patient dose than is increasing kVp. The addition of 0.1 mm of copper filtration allows for an average 46% decrease in entrance skin exposure, whereas a 15% increase in kVp with a 50% reduction in mAs decreases entrance skin exposure by 33%. Therefore, the dose reduction that occurs by increasing kVp by 1.3 is not substantial compared with the dose reduction that occurs when an additional 0.1 mm of copper filtration is used, although the 2 conditions produce similar image quality in terms of contrast resolution as indicated by the subjective image data analysis.

Furthermore, when copper filtration thickness is increased, no adjustments need to be made when automatic exposure control is used. However, when mAs level is selected manually (eg, mobile examinations), mAs levels will need to be increased to maintain the image receptor exposure when copper filtration is increased.

Objective Image Data Analysis

Objective image data analysis results are consistent with the subjective image data analysis results in terms of the relationship between CNR and kVp. However, objective image data analysis shows that increasing the kVp by 10 kVp reduces the CNR more than that shown in the subjective image data analysis. Increasing the kVp by 10 kVp reduces the CNR approximately 10 times more (−0.71/−0.07 = 10.1) than a 0.1 mm increase in copper filtration; subjective image data analysis indicated that CNR decreases 7.6 times more. Similarly, objective image data analysis shows that adding 0.1 mm of copper filtration has an equivalent effect on the number of disks resolved as increasing the kVp by 1 kVp (10 kVp/10); subjective image data analysis indicated this same effect occurs when kVp is increased by 1.3 kVp. Furthermore, when the authors plot CNR as a function of entrance skin exposure, the CNR decreases as kVp increases (see **Figure 3**). The authors' ALARA-compliant technique selection graph can be used to select the thickness of copper filtration needed for a desired CNR.

Summary of Analyses and Future Recommendations

The results from subjective and objective image data analyses are consistent with previous research focusing on chest imaging using digital flat-panel detectors, which found that images obtained using lower kVp with copper filtration had superior image quality compared with those obtained using high kVp without copper filtration at the same patient dose.[19] Another study found that patient dose can be reduced with copper filtration without compromising image

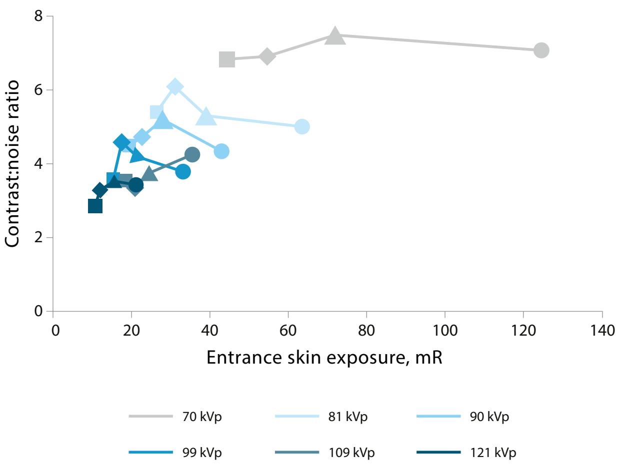

Figure 3. *Technique selection graph for contrast:noise ratio (CNR) and compliance with the ALARA (as low as reasonably achievable) principle. For each kilovoltage peak (kVp) level, the 4 copper filtration thicknesses are read from the left (0.3 mm of copper filtration with the lowest entrance skin exposure [square]) to the right (0 mm of copper filtration with the highest entrance skin exposure [circle]). This graph is valuable to clinical practice as it allows the user to choose technical factors based on desired CNR. For example, if a CNR greater than 6 is desired, then 81 kVp with 0.3 mm of copper filtration would be selected as a technique compliant with the ALARA principle. If a CNR greater than 4.5 is desired, then 99 kVp with 0.2 mm of copper filtration would be recommended. Figure courtesy of the authors.*

quality for the anterior and posterior projections of the abdomen, knee, and lumbar spine, and the lateral lumbar spine projections.[24] Therefore, this study validates previous research that concludes that copper filtration should be considered as a dose and image quality optimization strategy in digital radiography departments[19,24] and is consistent with the 1996 European Commission recommendations outlined in European Guidelines on Quality Criteria for Diagnostic Radiographic Images in Paediatrics to use copper filtration for pediatric chest imaging.[26]

Future investigation opportunities include repeating the experiment with different starting half-value layer levels than 2.75 mm of aluminum, analyzing the heart and abdomen regions of the chest phantom subjectively and objectively, and repeating the measurements without a grid and analyzing images processed with and without the application of scatter removal algorithms (ie, virtual grid software). A similar experiment could be performed with a focus on abdominal techniques, rather than chest, using a phantom that simulates an abdomen and contains test regions that can be used for contrast resolution measurements.

Limitations

Relying on subjective evaluation of image quality can be considered a weakness. To improve reliability, the subjective evaluation should collect data from more radiologists and radiologist assistants. In addition, the sequence of the images should be randomized. The data set for this study presented images in sequence starting with the lowest kVp level and no copper filtration, continuing with increasing kVp levels and thicknesses of copper filtration. This might have biased the radiologists' scoring of the image data because they reviewed the images with a higher quality first. Also, the use of a single digital radiography system for image acquisition might be considered a limitation. Future studies can replicate this experiment using digital systems produced by different vendors that use different image processing algorithms. The use of phantoms instead of real patients also can be considered a limitation because there is variation among patients who might have disease present, which cannot be replicated with phantoms.[17] Therefore, future studies could collect data retrospectively from patient or animal tissue examinations.

Conclusion

Subjective and objective image data analyses show a decrease in contrast resolution when increasing kVp and indicate that contrast resolution has a very strong correlation with kVp. A much smaller decrease in contrast resolution is demonstrated for a 0.1 mm increase in copper filtration as compared with an increase in 10 kVp. This study found that increasing the thickness of copper filtration should be considered as a dose reduction and image quality optimization strategy for routine chest imaging using digital flat-panel detectors.

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