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Reduction of Radiation dose and Relative Risk of Cancer Induction to Neonates Receiving Anterior-Posterior Chest X-rays

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Objectives: To derive exposure protocols that decrease the entrance surface dose (ESD) and relative cancer induction risk, while maintaining acceptable visual image quality.

Methods and materials: A phantom was designed and used to experimentally optimise x-ray imaging protocols by varying exposure technique factors, such astube voltage and current, exposure time and filtration. Images were ranked according to measured ESDs, visual image quality and relative cancer induction risks.

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Results: Comparison of derived protocols to a standard neonatal chest exposure protocol revealed that the ESD was reduced approximately by 63% while image quality was improved by about 27%. Relative cancer induction risk analysis showed that, despite reduced ESDs, the risk could be greater than the standard exposure risk.

Conclusion: Six exposure options that answer the aim were derived. The most optimal combination of decrease in the ESD and relative cancer induction risk with maintenance of visual image quality is a processed image at 57 kV, 2 mAs, 100 cm focus-to-film distance (FFD), fine focus, tight collimation and 0.1 mm Cu (copper) and 1 mm Al (aluminium) additional filtration.

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I. Introduction

Newborn babies are called neonates for the first 28 days of life. Babies born preterm who have problems with their hearts and lungs are included in this population group. CR x-ray imaging is used in the diagnosis and follow-up of disease conditions of the heart and lungs using chest AP radiographs. Neonates are more sensitive to radiation, have rapid cell division and growth and longer life expectancies. Cancer induction, especially leukaemia [1], in the young child is therefore a concern with this population group, as cancer induction is a stochastic risk. [2,3,4,5,6] The dose per chest x-ray must be minimised in order to honour the as low as reasonably achievable (ALARA) principle. [7] However dose reductions are generally associated with a loss of image quality. So dose, image quality and cancer induction risks must be evaluated simultaneously. The goal should be clinically acceptable rather than best or maximal image quality. With CR imaging, due the availability of post-processing and image manipulation, ESD can thus be decreased, theoretically decreasing the image quality, up to a certain lower limit after which image quality will not be useful and retakes will be necessary, defying the purpose. [4,8] This relationship is investigated experimentally in this study for neonatal chest AP radiographs, in order to derive optimised exposure protocols with acceptable visual image quality at reduced ESD and most importantly reduced cancer induction risk.

The investigation was done using a neonatal simulation phantom. The phantoms described in literature were not acceptable anatomical and radiological simulations of a real neonatal chest. A water filled one litre bottle was used by Brindhaban and Al-Khalifah [9] to simulate a 1000 g neonate. Vergara et al [10] used a rectangular PMMA perspex phantom where air gaps were used to represent lungs. Akahane et al [11] constructed a rigid and rectangular shaped phantom from tough water and lung phantom materials. The Gammex RMI© 610 phantom was the best anatomical simulation of a real neonatal chest, but the radiological equivalence of the phantom could not be determined. [12] As a suitable anatomical and radiological simulation phantom is not available, an anatomical and radiological neonatal chest simulation phantom was designed and constructed for ESD and image quality analysis.

Recommendations on tube kilovoltage (kV), current-time product (mAs), FFD, focus, collimation and additional filtration as dose reduction mechanisms are discussed in literature. These are tabulated in Table 1. [9,13,14,15,16] The standard exposure protocol for

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neonatal chest AP imaging was 50 kV, 2 mAs, 100 cm FFD, inherent filtration and collimation as tight as possible.

Table 1 : Exposure technique factor ranges as proposed in literature [9,13,14,15,16]

Technique factor	Range in literature
kV	40 - 80
mAs	0.5 - 4
Filtration	1 – 3.5 mm Aluminium; 0.1 mm Copper
FFD	80 – 115 cm
Focus	Fine

II. Aim

The aim of this study was to use an anatomical and radiological simulation phantom of a real neonatal chest to derive optimised exposure protocols that decrease the delivered ESD, while maintaining acceptable quality of the clinical image at a reduced relative risk for cancer induction in the young child.

