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FULL PAPER

Neonatal digital chest radiography– should we be using additional copper filtration?

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Objectives: Copper filtration removes lower energy X-ray photons, which do not enhance image quality but would otherwise contribute to patient radiation dose. This study explores the use of additional copper filtration for neonatal mobile chest imaging.
Methods: A controlled factorial-designed experiment was used to determine the effect of independent variables on image quality and radiation dose. These variables included: copper filtration (0 Cu, 0.1 Cu and 0.2 Cu), exposure factors, source-to-image distance and image receptor position (direct / tray). Image quality was evaluated using absolute visual grading analysis (VGA) and contrast-to-noise ratio (CNR) and entrance surface dose (ESD) was derived using an ionising chamber within the central X-ray beam.
Results: VGA, CNR and ESD significantly reduced (p < 0.01) when using added copper filtration. For 0.1 Cu, the percentage reduction was much greater for ESD (60%) than for VGA (14%) and CNR (20%), respectively. When compared to the optimal combinations of parameters for incubator imaging using no copper filtration, an increase in kV and mAs when using 0.1-mm Cu resulted in better image quality at the same radiation dose (direct) or, equal image quality at reduced dose (in-tray). The use of 0.1-mm Cu for neonatal chest imaging with a corresponding increase in kV and mAs is therefore recommended.
Conclusion: Using additional copper filtration significantly reduces radiation dose (at increased mAs) without a detrimental effect on image quality.
Advances in knowledge: This is the first study, using an anthropomorphic phantom, to explore the use of additional Cu for digital radiography neonatal chest imaging and therefore helps inform practice to standardise and optimise this imaging examination.

INTRODUCTION

Neonates, especially those born prematurely, often suffer from respiratory and cardiovascular complications and may require prolonged hospitalisation and periods of intensive care.[1] During this period, repeated chest radiographs are often requested to assess the progress of disease, tube and line placement, and acute complications of ventilation and/or prematurity. Chest radiography comes with radiation dose implications, and therefore, it is important to ensure examinations are optimised according to the as low as reasonably practicable principle. One simple method that can reduce radiation dose without compromising image quality, is the use of additional filtration.[2] Copper, aluminium or both materials combined are the commonest filters used in radiography. Copper will absorb a higher proportion of the lower energy photons than aluminium, which contribute significantly to entrance surface dose (ESD).[2] Theoretically, adding additional filtration, such as copper, can further remove lower energy X-ray photons which do not enhance image quality but would otherwise contribute to patient radiation dose.[3]

Studies have shown the dose saving benefits of additional copper filtration for adult chest radiography[4] and paediatric radiographs of the chest, pelvis and extremities.[3,5,6] To the authors' knowledge, no studies have explored the use of additional copper filtration in mobile neonatal digital radiography (DR). Schäfer et al[7] explored additional copper filtration for neonatal imaging using a fixed in-direct DR system with no incubator, making it difficult to transfer such findings into routine clinical practice. The incubator causes additional radiographic considerations

(*e.g.* additional beam attenuation) and the conversion of X-ray photons for direct digital systems is different. In addition, this study by Schäfer et al[7] advocates a lower kV to reduce neonatal radiation dose and has not explored the use of lower mAs values, such as 0.5, as advocated by numerous studies.[8,9] Another study by Smans[10] on neonatal chest imaging used Monte Carlo simulations to evaluate computed radiography (CR) with combined copper and aluminium filtration. No visual image quality evaluation was undertaken, and a consistent image receptor dose was achieved across all exposures. This approach, of using consistent image receptor dose, was also used in the studies of Butler and Brennan,[3] Jones et al,[5] Brosi et al[6]; these studies either did not explore the potential for further dose reduction using fixed mAs or they did not disclose the mAs values used. As a consequence, the results are difficult to translate into clinical practice. Also, DR systems do not necessarily require a constant detector dose due to their high dynamic range and post-processing capabilities.[11] Another study, by Hinojos-Armendriz[12] explored 2 mm of additional aluminium for CR mobile neonatal imaging, however they failed to control patient size nor consider whether an image receptor tray was used, rendering comparisons between filtration settings potentially unreliable.

