Are physical measures good indicators of image quality at low dose levels? A pilot study

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Abstract

Purpose: To evaluate if physical measures of noise predict image quality at high and low noise levels.

Method: Twenty-four images were acquired on a DR system using a Pehamed DIGRAD phantom at three kVp settings (60, 70 and 81) across a range of mAs values. The image acquisition setup consisted of 14 cm of PMMA slabs with the phantom placed in the middle at 120 cm SID. Signal-to-noise ratio (SNR) and Contrast-to-noise ratio (CNR) were calculated for each of the images using ImageJ software and 14 observers performed image scoring. Images were scored according to the observer`s evaluation of objects visualized within the phantom.

Results: The R^2 values of the non-linear relationship between objective visibility score and CNR (60kVp $R^2 = 0.902$; 70Kvp $R^2 = 0.913$; 80kVp $R^2 = 0.757$) demonstrate a better fit for all 3 kVp settings than the linear R^2 values. As CNR increases for all kVp settings the Object Visibility also increases. The largest increase for SNR at low exposure values (up to 2 mGy) is observed at 60kVp, when compared with 70 or 81kVp.CNR response to exposure is similar. Pearson *r* was calculated to assess the correlation between Score, OV, SNR and CNR. None of the correlations reached a level of statistical significance ($p>0.01$).

Conclusion: For object visibility and SNR, tube potential variations may play a role in object visibility. Higher energy X-ray beam settings give lower SNR but higher object visibility. Object visibility and CNR at all three tube potentials are similar, resulting in a strong positive relationship between CNR and object visibility score. At low doses the impact of radiographic noise does not have a strong influence on object visibility scores because in noisy images objects could still be identified.

Introduction

Medical radiation exposure is increasing worldwide. From 1993 to 2008 the annual effective dose per capita more than doubled from 3.0mSv to 6.2mSv respectively for diagnostic medical radiological examinations(1). Low radiation exposure can cause stochastic effects which occur by chance and are primarily related to cancer and genetic mutations(2). It is important to minimise unnecessary patient exposure and to ensure radiation doses delivered are as low as reasonably achievable (ALARA) whilst maintaining an image quality suitable for diagnostic purposes(3).

Quantum noise has an impact on physical and quality measures of X-ray image. This type of noise is a variation in the image signal due to the random Poisson distribution of photons(4). This means that quantum noise is inversely proportional to the exposure dose(3) and can be measured by using the standard deviation of the signal variations in a radiograph(5). Quantum noise influences contrast, resolution and consequently, the representation of an object in the image (e.g. an anatomical body part). For visual perception however, the observer may still be able to the see the image detail despite the noise presented in the radiographic image.

Visual evaluation and measures of radiographic noise can appear to be different from the physical measures(3). For dose reduction, it is important to know if the physical measures and visual image quality relate. If there is no noticeable effect on the visual image quality with a low dose but there is a mathematical impact, then the overall dose may be reduced without compromising the diagnosticimage quality.

In a clinical setting, the observer evaluates the image quality and determines whether it is suitable for diagnosis. According to some literature(3,6) low dose and low image quality can be used for a certain type of examinations: for example to determine the shape and size of the heart, measuring the angles of thoracic scoliosis, locating the presence of metallic foreign body in oesophagus, internal fixation of clavicle fracture, monitoring metal implantation for osteosynthesis, pacemaker implantation and metal valve replacement, and to some extent for reviewing pneumonia and tuberculosis, and follow-up atelectasis. A research question arises from this background literature – 'what impact does radiographic noise have on physical measures and observermeasures of 2D x-ray image quality'?

This pilot study aims to establish whether physical measures of noise predict image quality at high and low noise levels. The specific objectives are to measure image noise using physical indicators such as Signal-to-Noise Ratio (SNR) and Contrast-to-Noise Ratio (CNR) and to compare with visual perception measures. In addition, dose reduction was investigated and the impact it has on physical measures of image quality without compromising image quality.