III. Methods and Materials

A neonatal chest simulation phantom was developed. It consisted of plastics and gels that were radiologically equivalent to real neonatal bone, muscle, healthy or inflated lung and collapsed, sick or deflated lung. Radiological equivalence was obtained by matching the density, elemental composition, attenuation, scatter and absorption characteristics of different possible substitute materials to that of real neonatal tissues. For anatomical equivalence a computed tomography (CT) scan was done on a 7 month old preterm neonatal cadaver and software measuring tools available at the scanner were used to measure the dimensions of different organs and structures using different window and level settings. These measurements were combined with simplifying assumptions, due to machining limitations, to manufacture posterior ribs, a vertebral column, a sick and a healthy lung, anterior ribs and sternal blocks from the radiologically equivalent plastics. A central line was included in the phantom for image quality evaluation. The phantom was validated with region of interest (ROI) analyses as described by Duggan et al. [13]. This anatomical and radiological simulation phantom of a real neonatal chest was used to evaluate the obtained image quality for different exposure protocols.

Images were acquired using a Shimadzu Mobile Art Evolution mobile x-ray unit exposing 18 cm x 24 cm Fujifilm FCR Fuji IP CC cassettes and processing the images in a Philips PCR Eleva Corado reader. The ESD associated with each exposure was measured using a PTW Conny II dosimeter (PTW, Freiburg), with a calibration traceable to a standards laboratory. The detector was placed on top of the phantom, which was 53 mm thick, to measure ESD. The standard exposure used routinely for AP imaging of neonatal chests in our department was 50 kV, 2 mAs, 100 cm FFD, fine focus, inherent filtration and processed image readout.

The optimal combination of kV, mAs, FFD, focus, collimation, filtration and raw or processed image readout was determined experimentally. The recommendations in literature, as in Table 1, were used in four preliminary exposure sets. The phantom was placed on the x-ray bed and an AP image was acquired. The dosimeter was then placed on top of the phantom and another exposure at the same setting was made to measure the ESD. Incubators were not considered. The results, measured ESD and image quality, from each of these sets were used to derive a final set of exposures, which consisted of the standard exposure and eight other possible optimised options. In the first set, 12 images investigated the effect of changing FFD and filtration at a constant kV and mAs setting. With all other parameters constant, the effect of changing kV was assessed. In the second set, consisting of 20 images, a wider kV range and different filtration options were considered at a constant mAs setting. It was decided to use 100 cm FFD and this was constant in the third set. Different kV, mAs and filtration options were assessed in 38 images. In the fourth set, consisting of 56 images, a finer kV and mAs range was used and the effect of 0.1 mm Cu and 1 mm Al additional filtration, compared to inherent filtration of 1.5 mm Al only, was evaluated. The final set of exposures was derived from these preliminary exposure results. These preliminary exposure sets are shown in Table 2.

Table 2 : Preliminary exposure sets

Exposure set	kV	mAs	FFD	Filtration	Focus	Mode
1	Change Constant	Constant	Constant Change Constant	Constant Change	Constant	Processed
2	Change Constant	Constant	Constant	Constant Change Constant	Constant Change	Raw and processed
3	Constant Change	Change Constant Change	Constant	Constant Change Constant	Constant	Raw and processed
4	Constant	Change	Constant	Change	Constant	Raw and processed

Image quality was evaluated visually with image quality scoring. This analysis was a blind process in which 11 observers, medical physicists and radiographers, scored the images according to the criteria in Fig. 1 and Table 3. Observers were not aware of the exposure parameters used with each of the images. The scoring system was a simple one, where a mark was assigned to a criterion based on the visibility of that criterion in each image. This was also done for the overall impression of the image. The marks were added for a total score. The average score for each image from the 11 observers was calculated.