Several recent studies[1,8,9] have also shown considerable variation in neonatal imaging protocols. They have further highlighted the need for standardisation and optimisation, especially when using DR systems. Gunn and colleagues[8] found that none of the four hospitals within their study used additional filtration for neonatal chest imaging with Al-Murshedi and collagues[1] also demonstrating that only two out of the eight hospitals within their study used additional filtration. These protocol variations, and the consequential variability in image quality and patient radiation dose, are concerning. Especially, since neonates are more sensitive to the effects of radiation owing to their developing organs and their rapid cell reproduction. A neonate's life expectancy is also theoretically longer allowing more time for the harmful effects of radiation to manifest.[13] It is essential to fully optimise imaging protocols and techniques for this cohort of patients. This project will explore the use of additional copper filtration in neonatal mobile DR chest imaging, with a view to contributing to the development of an evidence-based optimised imaging protocol.

METHODS AND MATERIALS

Imaging equipment and technique

Quality assurance testing was conducted prior to commencing the study in accordance with the Institute of Physics and Engineering in Medicine (IPEM) Report 91.[14] The results of the quality assurance testing were within accepted limits.

Images were acquired using a Samsung GM85 mobile with a 25 × 30 cm wireless, lightweight S-Detector™ (MIS Healthcare, London, UK). To allow for multiple exposures under controlled conditions, the commercially available Gammex 16 neonatal anthropomorphic phantom (Rothband LTD, Haslingden, UK) was used to simulate a 1–2 kg neonate, replicating both the anatomic structures (heart, bone and lung) and the tissue attenuation characteristics of a real neonate. Images were acquired on a GE Giraffe Omnibed incubator, which is commonly used within many neonatal units.[9]

Table 1. Summary of the incremental changes to acquisition factors modified within the study

Variable	Variations	n
Incubator tray	Direct *vs* In-tray	2
Tube potential, kV	60 or 65	2
Tube current-time product, mAs	0.5, 1.0 or 1.5	3
SID, cm	100 or maximum (117 direct / 126 in-tray)	2
Additional copper filtration, mm	No, 0.1 or 0.2	3

SID, source-to-image distance.
Using a factorial design there were 2 × 2 x 3 x 2 × 3 combinations (total = 72).

The phantom was positioned in the incubator for a standard supine anteroposterior (AP) chest projection ensuring the median sagittal plane was coincident with, and at right angles to, the incubator tabletop and tray beneath.[15] The centring point was fixed in the midline at the level of the sternal angle (between the nipples on the skin surface), with the collimation adjusted to include all required anatomy in line with radiographic textbooks.[15,16] This area was marked with tape to ensure a fixed and consistent collimation size for all acquired images.

Study acquisition parameters were based upon local clinical protocols, and those reported in the literature.[8,9,17–20] This allowed for numerous different acquisition parameter combinations to be explored (Table 1). The mattress thickness for the Giraffe incubator is 3.5 cm with the object-to-image distance (OID) 7 cm from the top of the mattress to the surface of the image receptor within the tray.

All other acquisition parameters remained constant and reflected those normally employed in clinical practice and within the literature; these included a small focus (0.6 mm) and 2.8 mm Al total filtration.[18,20]

Visual image quality evaluation

All images were displayed on a high quality 24.1 inch NEC (EA243WM) monitor (NEC Europe, Ruislip, UK) with a resolution of 5 megapixels. The images were evaluated using ViewDEX computer software.[21] ViewDEX is a Java-based program developed to display images in a random order, without any acquisition data. Images were analysed independently by one specialist radiologist with a subspecialist interest in paediatric radiology, two reporting radiographers (with neonatal chest reporting within their scope of practice) and two general radiographers with more than 5 years' clinical experience. All five observers were blinded to the acquisition parameters and were provided with pseudo-names to ensure anonymity. Images were evaluated using an absolute visual grading analysis (VGA) method where each observer rated the visability of specific features within the aquired images.Observers were provided with a demonstration of the VGA software to help familiarise themselves with the

