Radiography xxx (xxxx) xxx

Contents lists available at ScienceDirect

Radiography

journal homepage: www.elsevier.com/locate/radi

Optimising image quality and radiation dose for neonatal incubator imaging

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ARTICLE INFO

Article history:
Received 24 February 2020
Received in revised form
19 March 2020
Accepted 23 March 2020
Available online xxx

Keywords:
Optimisation
Neonate
Incubator
Visual image quality
Effective dose
Balance

ABSTRACT

Introduction: Neonates often require imaging within incubators however limited evidence exists as to the optimal method and acquisition parameters to achieve these examinations. This study aims to standardise and optimise neonatal chest radiography within incubators.
Methods: A neonatal anthropomorphic phantom was imaged on two different incubators under controlled conditions using a DR system. Exposure factors, SID and placement of image receptor (direct v tray) were explored whilst keeping all other parameters consistent. Image quality was evaluated using absolute visual grading analysis (VGA) with contrast-to-noise ratio (CNR) also calculated for comparison. Effective dose was established using Monte Carlo simulation using entrance surface dose within its calculations.
Results: VGA and CNR reduced significantly ($p < 0.05$) whilst effective dose increased significantly ($p < 0.05$) for images acquired using the incubator tray. The optimal combinations of parameters for incubator imaging were: image receptor directly behind neonate, 0.5 mAs, 60 kV at 100 cm SID, however, if tray needs to be used then these need to be adapted to: 1 mAs at maximum achievable SID. Effective dose was highest for images acquired using both incubator tray and 100 cm SID owing to a decrease in focus to skin distance. There is significant increase ($p < 0.01$) in VGA between using 0.5 mAs and 1 mAs but an apparent lack of increase between 1 and 1.5 mAs.
Conclusion: Using the incubator tray has an adverse effect on both image quality and radiation dose for incubator imaging. Direct exposure is optimal for this type of examination but if tray needs to be used, both mAs and SID need to be increased slightly to compensate.
Implications for practice: This study can help inform practice in order to both standardise and optimise chest imaging for neonates in incubators.

Introduction

When neonates are born prematurely or have health concerns, they are commonly placed within an incubator or warmer system. During this period, they are likely to require mobile chest radiography (CXR) to diagnose and monitor their condition, whilst remaining within their incubators.[1] During such examinations the radiographer will need to consider whether to place the image receptor directly beneath the neonate or in a dedicated tray/drawer. These two scenarios have advantages and disadvantages in relation to infection control, magnification, attenuation differences, collimation and alignment, which all impact on image quality, safety and the radiation dose to the neonate.[1–4] Two recent studies[1,5] have shown considerable variation in neonatal imaging protocols and have highlighted the need for standardisation and optimisation. Previous optimisation studies are limited and have either focused only on one or two acquisition parameters or have failed to correlate the additional attenuation of the incubator design with the increased risk associated with the radiation dose or with any decline in visual image quality.[3,4,6,7]

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https://doi.org/10.1016/j.radi.2020.03.011
1078-8174/

This study advances work from a recent systematic review[2] and a clinical practice survey[5] on neonatal incubator imaging. Within these reports the lack of empirical evidence and wide variability in radiographic technique was evident. This is a concern since neonates are more sensitive to the effects of radiation owing to their rapid development. A neonate's life expectancy is also theoretically longer meaning that there is more time for the harmful effects of radiation to manifest.[8] This project aims to build on previous knowledge to standardise and optimise neonatal CXR within incubators. This study will assess how each component of the incubator design and choice of acquisition parameters affects image quality and radiation dose.

Method

Imaging equipment and technique

Quality assurance testing was conducted prior to commencing the study in accordance with IPEM Report 91,[9] and results were within accepted tolerances. Images were acquired using a DR Samsung GM85 mobile and a 25 × 30 cm wireless, lightweight S-Detector™ (MIS Healthcare, London, UK). To allow for multiple exposures under consistent conditions, the commercially available Gammex 16 neonatal anthropomorphic phantom was used (Rothband LTD, Haslingden, UK) to simulate a 1–2 kg neonate. For comparison purposes, images were acquired using two different neonatal incubators, both had an integrated X-ray tray: 1) Drager Caleo and 2) GE Giraffe and both are commonly used incubators.[5]

The phantom was positioned for a standard supine anteroposterior (AP) chest examination, ensuring the median sagittal plane was coincident with, and at right angles to the incubator tabletop and tray beneath.[10] The centering point was fixed in the midline at the level of the sternal angle (between the nipples), the collimation was adjusted to include the lung apices, lateral margins of both lungs, cardiophrenic and costophrenic sucli in accordance with radiographic textbooks.[10,11] This area of clinical interest was marked with tape in order to maintain a fixed collimation size for all exposures (Fig. 1).