The operational hypothesis for this pilot study was that physical measures of image quality do not inversely correlate with measures of image quality at high noise levels for radiological decisions that are not noise limited (such as those cited in refs 3 & 6)

Methods

Study design

An experimental pilot study was undertaken to determine whether physical measures such as SNR and CNR can predict visual measures of image quality. Visual measures are represented by the image scoring of a test set of images with 14 observers using a mixture of subjective and objective questions.

Twenty-four digital radiographic images were acquired in Martini Hospital, Groningen (NL). SNR and CNR were calculated in ImageJ software (National Institute of Health, Bethesda, MD). The image-scoring test was runon a clinical quality controlled monitor.

Materials, equipment and image acquisition

All the images were acquired using standard Digital Radiography (DR) equipment (Phillips, Digital Diagnostic NZR 83).

A Pehamed DIGRAD phantom was used as the imaged object for both physical measurements (SNR and CNR) and image quality evaluation. This phantom consists of a 7 copper step wedge, 6 low contrast circles (15 mm diameter) for low contrast resolution and resolution line pattern angled at 45° to determine spatial resolution up to 5 LP/mm.

The set up for image acquisition consisted of adding 14cm of PMMA and placing the phantom in the middle of the PMMA slabs (figure 1). The source to image detector distance (SID) was 120 cm and all images were acquired using the same CsI+TFT detector (43cm × 43cm; 3.5lp/mm, 143 μm pixel size) and an anti-scatter grid with 36 lines/cm.The X-ray beam was collimated 32 cm × 33 cm.

The 24 digital X-ray images were obtained with kVp values (60, 70 and 81) and a range of mAs in each kVp setting. The corresponding exposure (mGy) delivered

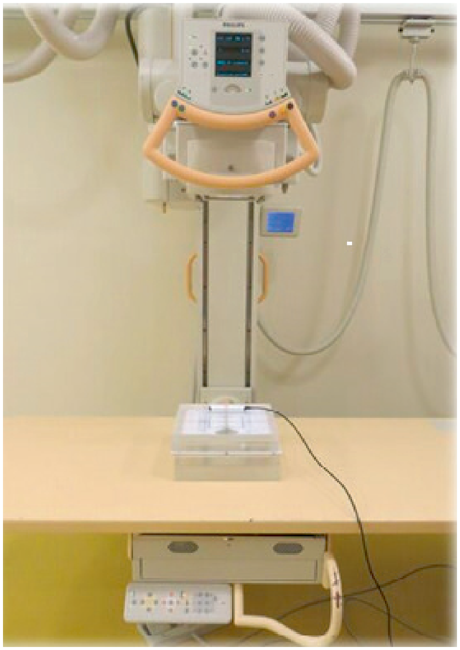


Figure 1 The setup for the X-ray equipment, phantom and the PMMA build up

60 kVp		70 kVp		81 kVp	
mAs	Exposure (mGy)	mAs	Exposure (mGy)	mAs	Exposure (mGy)
159.9	5.0	124.9	6.9	124.8	9.3
99.9	3.2	79.9	4.4	79.9	5.9
62.9	2.0	49.9	2.8	49.8	3.7
31.4	1.3	31.4	1.7	31.3	2.3
19.9	0.8	24.9	1.4	19.8	1.5
12.4	0.5	15.9	0.9	12.3	0.9
7.9	0.3	12.4	0.7	6.1	0.5
6.2	0.2	6.2	0.3	2.9	0.2

Table 1 Overview of the kVp, mAssettings and correspondent exposure (mGy) delivered to the detector

to the detector was measured using a calibrated Unfors™ Xi Prestige Platinum dosimeter. As expected the dose delivered to the detector decreased as the mAs decreased at each kVp setting (table 1).

Physical measures

The acquired images were first analysed by measuring the mean and the standard deviation (sd) pixel values of twofixed regions of interest (ROI's) to calculate SNR usingImageJ (figure 2 and equation 1a).CNR was also calculated usingtwo ROIs (Figure 3and equation1b).