Table 2. The criteria and rating scale (1–5) used within the VGA method

Chest criteria	Rating scale used to assess image quality
1.Reproduction of the lung pattern in the displayed lungs	(5) *excellent image quality* (no limitations for clinical use)
2.Reproduction of the trachea and proximal bronchi	(4) *good image quality* (minimal limitations for clinical use)
3.Reproduction of the diaphragm and costo-phrenic angles	(3) *sufficient image quality* (moderate limitations for clinical use but no considerable loss of information)
4.Reproduction of the spine through the heart shadow	(2) *restricted image quality* (relevant limitations for clinical use, clear loss of information)
5.Reproduction of the mediastinum and heart borders	(1) *poor image quality* (image must be repeated because of information loss).
6.Overall levels of noise within the image	
7.Overall image quality	

VGA, visual grading analysis.

image quality scale and setup. Training material was also sent to observers including the demonstration of four different experimental images with varying level of image quality (based on CNR values).[22] I VGA methods are sensitive to small changes in image quality and are characterised by attractive simplicity and powerful discriminating properties.[23] Image quality criteria were adapted from Uffmann et al,[24] Martin et al,[25] Ladia et al,[26] and the European Commission Recommendations.[27] Overall, seven criteria were used to evaluate each image (Table 2).

Contrast-to-noise ratio (CNR)

CNR was calculated by placing a 2 mm^2 region of interest (ROI) on two contrasting homogeneous structures, equating to the cardiac shadow (A) and gastric bubble (B), within the acquired images (Figure 1). ROIs were placed in the same position for all acquired images in accordance with Bloomfield et al.[28] 'Image J' software (National Institutes of Health, Bethesda, MD) was used to calculate CNR. Mean pixel values (signal) for the two ROIs, A and B, and the standard deviation of signal intensities within the ROI B (a ROI with relatively little signal) were used to calculate CNR using the following equation:

$$C = \frac{|S_A - S_B|}{\sigma_o}$$

Where S_A and S_B are the mean signal intensities for signal producing structures A (ROI_1) and B (ROI_2) and σ_o is the standard deviation of signal intensities in ROI_2 to represent the pure image noise.[1,29,30]

Radiation dose assessment

Entrance surface dose (ESD), including backscatter, was measured at the surface of the phantom at the centre of the collimation field using an Unfors Mult O-Meter 407L (Unfors Equipments, Billdal, Sweden). To reduce random error, three repeated exposures were recorded and then averaged.

Statistical analysis

Data were inputted into Excel 2007 (Microsoft Corp, Redmond, WA) and transferred to GenStat v. 13.3 (VSN International, Hemel Hempstead, UK) and SPSS v. 18.0.2 (SPSS Inc, Chicago, IL) for analysis. For the visual grading analysis (VGA), interobserver variability was evaluated using the intraclass correlation coefficient (ICC) with an ICC >0.75 indicating excellent, 0.40–0.75 fair to good and <0.40 poor consistency.[31] Image quality data (both visual, in the form of the VGA scores (VGAS) and CNR) and radiation dose data were analysed using a multifactorial $2^3 \times 3^2$ design. This was achieved with five repetitions (observers) using the general analysis of variance (ANOVA) model, with observer as the blocking factor. Statistical significance was considered where $p < 0.05$. Kendall coefficient of concordance rankings was also used to correlate with the ANOVA. Pearson's r correlation was generated to assess the correlation between visual image quality and CNR.

RESULTS

On average, there was good consistency amongst the five observers when evaluating visual image quality (ICC 0.73 [CI 95% 0.59 to 0.83]). In addition, visual image quality and CNR had a moderately good positive correlation (Pearson's r value = 0.6).