Study acquisition parameters were based on local clinical protocols and those reported in the literature[2–7,12] Various acquisition parameters were changed in this factorial study design. The main independent variables for the study were: 1) image receptor position *(direct v tray)*, 2) incubator design *(Caleo v Giraffe)*, 3) mAs *(0.5, 1, 1.5)*, 4) kV *(60, 65)* and 5) source-to-image distance (SID) *(*100 cm*, max).* For tray exposures, the mattress, SID and object-to-image to distance (OID) were measured using both a tape measure and ruler. The mattresses of both incubators were identical in terms of thickness (3.5 cm) and the distance from the phantom. The OID was 6 cm for the Drager Caleo and 7 cm for the GE giraffe. The maximum achievable SID, with the incubator at the lowest height setting and X-ray tube in the highest achievable position, is described in Table 1.

All other acquisition parameters were kept consistent and according to those typically employed in clinical practice and within the literature.[4–6] These included a small focus (0.6 mm) and 3.2 mm Al total filtration.

Visual image quality evaluation

All images were displayed on a high quality 24.1 inch NEC (EA243WM) monitor with a resolution of 5 megapixels. The images were evaluated using the ViewDEX computer software.[13] ViewDEX is a Java based program developed to display images in a random order, without any acquisition data, with the facility of providing a direct assessment of image quality via options displayed on the screen. Images were analysed independently by two radiologists, two reporting radiographers and two general radiographers with more than 5 years clinical experience. All six observers were blinded to the acquisition parameters used to acquire the images. Images were evaluated using an absolute visual grading analysis (VGA) method whereby each observer rated their opinion on the visibility of specific features within the various acquired images. Image quality criteria were taken from Uffmann et al.[14] Martin et al.,[15] Ladia et al.[16] and the European Commission criteria.[17] Numerous criteria were excluded as they did not relate to an anthropomorphic phantom (e.g. amount of inspiration) and those unaffected by adjustment in acquisition parameter (positional criteria). Some adjustments were made to terminology in order to reflect more closely anatomy within the phantom. Overall seven criteria were evaluated for each image (Table 2).

Contrast-to-noise ratio (CNR)

CNR was also calculated by placing a region of interest (ROI) on two contrasting homogeneous structures within the acquired images (Fig. 2). The ROI was placed in the same position for all acquired images in accordance with Bloomfield et al.[18] The Image J software (National Institutes of Health, Bethesda,MD) was used to calculated CNR whereby the mean pixel values (signal) and the standard deviation (noise) for the ROI was determined by the following equation.[19]

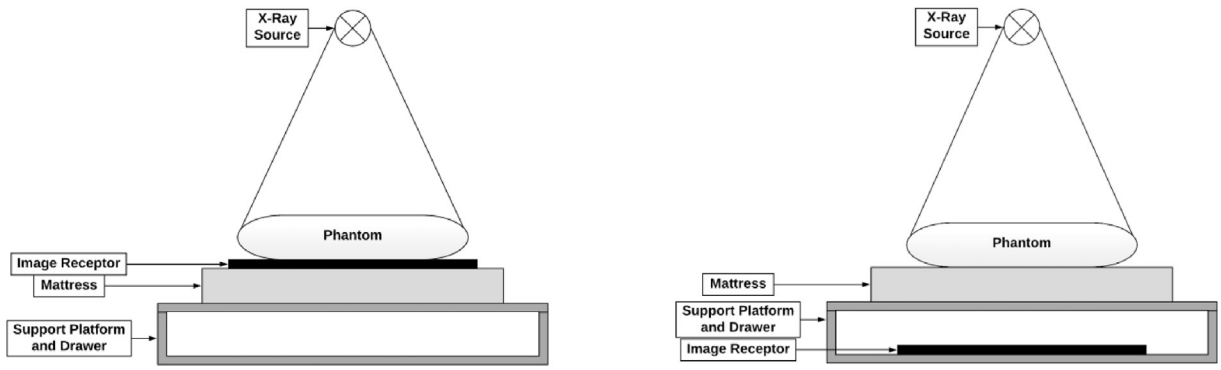

Figure 1. Figure demonstrating experimental set up for direct and tray exposure.