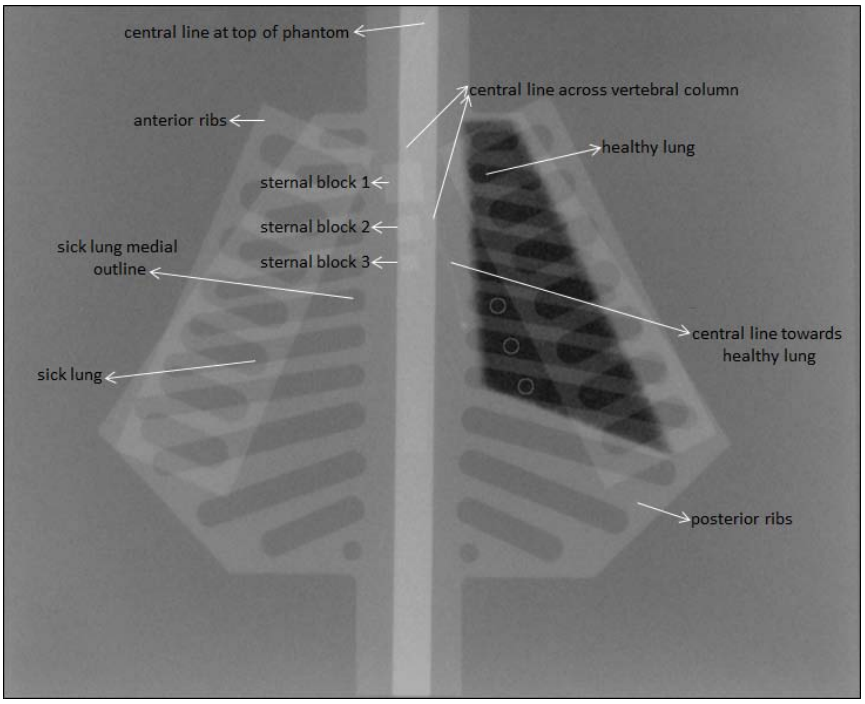

Figure 1 : Location of visual image quality scoring criteria in the simulation phantom

Table 3 : Visual image scoring criteria.

Criteria		Scoring Scale
Sternum	All 3 blocks are clearly visible	5
	2 blocks are clearly visible	4
	1 block is clearly visible	3
	1 block is partially visible	2
	1 block is not clear	1
	No blocks are visible	0
Central line	Seen completely, from top of phantom across spinal column to healthy lung	3
	Seen at top of phantom and towards healthy lung only	2
	Seen towards healthy lung only	1
	Not seen	0
Healthy lung	Posterior ribs are clearly visible behind the lung	3
	Posterior ribs are partially visible behind the lung	2
	Posterior ribs are not clear behind the lung	1
	Posterior ribs are not seen / black lung	0
Sick lung	Sick lung is completely seen	3
	Medial outline of lung is clearly visible	2
	Medial outline of lung is partially visible	1
	Lung is not seen	0
Overall impression	Very good	5
	Good	4
	Acceptable	3
	Not good	2
	Poor	1
	Unusable	0

Cancer induction risk is the product of the effective dose and an International Commission on Radiological Protection (ICRP) risk factor.[7] These were 2.8-13 x 10^{-2} Sv^{-1} for foetal or prenatal exposures to radiation. [9]Effective doses were obtained from the measured ESDs by using conversion coefficients published by the National Radiological Protection Board (NRPB). [17]These effective doses were used as relative dose indicators for quantitative comparison of the different images and were not absolute dose values. An average of 15 x-rays per patient was assumed.

IV. Results

The developed neonatal chest simulation phantom is shown schematically in Fig 2. The phantom was used to assess visual image quality and ESD measurements for the final set of exposures as shown in Table 4.