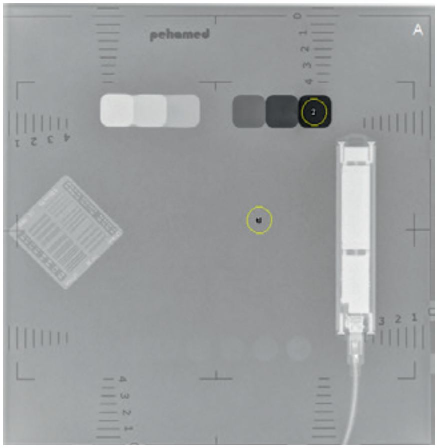
Similar studies have been done with these analytic tools (7,8).The equations *1a* and *1b*for calculating SNR and CNR are based on work by Bourne (4).

Observers and image scoring

Fourteen observers (10 female; 4 male) volunteered for the image-scoring test (mean age = 32; range, 20 – 57). All participants had normal or corrected-to-normal vision (9 corrected, 5 uncorrected) and were asked whether or not they had been to an optician in the last 12 months (11 had been to the optician, 3 had not). Observers were final year radiography students with clinical experience and qualified radiographers all of whom were participating in a European Dose Optimisation Summer School.

Figure 2 SNR region of interest

Figure 3 CNR region of interest



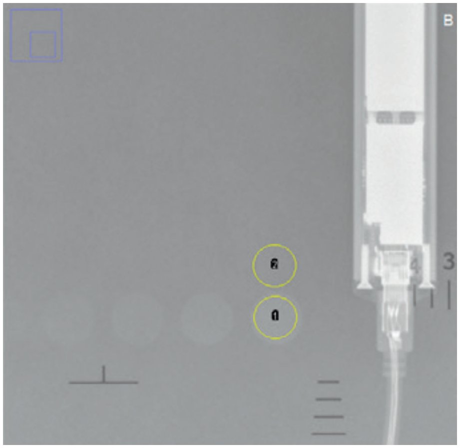


Figure 2 The homogenous area (1) of the phantom was used for the mean intensity and the air filled square (2) was used for the standard deviation of the background.
Figure 3 The area inside (1) the low contrast circle provided the mean intensity aand the homogenous background (2) provided the mean intensity b and the standard deviation b.

Equation 1a) μ_a is the mean intensity of the area of interest,$\sigma_b$is the standard deviation of the air filled area of the phantom. One standard deviation for 'correction factor' has been added. *Equation 1b)* μ_a is the mean intensity of one low contrast circle, μ_b is the mean intensity of the homogenous background and $\mu_b$is the standard deviation of the homogenous background.

$$= 0.66x = \mu \quad \textit{(eq.1a)}$$

$$= |\mu - \mu| \quad \textit{(eq.1a)}$$

Prior to the image scoring the observers were given full instructions and subjected to a short training session, which included examples of noise levels and images of objects to be evaluated. The observers were provided with definitions for each image quality criterion. The images were displayed in a semi-randomized order and evaluated by using an absolute scale (1 Low – 6 High). All of the images were scored according to the observer's evaluation concerning the objects visualized within the phantom. The observers were asked six questions, of which two were 'counting objects' – Objective Visibility (OV) scores - and the other 4 pertained the perception of image quality (table 2).

Question to observer	Possible answers
How sharp are the edges of the third square from the right?	On a scale from 1 – 6 (Low – High)
How many Line Pairs per millimeter do you see?	1: (0.8-0.9) lp/mm 2: (1.0-1.2) lp/mm 3: (1.4-1.6) lp/mm 4: (1.8-2.5) lp/mm 5: (2.8-3.7) lp/mm
How is the resolution of Line Pairs per millimetre?	On a scale from 1 – 6 (Low – High)
How many circles do you see?	0 – 8 circles visible
How great is the contrast between the third circle from the top and the background?	On a scale from 1 – 6 (Low – High)
Rate the quality of the image (globally)?	On a scale from 1 – 6 (Low – High)

Table 2 Complete questionnaire for image quality scoring.
For the second question the observers counted complete groups of Line Pairs (lp/mm).

The image analysis and the scoring of the images were undertaken on an EIZO Radiforce MX242W 2.3 Megapixel 24.1“LCD.

Statistical analysis

SPSS software (IBM Corp., 2011) was used to obtain descriptive and linear regression statistics.The assumptions for linear regression were not fulfilled so curve fitting was utilized to explore the trend (SNR – OV, CNR – OV) at the different kVp levels. R^2 was calculated with a linear and non-linear equation.