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Table 1
Independent variables within the experimental study.

Type	Parameter	
Independent Variables	Incubator	Drager Caleo GE Giraffe
	Image receptor position	Direct Tray
	kV	60 65
	mAs	0.5 1 1.5
	FRD	100 cm Maximum achievable; Drager direct = 119cm/Drager tray = 126.5 cm/GE Giraffe direct = 117 cm/GE Giraffe tray = 128 cm

Table 2
Image quality criteria and rating scale used to assess chest X-ray image quality.

Chest criteria	Criteria rating scale
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	

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

where S_A and S_B are signal intensities for signal producing structures *A* (*ROI1*) and *B* (*ROI2*)and σ_o is the standard deviation (blue ROI) of the pure image noise.

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 detector (Unfors Equipments, Billdal, Sweden). In order to reduce random error, three repeated exposures were performed and then averaged.

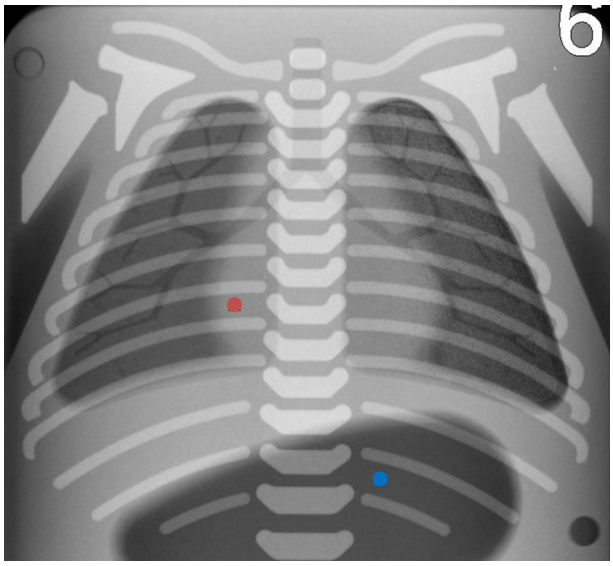

Figure 2. ROI position to calculate CNR; ROI1 (red circle) and ROI2 (blue circle). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Effective dose was estimated using PCXMC 2.0 (STUK, Helsinki, Finland)and tissue weighting factors from the ICRP Publication 103.[20] The software has a phantom representative of a 1 kg newborn. Entrance surface dose (ESD) was used in this estimation along with the respective acquisition parameters.

Statistical analysis

All data were inputted into Excel 2007 and transferred to GenStat (GenStat version 13.3, VSN International Ltd) and SPSS software package (PASW Statistics 18: version 18.0.2, SPSS Inc., Chicago, IL) for analysis. For the visual image quality data, inter-observer variability was evaluated using the Intra-Class Correlation Coefficient (ICC). An ICC > 0.75 is indicated as excellent, 0.40−0.75 as fair to good and < 0.40 poor.[21] Image quality data (both visual and physical) and radiation dose data were analysed in a multi-factorial $2^4 \times 3$ design (2 incubators, 2 image receptor positions, 2 kV, 2 SID, 3 mAs). This was achieved with 6 repetitions (observers) using the general ANOVA model with observer as the blocking factor and a significance level of $p < 0.05$ (95%). Pearson's r correlation was also generated to determine correlation between visual image quality and CNR.

Results

On average, there was good consistency amongst the six observers when evaluating visual image quality, with an ICC of 0.73 (CI 95% 0.59−0.83); with agreement being stronger for images that were scored very low or very high. In addition, visual image quality and CNR had a moderately good positive correlation r = 0.65 which can also be seen from the ANOVA coefficients (Tables 3 and 4)

Of the 48 experimental images, as expected, the images with the highest image quality also had the highest radiation dose. However, in order to ensure optimisation, these results have to be explored further for optimal combinations. Interestingly, there was a statistically significant difference in visual image quality and CNR

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Table 3
Results of the ANOVA for visual image quality.