The use of copper filtration significantly reduced ESD. There was a 60% reduction in radiation dose between 0 Cu and 0.1-mm Cu and a 45% reduction between 0.1-mm Cu and 0.2-mm Cu (Table 3). A reduction in image quality was found for both VGA and CNR. When adding 0.1-mm Cu, there was a 14% reduction in VGA and a 20% reduction in CNR. The reduction in VGA and CNR, when increasing the thickness from 0.1 to 0.2-mm Cu, was 13 and 17% respectively. Therefore, adding copper filtration caused a much larger percentage reduction in ESD compared to the percentage reduced image quality. The statistical significance of these findings are illustrated in Table 4, where a significant interaction ($p < 0.01$) between mAs and copper filtration was evident for ESD.

Regarding the effect of altering the mAs and copper filtration on image quality, no significant relationship between the mAs or copper filtration was evident for the VGA. However, ANOVA did highlight a significant reduction in both CNR and VGAS when using both 0.1 mm Cu and 0.2 mm Cu filtration (Tables 5 and 6).

VGA scores, CNR and ESD followed a similar trend for all five independent variables explored, with an increase in exposures factors significantly increasing VGA and CNR but with an associated increase in ESD. Conversely, source-to-image distance (SID), the use of the incubator tray and copper filtration all

Table 3. Summary of the percentage difference between image quality (VGAS and CNR) and radiation dose (ESD) for the different copper filtration settings

					Percentage difference		
	Copper (mm)	0	0.1	0.2	0 v 0.1	0.1 v 0.2	0 v0.2
Average across all images	**VGAS**	4	3.5	3	−14%*	−13%*	−25%*
	CNR	34.2	27.3	22.7	−20%*	−17%*	−34%*
	ESD (μGy)	36.2	14.6	8.1	−60%*	−45%*	−78%*

CNR, contrast-to-noise ratio; ESD, entrance surface dose; VGA, visual grading assessment.
*Corresponds to a significant difference (p<0.01) when correlated to Tables 5–7 below.

significantly reduced VGA and CNR but with a significantly reduced dose (Tables 5–7). The exception to this trend is that no significant difference in ESD (p = 0.91) was found between direct and in-tray exposures and yet image quality for both VGA and CNR significantly reduced when using the tray (Tables 5–7). Using the Kendall coefficient of concordance rankings (W = 0.628, p < 0.001) the least favoured image corresponded to acquisitions in-tray, SID = 126 cm, Copper = 0.2 mm, kV = 60, mAs = 0.5, supporting the ANOVA predictions. VGA scores had a direct correlation with ESD, with the most favoured image from the Kendall coefficient of concordance ranking with a direct exposure being SID = 117 cm, mAs = 1.5, Copper = 0 mm and 65kV, and in-tray being kV = 65, mAs = 1, SID = 100, Cu = 0. Neither of these 'best' images quite tie in with the ANOVA and does not take into account radiation dose.

From an optimisation perspective, the experimental images were compared to the recommended acquisition parameters for both direct and in-tray exposures for neonatal chest imaging from a recently published neonatal DR optimisation study.[20] This study used the same equipment and similar acquisition parameters and is compared in Table 8. From this table, increasing kV from 60 to 65 and mAs from 0.5 to 1 whilst using 0.1-mm Cu for direct neonatal imaging results in the same ESD but with higher CNR and VGA scores. This was similar for an in-tray exposure, if kV and mAs is increased to 65 and 1.5 whilst using 0.1-mm Cu, image quality remains the same but at a reduced ESD (Table 8).