After the initial exploration of the relationship between SNR/CNR and exposure, correlation (Pearson *r*) analysis was done to explore the relationship between the physical and image qualitymeasures (individual scores for perception of image noise) for exposure doses ≤2 mGy (SNR – OV, CNR – OV, SNR – Score, CNR – Score).

Results

SNR

Figure 4and 5show the relationship between OV score and SNR.

Figure 4 demonstrates that at 60 kVp curve fitting for the SNR and objective visibility score has a linear R^2 value of 0.772, however the quadratic R^2 value is 0.878 (Fig 5). Both Figure 4 and 5 purposefully force the curve through the origin as zero (0) represents the absence of any visible object. At 70 kVp curve fitting for the SNR and objective visibility score has a linear R^2 value of 0.848, the quadratic R^2 value is 0.901. Finally, for the 81 kVp setting curve fitting for the SNR and objective visibility score has a linear R^2 value of 0.890, the quadratic R^2 value is 0.891.

The difference between the linear and quadratic R^2 values for 60kVp is +0.106, 70kVp is +0.053 and 81kvp is +0.001. This shows that at higher SNR values, the non-linear relationship with visual detection appears to be most fitting curve for the SNR values.

CNR

Figure 6 and 7 show the relationship between objective visibility score and CNR.

In the non-linear graph (Fig.6) the R^2 values (60kVp R^2 = 0.902; 70Kvp R^2 = 0.913; 80kVp R^2 = 0.757) demonstrate a better fit for all 3 kVp settings than the linear R^2 values (Fig.7).

As CNR increases for all kVp settings the Object Visibility also increases. However, there seems to be a point of saturation (CNR=2.8) for 81kVp.

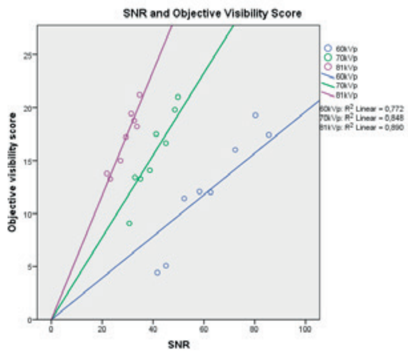


Figure 4 SNR and Objective Visibility Score (linear)

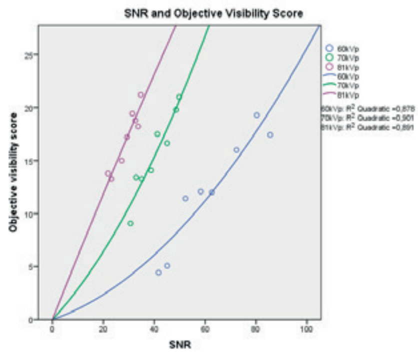
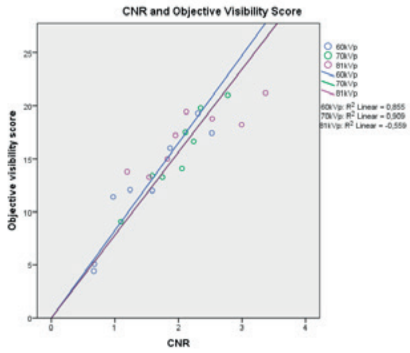


Figure 5 SNR and Objective Visibility Score (non-linear)



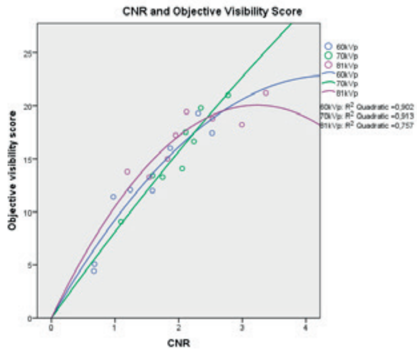
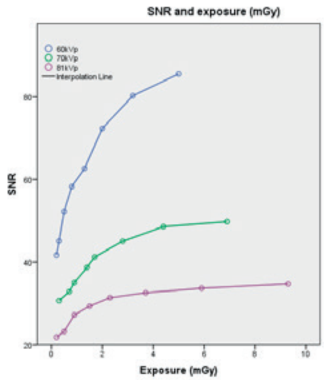