Visual image quality	Coefficient	Confidence Interval 95%	p-value
Intercept (Visual image quality when kV = 65, mAs = 0.5, FRD max, no tray, Giraffe)	3.34		
kV = 60	−0.15	(−0.25, −0.05)	p = 0.003
mAs = 1	0.45	(0.36, 0.54)	p < 0.001
mAs = 1.5	0.55	(0.46, 0.64)	p < 0.001
FRD = 100	0.26	(0.16, 0.36)	p < 0.001
location = tray	−0.17	(−0.27, −0.07)	p = 0.01
Incubator = Drager	−0.18	(−0.28, −0.08)	p < 0.001

Table 4
Results of the ANOVA for CNR.

CNR	Coefficient	Confidence Interval 95%	p-value
Intercept (CNR when kV = 65, mAs = 0.5, FRD max, no tray, Giraffe)	22.18		
kV = 60	−2.38	(−3.37, −1.4)	p < 0.01
mAs = 1	6.22	(5, 7.43)	p < 0.01
mAs = 1.5	9.94	(8.73, 11.15)	p < 0.01
FRD = 100	3.94	(2.95, 4.92)	p < 0.01
location = tray	−4.84	(−5.83, −3.85)	p < 0.01
Incubator = Drager	−1.59	(−2.58, −0.61)	p = 0.002

between 0.5 mAs and the other mAs values of 1 and 1.5 (Tables 3 and 4). However, there is an apparent lack of an increase in visual image between 1 and 1.5 mAs. It is estimated that when using the incubator tray in comparison to direct exposure, visual image quality decreases slightly by 0.15 (3%) and yet was statistically significant ($p < 0.05$). This means that an increase in mAs from 0.5 to 1 is required to achieve identical VIQ when using tray. Using a non-tray exposure and 100 cm SID with 0.5 mAs and 60 kV, resulted in above average visual image quality (3 and above) and high CNR with a lower effective dose; making them the most suitable combination for optimisation.

For most variables explored within this study, a significant increase in image quality meant a significant increase in effective dose and vice versa. For example, the Drager incubator had significantly lower image quality than the GE Giraffe but also allowed images to be acquired at a significantly lower dose (Tables 3–5). The same was seen for SID, where there was a significant increase in both visual image quality and CNR for 100 cm SID compared to maximum achievable SID yet there was also a significant increase in effective dose. From the 48 experimental images, the images acquired using the tray at 100 cm SID resulted in the highest effective dose (Figs. 3 and 4). This is not surprising as the OID when using the tray for the Drager and Giraffe incubator were 6 cm and 7 cm, respectively. This meant that when using an SID of 100 cm, with the tray, the source to skin distance was shorter compared to a direct exposure (has no OID)

Table 5
Results of the ANOVA for effective dose.

Effective Dose	Coefficient	Confidence Interval 95%	p-value
Intercept (Dose when kV = 65, mAs = 0.5, FRD max, no tray, Giraffe)	5.94		
kV = 60	−2.37	(−3.73, −1.01)	p = 0.001
mAs = 1	5.35	(3.68, 7.02)	p < 0.01
mAs = 1.5	10.97	(9.3, 12.64)	p < 0.01
FRD = 100	4.4	(3.04, 5.76)	p < 0.01
location = tray	1.86	(0.5–3.22)	p = 0.01
Incubator = Drager	−3.7	(−5.06, −2.34)	p < 0.01

The only independent variable where the inverse correlation seen above (increase dose = increase image quality) was not present was for direct verses tray exposures. Both VIQ and CNR were significantly decreased for tray exposure but at significantly higher doses to a direct exposure (Tables 3–5). This means that the tray had an adverse effect on both image quality and radiation for incubator imaging.

From an image quality perspective, 0.5 mAs should not be used in combination with maximum SID and/or with incubator tray as both SID and tray decreased image quality and hence 0.5mAs is not sufficient to ensure optimal image quality for these variables (Figs. 2 and 3).