DISCUSSION

This is the first study to explore the use of additional filtration in mobile neonatal DR. Results from our study indicate that, when imaging within incubators, added copper filtration can significantly reduce the radiation dose. However, this reduction in radiation dose is accompanied by a reduction in image quality and therefore modifying acquisition parameters is necessary to counteract this reduced quality. Interestingly, when compared to those acquisition parameters recommended from the recent study by Tugwell-Allsup et al,[20] using no copper filtration, an increase in kV and mAs when using 0.1-mm Cu resulted in either better image quality at the same radiation dose for direct exposures or, for in-tray exposures, equal image quality at reduced dose. It is therefore reasonable to recommend the use of 0.1-mm copper filtration for neonatal chest imaging using DR with a corresponding increase in kV and mAs (Table 8). This strengthens previous recommendations where 0.1-mm Cu is advocated for chest imaging across different age groups with sufficient kV.[11,27,32,33] Mutch and Wentworth[34] also used 0.1-mm Cu as standard practice within their neonatal chest radiography experiments. There are those who do not recommend additional filtration for neonatal imaging but have used relatively low kV for these examinations (50–55 kV) and would therefore need to increase kV when an additional filter is present[8,9,13,18,35]; these recommendations are also based on anecdotal evidence and/or when using CR technology.

There is significant reduction in ESD when using added copper filters. However, this reduction is exacerbated for ESD and would be less significant for effective dose (although the reduction may still be deemed significantly lower).[33] This is due to the low energy photons that add to skin dose being absorbed by the additional filtration and increasing the penetrating power of the beam, therefore the same reduction is not apparent for effective dose.[3,33] Brosi et al,[6] highlighted this and suggest that the decrease in ESD from additional filtration is only beneficial

Table 4. Summary of means from ANOVA demonstrating a significant interaction between mAs and copper filtration (p < 0.01) on ESD and VGAS

	Copper (mm)	mAs	0.5	1	1.5
ESD (μGy)	0		17.8	36.1	54.8
	0.1		6.9	14.6	22.4
	0.2		3.8	8.1	12.4
Average VGAS	0		3.7	4.2	4.4
	0.1		3	3.7	4
	0.2		2.6	3.4	3.6

ANOVA, analysis of variance; ESD, entrance surface dose; VGA, visual grading assessment.

Table 5. Results of the ANOVA model for visual image quality

Visual image quality	Coefficient	Confidence Interval 95%	*p*-value
Intercept (Visual image quality when kV = 60,			
mAs = 0.5, SID 100, no tray, Cu = 0)	3.61		
kV = 65	(+)0.17	(0.07, 0.27)	$p < 0.001$
mAs = 1	(+)0.68	(0.60, 0.76)	$p < 0.001$
mAs = 1.5	(+)0.88	(0.80, 0.96)	$p < 0.001$
SID = max	(−)0.34	(−0.44, −0.24)	$p < 0.001$
Location = tray	(−)0.20	(−0.30, −0.10)	$p < 0.001$
Cu = 0.1	(−)0.53	(−0.61, −0.45)	$p < 0.001$
Cu = 0.2	(−)0.92	(−1.00, −0.84)	$p < 0.001$

ANOVA, analysis of variance.

Table 6. Results of the ANOVA model for CNR

CNR	Coefficient	Confidence Interval 95%	*p*-value
Intercept (Visual image quality when kV = 60,			
mAs = 0.5, SID 100, no tray, Cu = 0)	28.1		
kV = 65	(+)3.1	(1.6, 4.6)	$p < 0.001$
mAs = 1	(+)8.3	(7, 9.6)	$p < 0.001$
mAs = 1.5	(+)14.7	(13.4, 16)	$p < 0.001$
SID = max	(−)5.25	(−6.79, −3.71)	$p < 0.001$
Location = tray	(−)15.7	(−17.2, −14.2)	$p < 0.001$
Cu = 0.1	(−)6.9	(−8.2, −5.6)	$p < 0.001$
Cu = 0.2	−11.6	(−12.9, −10.3)	$p < 0.001$

ANOVA, analysis of variance; CNR, contrast-to-noise ratio.