Figure 6 CNR and Objective Visibility Score (linear)

Figure 7 CNR and Objective Visibility Score (non-linear)



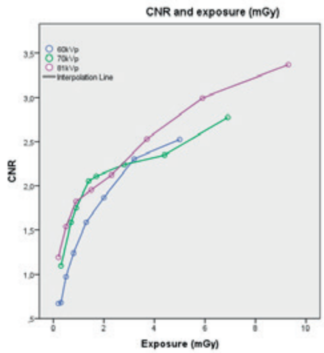


Figure 8 SNR and exposure (mGy)

Figure 9 CNR and exposure (mGy)

Exposure

It is shown in figures 8 and 9 that as the exposure increases the SNR and CNR increase, as expected.

SNR measures the potential information content of the image data related to the detector exposure. The largest increase for SNR at lower exposure values (up to 2 mGy) is observed at 60kVp when compared with 70 or 81kVp (Fig. 8). At 81kVp the SNR is relatively stable from 2mGy up to 9.3mGy (Fig. 8), showing no benefit when increasing the dose to the detector.

For all 3 kVp settings, CNR response to exposure is similar, with CNR variation is 1.87-2.11, for low exposures ranging between 1.5 - 2mGy (Fig.9). Although the CNR increases with dose, the contrast provided by the detector is very similar in terms of CNR among the three kVp settings. This may indicate thehuman visual perception of an object in the radiograph could not depend only on the CNR but on other factors (e.g. the size and shape of a structure). At low exposure (<2mGy) the detector is providing a CNR at the three kVp settings where the observers can see the objects. A correlation analysis between object visibility (OV), the image quality score given by the observers, SNR and CNR is given below.

Correlation analysis for low dose exposure (<2mGy)

Table 3 presents the descriptive statistics at low dose exposure (<2mGy): minimum and maximum values, mean and standard deviation for all 4 variables.

Analysis for Pearson *r* was calculated to assess the relationship between Score, SNR and CNR (table 4). For 60 kVp the correlation between Score, SNR and CNR suggest a nonlinear relationship (r = .009, r = .069). At the 70 kVp level the correlation between the 3 variables suggest a strong linear relationship (r = .782 r = .718). However, the p-values for the 70 kVp level did not reach the set level of significance ($p>0.01$). At the 81 kVp level the Score and SNR have a strong relationship

Table 3 Descriptive statistics with Object Visibility, image qualityscore, SNR and CNR at low dose exposure (<2mGy)

kVp	Measure	Minimum	Maximum	Mean	sd
60	OV	0	20	10.17	5.015
	Image quality score	1	5	2.61	1.059
	SNR	41.69	72.33	55.38	11.41
	CNR	0.69	1.86	1.17	0.49
70	OV	4	24	13.47	4.442
	Image quality score	1	6	3.25	0.881
	SNR	30.67	41.23	35.71	4.3
	CNR	1.09	2.10	1.71	0.41
81	OV	4	24	14.82	4.099
	Image quality score	1	6	3.83	0.974
	SNR	21.84	29.32	25.39	3.47
	CNR	1.19	1.95	1.62	0.33

Table 4 Correlation for image quality score, SNR and CNR. Pearson r and p-value reportedat low dose exposure (<2mGy)

		60 kVp		70 kVp		81 kVp	
		SNR	CNR	SNR	CNR	SNR	CNR
Image quality score	Pearson *r*	.009	.069	.782	.718	.720	.503
	p-value	.987	.896	.118	.172	.280	.497

Table 5 Correlation for Object Visibility, SNR and CNR. Pearson r and p-value reportedat low dose exposure (<2mGy)

		60 kVp		70 kVp		81 kVp	
		SNR	CNR	SNR	CNR	SNR	CNR
Object Visibility	Pearson *r*	.559	.538	.372	.179	-.046	.151
	p-value	.249	.271	.538	.774	.954	.849

(r = .720), but score and CNR have moderate correlation (r = .503). The p-values for the 81 kVp level did not reach the set level of significance (p>0.01).