Discussion

Results from our study indicate that when imaging neonates within incubators, numerous variables affect image quality and radiation dose. Most findings were expected in terms of the relationship between effective dose and increases in VIQ and CNR. However, when optimising an imaging technique, a balance is required to ensure optimal image quality at lowest radiation dose. Overall, the optimal protocol for incubator imaging came from images acquired with the image receptor directly behind neonate, with a 100 cm SID (60 kV and 0.5 mAs) for both incubator designs. These combinations produced images above average image quality with a very low effective dose. However, in clinical practice, it is not always feasible to image a neonate using a direct exposure as it requires the positioning and movement of an already vulnerable neonate. Although use of the incubator tray has been shown to increase beam attenuation, many studies[6,7,22] still advocate the use of the incubator tray when imaging neonates as it reduces the risk of cross infection and displacing lines and tubes without any significant impact on image quality. Also, historical studies have demonstrated that handling neonates can be associated with bradycardia and hypoxia.[22–24] In addition, 58% of respondents within Tugwell et al.'s study[5] used the tray as standard practice, with 32% using it only in unavoidable circumstances such as when the neonate's condition was unstable, if they had multiple lines, and/or very premature/low birth weight. It is therefore important to also consider the optimal acquisition parameters and technique when using the incubator tray. From all acquisitions using tray, the current study found that the optimal acquisition parameters to be 60 kV, 1 mAs at maximum achievable SID.

Unlike previous studies, our work did not attempt to calculate the attenuation properties for the various components of both incubators used. The difference in image quality and radiation dose would reflect this and thus be more clinically relevant. The Drager incubator had significantly lower image quality but had significantly lower effective dose too. Incubator design would be a reasonable explanation for this. Both OID and SID when at maximum achievable height was different for both incubators with the Drager unit having larger OID and SID. This means the distance from the tube to tray is larger for Drager which would result in a reduction in radiation dose according to the inverse square law and similar trends found in SID related studies.[25–27] In addition, the materials/construction of the incubator may have added additional attenuation and influenced radiation dose and image quality between both incubators. It was noticed that for direct exposures at 100 cm SID, DAP for both incubators were identical but the ESD at the surface of phantom was not, which means that the canopy for Drager seemed to absorb more primary radiation; this could also

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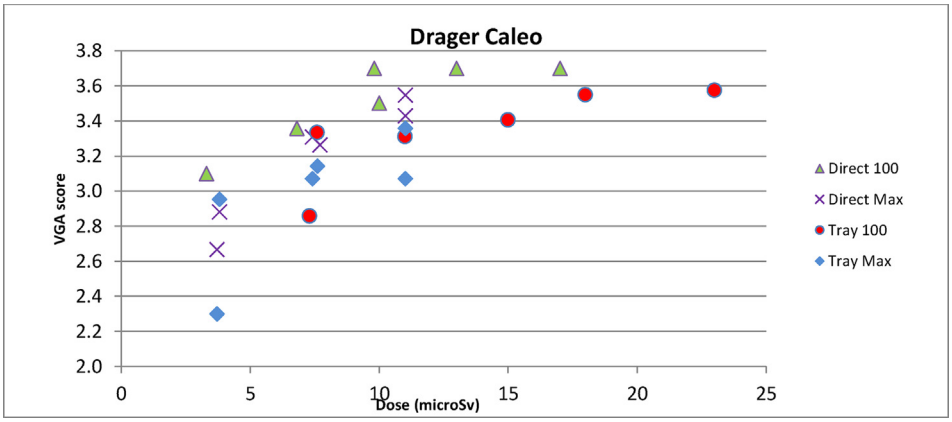

Figure 3. Visual image quality versus effective dose for the different variables used on the Drager incubator.

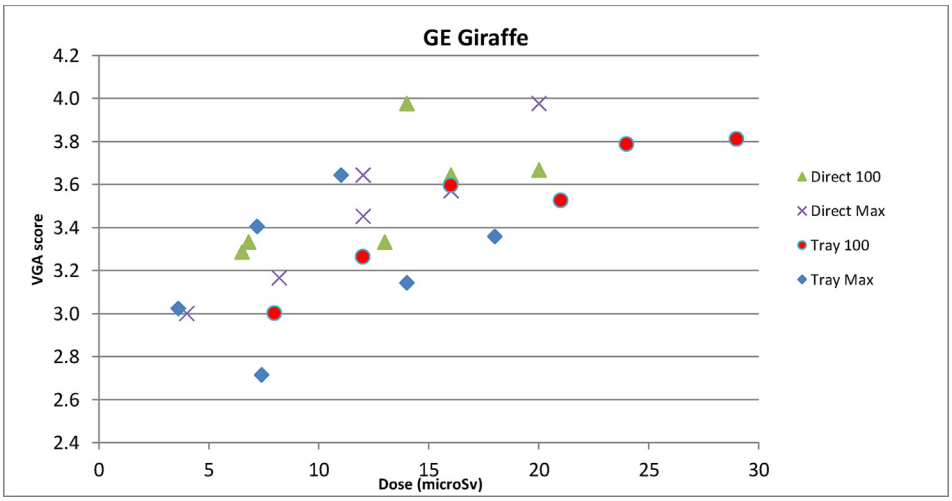

Figure 4. Visual image quality versus effective dose for the different variables used on the Giraffe incubator.

contribute to the differences seen between both incubators for the study.