for examinations exposing areas with superficial and radiosensitive organs such as breast issue and thyroid. This highlights the importance of using copper filters for neonatal chest imaging, especially, since the examination is performed AP and supine as opposed to posteroanterior, limiting the maximum achiavble distance too

There are also promising findings from using 0.2-mm Cu within our study since, on average, using no copper with 0.5 mAs had a higher ESD than if 1.5 mAs was used in conjunction with 0.2-mm Cu, whilst maintaining a similar image quality. However, this image quality was based on average visual image quality scores and therefore for the purpose of optimisation,

Table 7. Results of the ANOVA model for ESD

Dose	Coefficient	Confidence interval 95%	*p*-value
Intercept (Visual image quality when kV = 60,			
mAs = 0.5, SID 100, no tray, Cu = 0)	19.7		
kV = 65	(+)4.3	(1.3, 7.3)	$p = 0.007$
mAs = 1	(+)10.1	(7.5, 12.7)	$p < 0.001$
mAs = 1.5	(+)20.4	(17.8, 23)	$p < 0.001$
SID = max	(−)8.7	(−11.7, −5.7)	$p < 0.001$
Location = tray	(−)0.19	(−3.19, + 2.84)	$p = 0.91$
Cu = 0.1	(−)21.6	(−24.2, −19)	$p < 0.001$
Cu = 0.2	(−)28.1	(−30.7, −25,5)	$p < 0.001$

ANOVA, analysis of variance; ESD, entrance surface dose.

Table 8. Summary of the advantages of using 0.1-mm Cu for both direct and in-tray exposures when compared to the Tugwell-Allsup et al[19]

	KV	mAs	Cu (mm)	SID (cm)	VGAS	CNR	ESD (μGy)
	Direct exposure						
Tugwell-Allsup et al.,[19]	60	0.5	0	100	3.7	37.8	19
New technique with equivalent dose	65	1	0.1	100	4.2	44	19
	In-tray exposure						
Tugwell-Allsup et al.,[19]	60	1	0	max	3.8	24	25
New technique with equivalent IQ	65	1.5	0.1	max	3.8	26	19

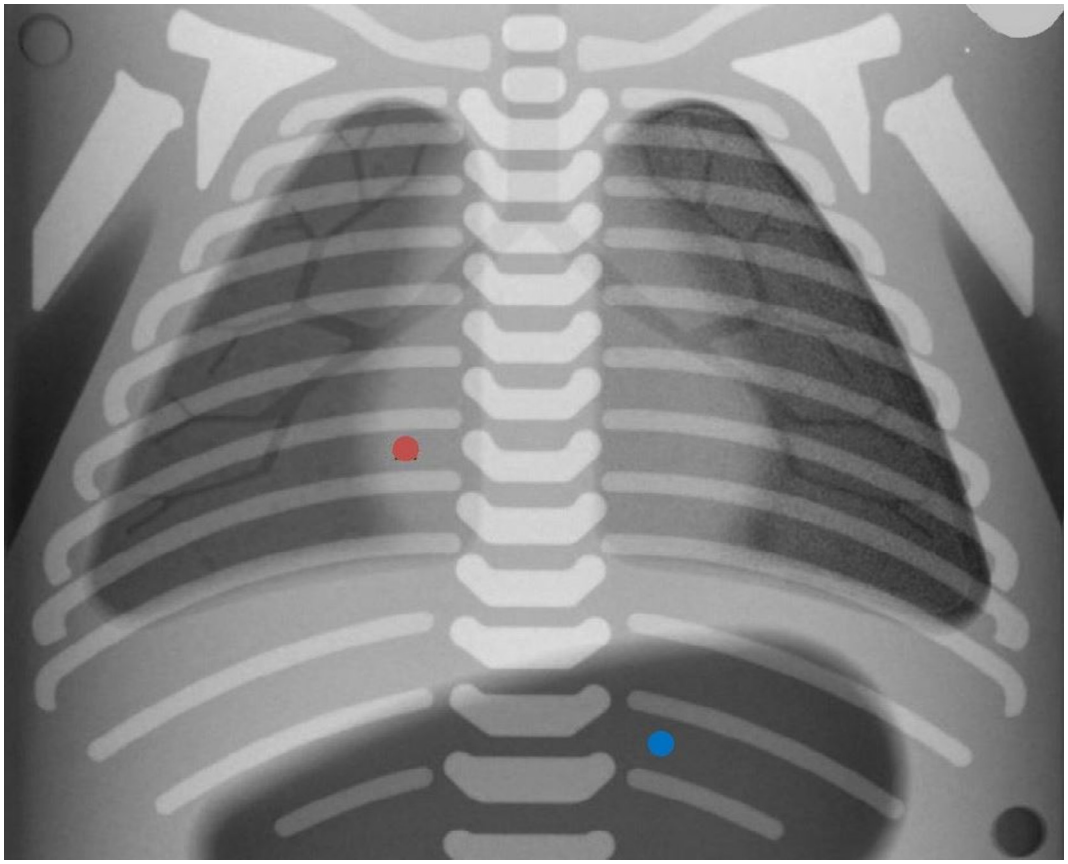
CNR, contrast-to-noise ratio; ESD, entrance surface dose; VGA, visual grading assessment.