Analysis for Pearson r was calculated to assess the relationship between OV, SNR and CNR (table 5). For 60 kVp the correlation between OV, SNR and CNR shows a moderate relationship (r = .559, r = .538). At the 70 kVp level the correlation between the 3 variables suggest a weak linear relationship between the variables (r = .372,r = .179). At the 81 kVp level the Score and SNR suggest a nonlinear relationship (r = .720), but score and CNR show a weak correlation (r = .503).

Discussion

In this study an attempt was made to produce test object images under different exposure conditions and measure SNR and CNR of those images and compare the results with observer scores from the same test object images. SNR and CNR were measured from all the 24 images and special attention was given to low dose exposure images (<2mGy).

A common way to quantify the level of noise in an image is to estimate the SNR(4). At low SNR values an increase in SNR will not affect detection as much as at higher SNR values. The results from our study suggest a non-linear relationship exists between SNR and Objective Visibility Score. It is possible that at low SNR values, SNR may not accurately predict visual image quality, because visibility depends on contrast (the difference between signals) (4).

In this study, as the CNR value increases the object visibility also increases for all 3 kVp settings. However, figure 6 shows that object visibility does not differ between all three tube potentials. The non-linear relationship for 81 kVp between object visibility and CNR reaches a point of saturation; this may indicate that beyond a certain point an increase in CNR does not improve object visibility further. Contrast constancy, is found when observers adjust the physical contrast of different frequency ratings in order to achieve the perception of an equal apparent contrast(9). Threshold sensitivity is assumed to be a function of the signal to noise ratio, whereas perceived contrast is assumed to be a function of the signal alone and to be independent of the noise (10). In observer studies, the fall-off in threshold sensitivity to spatial contrast at high frequencies has been attributed both to optical and neural factors of contrast attenuation.

It appears that at 81 kVp the CNR continues to increase with no further increase in objective visibility score (Fig. 7), so it may be true that its unnecessary to increase the contrast in an image to see a the object more clearly. Radiologic assessment of spine scoliosis in paediatric patients is an example of a procedure which does not require high contrast to be clinically valid (3). However, further work is required to explore this finding.

As expected, increasing exposure increases both SNR and CNR (Fig. 8 and 9) in a broad range of exposures up to approximately 10mGy. However, analysing the data at low exposures up to 2mGy special attention should be given to evaluate objective visibility and image quality score.

For low dose exposures (≤ 2 mGy) there is a decrease in SNR from 60 kVp (55.38) to 81 kVp (25.39), confirming the findings from other authors (11), and giving a normal response from the detector to the absorbed dose: at lower kVp and the same dose, SNR is higher, although it could not affect image visibility as the ability to see objects in an image depends on contrast. The mean values for image quality score and Object visibility increase from 60 kVp to 81 kVp (table 3). This implies that the observers are able to see more objects and evaluate the image quality on higher kVp levels. Even though the exposure doses at 70 and 81 kVp are comparable with 60 kVp. This might be because a higher tube potential results in higher energy photons that are more able to penetrate the phantom and reach the detector than lower energetic photons.

The correlation for all three kVp settings at low dose exposure (table 5 and 6) varied between nonlinear to strong linear relationship. However none of the correlations reached the set level of statistical significance (p>0.01). Because the values were not significant, these findings should be interpreted with caution. However, practical implication could be important on the choice of the tube potential regarding the anatomical region of a radiological study, suggesting that at low exposure levels, objects are detected by the observers with no significant differences.

The correlations and the descriptive statistics suggest that object visibility and subjective evaluation measures may not be related to SNR and CNR at low dose levels. Although the higher correlation values at 70 kVp between Score, SNR and CNR ($r = .782$ $r = .718$) cannot be ignored.

The results for 60 kVp (Score – SNR, Score - CNR) presented in table 5 show a non-linear correlation between physical and visual image quality measures. This might be explained by a low agreement among the observers when evaluating low dose noisy images. Tube potential setting for 60 kVp produces a low energy X-ray beam when compared with 70 and 80 kVp. This would cause different pixel intensity values at the DR detector providing lower intensity values thus more noisy images.