Some additional findings within this study became apparent. It is already noted within the literature that differences occur between incubator designs such as the attenuation of various components such as the canopy, support tray and mattress.[3,4,6] The above experiment aimed to explore the radiology aspects of imaging a neonate within an incubator by considering the impact of various variables on image quality and radiation dose. However, in order to make a more informed holistic decision as to the optimal parameters/method to image the neonate, other factors need to be considered. It was noted during the experiments that in order to place the image receptor within the incubator tray for the GE Giraffe, the incubator side panel needed to be open. This means that the temperature within the incubator could be compromised. One of the main purposes of an incubator is to ensure a stable warm environment for the neonate[10] and therefore the use of the tray in this instance does not eliminate all of the disadvantages associated with a direct exposure. Another design feature noted for the Drager Caleo was the tray could only be accessed from one side of the incubator which is not flexible. In addition, the tray/drawer for this incubator is large and the image receptor seemed to move considerably when opening and closing into position which meant it could easily be misaligned for imaging. The drawer was large and yet it still cannot accommodate a large DR image receptor. This was also found in other studies[1,5] where the use of the tray was limited by the size of the image receptor as a 35 × 43cm receptor would not fit into the incubator drawer. It is therefore important that each imaging department, when purchasing new DR portable equipment, should consider purchasing a small image receptor if undertaking neonatal imaging. Lastly, as already discussed, the distance of the tray/drawer from the surface of the mattress can also be a variable that increases effective dose and reduces image quality. Radiology should be consulted when designing such equipment similar to that seen for trolley imaging.[28]

There are several limitations in our study. Using an anthropomorphic phantom is not fully representative of the human body since it lacks anatomical and pathological variation. Furthermore, the study was conducted using only a single DR system and therefore needs to be confirmed using other portable DR

Table 6
Recommendations for practice for both incubators used within the study based upon using a Samsung portable machine.

	FRD	kV	mAs
Neonatal chest x-ray with direct exposure[a]	100 cm	60	0.5
Neonatal chest x-ray in the incubator tray[b]	Maximum achievable	60	1

[a] A direct exposure should only be used if the neonate is stable and under the guidance of the nurse in charge.
[b] The tray is advocated especially to reduce movement of neonate.

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equipment. Although the thickness of both incubator mattresses were identical, the full composition of mattress specification was unknown and therefore future studies need to consider this especially with the introduction of warming gel mattresses for incubators. The statistics used for this study found significant difference between each variable and acquisitions parameters, however this statistical significance may not be clinically important. Although image quality may have significantly deteriorated using some combination of parameters/technique, these images may still be of diagnostic quality. None of the images scored below two meaning that none of the observers deemed any of the images as unacceptable for diagnostic purposes and thus requiring a repeat exposure. Based on the findings of this study, the recommended technique for chest imaging for neonates in incubators is summarised in Table 6. Consideration should however be determined by the clinical question and the technique should be evaluated at each hospital, using their own equipment.

Conclusion

This study has highlighted how different conditions and acquisition parameters used for neonatal chest imaging in incubators can influence both radiation dose and image quality. The main finding within this study was that image quality decreased whilst radiation dose increased when the images receptor was placed in incubator tray for imaging as oppose to directly behind the neonate. For the purpose of optimisation, direct exposure favoured a lower dose at higher image quality, however, from a holistic clinical perspective, it is not always feasible to move the neonate and therefore this study also gives recommendations on the optimal combination of acquisitions parameters if the incubator tray was to be used.

Conflict of interest statement

None.

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Please cite this article as: Tugwell-Allsup J et al., Optimising image quality and radiation dose for neonatal incubator imaging, Radiography, https://doi.org/10.1016/j.radi.2020.03.011