these two different combinations may not provide the optimal acquisition parameters to provide best possible image quality at lowest possible dose. Although observers had good consistency when evaluating image quality, subjectivity is still present, which can skew results. The interpretation of the term 'diagnostic image quality' within such a task is also variable. For the purpose of this study, the optimisation strategy was to achieve 'good image quality – with minimal limitations for clinical use at the lowest possible radiation dose'. Using 0.1-mm Cu allowed for this to be achieved. We propose that, if a neonate undergoes multiple chest radiographs, the use of 0.2-mm Cu with 1–1.5 mAs may provide sufficient image quality at significantly reduced radiation dose (clinical indication-based optimisation).

Having no clinical indication when evaluating the images in this study is likely to have affected decision-making in terms of judgements on the quality. This was highlighted anecdotally whereby some observers visually evaluated image quality based upon the best possible image quality, whereas others base it upon the lowest possible image quality necessary to ensure diagnostic worth. This may ultimately skew results even when there is good ICC consistency (as opposed to absolute agreement) because the ranking of images may be consistent but the scoring on the quality might differ.

Transposing the findings of this research study into techniques for clinical application requires consideration of a number of other additional factors and further, local level, clinical research.

Figure 1. Illustrating the size and position of the ROIs for the CNR calculations with red circle denoting *A* (ROI_1) and blue circle *B* (ROI_2). CNR, contrast-to-noise ratio; ROI, region of interest



Any new technique implemented clinically must be evaluated in terms of impact on image quality and radiation dose at a local level. Although the findings of this study support the use of additional copper filtration of 0.1-mm Cu, in combination with modifications to acquisition parameters, it is noted that these recommendations are specifically for one incubator, under controlled conditions, using a phantom, representing a 1–2 kg neonate, rather than a real neonate patient. There are multiple variables that can influence image quality and dose outcomes. These include, but are not limited to, the maximum achievable SID, incubator and mattress specifications, and the individual specifications of the mobile DR system. The next stage of this research is to evaluate the additional copper filtration in real patients. Depending on the local equipment used, specifically if it differs from that used in this study, further research into the effects of additional copper filtration on image quality and patient dose may be required before this can occur.

CONCLUSION

Neonates often require repeated chest radiographs which has a cumulative radiation burden. In line with as low as reasonably practicable principles, there is a duty to minimise this radiation exposure, whilst maintaining satisfactory diagnostic quality. This phantom-based DR study provides evidence that using additional copper filters and simultaneously increasing the kV and mAs can maintain, or at times enhance image quality whilst also providing a significant radiation dose reduction (ESD) to the neonate. The next stage is to establish whether the outcomes achieved in this research translate to real neonates within the clinical setting.

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