For object visibility the observers might not be affected by variation in image noise level. This means that the observers are still able to differentiate between objects and the noisy image background. However when observers score the image quality at 70 and 81 kVp, SNR and CNR have strong correlation although a non-statistical significant relationship. The score for low dose images at 60 kVp do not correlate with SNR and CNR. One explanation could be related to the lower tube potential at 60 kVp, which results in a lower energetic X-ray beam reaching the digital detector and thus producing noisy images.

For the objective visibility score against SNR (Fig. 4 and 5) and CNR (Fig. 6 and 7) it was also found that the R^2 value for the fitted curve which was forced through the origin. This was decided as when the SNR is 0 the objective visibility score cannot theoretically be different than zero. However, it would be better to have more data of the lower SNR and CNR values for a more reliable extrapolation. A larger amount of data would open more possibilities in terms of statistical tests. This pilot study utilized analyses which should be considered exploratory.

A questionnaire was used to collect information about the eyesight of the observers but further research might involve an eyesight test performed before the start of the data collection to increase the reliability/ validity of the research.

The observers were able to score 24 images in this research. By conducting further research more data can be collected by increasing the number of observers and the number of images displayed. As well as using observers with for example more than 5 years of experience in image interpretation.

The relationship between physical measures and visual image quality at low exposure levels may be determined. To get more reliable correlations between SNR, CNR and objective visibility scores, more images should be analysed for each kVp setting, with the possibility of using other kVp settings in addition.

Conclusion

For object visibility and SNR, tube potential variations may play a role in object visibility. Higher energetic X-ray beam settings give lower SNR but higher object visibility. Object visibility and CNR at all three tube potentials are similar, resulting in a strong positive relationship between CNR and object visibility score.

At low doses the impact of radiographic noise does not have a strong influence on object visibility scores because in noisy images objects could still be visible and suitable for image interpretation.

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References

1. UNSCEAR. Annex A: Medical Radiation Exposures. Sources and Effects of Ionizing Radiation Volume I. 2010. 1-220 p.
2. ICRP. Annals of the ICRP Annals of the ICRP. Ann ICRP. 2007;2007.
3. Uffmann M, Schaefer-Prokop C. Digital radiography: The balance between image quality and required radiation dose. Eur J Radiol. 2009;72(2):202–8.
4. Bourne R. Fundamentals of Digital Imaging in Medicine. Springer; 2010. 200 p.
5. Lanca L, Silva A. Image quality in Diagnostic Radiology. In: Digital Imaging Systems for Plain Radiography. New York: Springer; 2013. p. 63–77.
6. Zhang M, Zhao B, Wang Y, Chen W, Hou L. Dose Optimization for Different Medical Imaging Tasks From Exposure Index, Exposure Control Factor, and mAs in Digital Radiography. Health Phys. 2012;103(3):235–40.
7. Mraity H, England a., Akhtar I, Aslam a., De Lange R, Momoniat H, et al. Development and validation of a psychometric scale for assessing PA chest image quality: A pilot study. Radiography [Internet]. Elsevier Ltd; 2014;20(4):312–7. Available from: *http://dx.doi.org/10.1016/j.radi.2014.03.007*
8. Yuan L, Hui L, III JTD, McAdams HP, Wang X, Sehnert WJ, et al. An image-based technique to assess the perceptual quality of clinical chest radiographs. Med Phys. 2012;39:7019–31.
9. Committee on Vision; Commission on Behavioral and Social Sciences and Education; Division of Behavioral and Social Sciences and Education; National Research Council. Emergent Techniques for Assessment of Visual Performance. Washington, D.C.: National Academies Press; 1985. doi:10.17226/916
10. Brady N, Field DJ. What's constant in contrast constancy? The effects of scaling on the perceived contrast of bandpass patterns. Vision Research.1995;35(6), 739–756. doi:10.1016/0042-6989(94)00172-I
11. Schaefer-Prokop C. Digital chest radiography : an update on modern technology, dose containment and control of image quality. Eur J Radiol. 2008;18:1818–30.