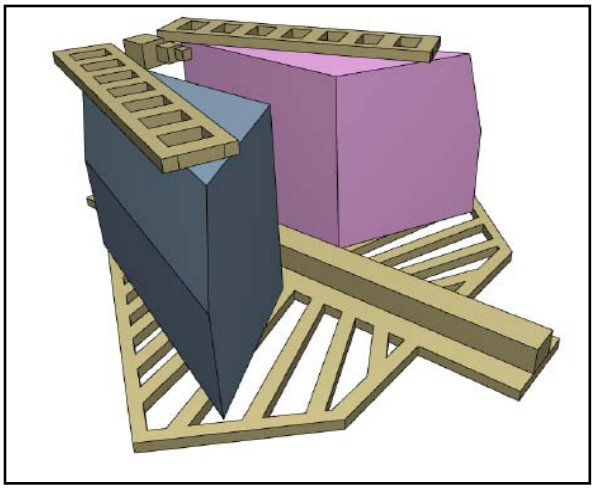

Figure 2 : Schematic representation of the neonatal chest simulation phantom

Table 4 : Standard and derived optimised exposure protocols

Image number	Acquisition mode	Focus	FFD (cm)	kV	mAs	Filtration
1	Processed	Fine	100	50	2.0	Inherent
2	Raw	Fine	100	60	2.0	Inherent and 0.1 mm Cu + 1 mm Al
3	Raw	Fine	100	64	2.0	Inherent and 0.1 mm Cu + 1 mm Al
4	Raw	Fine	100	61	0.8	Inherent
5	Raw	Fine	100	62	0.8	Inherent
6	Processed	Fine	100	57	2.0	Inherent and 0.1 mm Cu + 1 mm Al
7	Processed	Fine	100	57	3.2	Inherent and 0.1 mm Cu + 1 mm Al
8	Processed	Fine	100	60	2.0	Inherent and 0.1 mm Cu + 1 mm Al
9	Processed	Fine	100	61	0.8	Inherent

Table 5 shows the measured ESDs. The images were ranked from high to low quality according to the ESDs. Relative cancer induction risks were then considered for derivation of optimised exposure protocols that decreased delivered ESD and relative cancer induction risks, whilst maintaining acceptable visual image quality. Calculated relative cancer induction risks were noted in Table 5 for an average of 15 chest AP x-rays per neonate. The risks in Table 5 are relative risks only, and should not be interpreted as absolute risk values.

The images used for the evaluation are shown in Fig. 3. Image 1 was the standard exposure image of 50 kV, 2 mAs, 100 cm FFD, inherent filtration and processed readout. Images 2 – 9 were derived optimised images, with exposure technique factors as recorded in Table 4.

Table 5 : ESD and image quality evaluation and relative cancer induction risk results

Image number	ESD (μGy)	ESD ranking	Average total visual image quality score	Visual image quality ranking	Minimum relative cancer induction risk	Maximum relative cancer induction risk	Overall ranking with relative cancer induction risk
1	44.0±2.2	6	11	8	$1.8x10^{-6}$	$8.3x10^{-6}$	Standard
2	19.1±1.0	2	13	3	$1.4x10^{-6}$	$6.3x10^{-6}$	4
3	22.8±1.1	3	14	2	$1.7x10^{-6}$	$7.9x10^{-6}$	Not optimal option
4	25.8±1.3	4	12	7	$1.3x10^{-6}$	$5.9x10^{-6}$	6
5	26.4±1.3	5	13	4	$1.3x10^{-6}$	$6.1x10^{-6}$	2
6	16.2±0.8	1	12	6	$1.1x10^{-6}$	$5.0x10^{-6}$	1
7	26.3±1.3	5	14	1	$1.8x10^{-6}$	$8.1x10^{-6}$	Not optimaloption
8	19.1±1.0	2	13	5	$1.4x10^{-6}$	$6.3x10^{-6}$	3
9	25.8±1.3	4	11	9	$1.3x10^{-6}$	$5.9x10^{-6}$	5

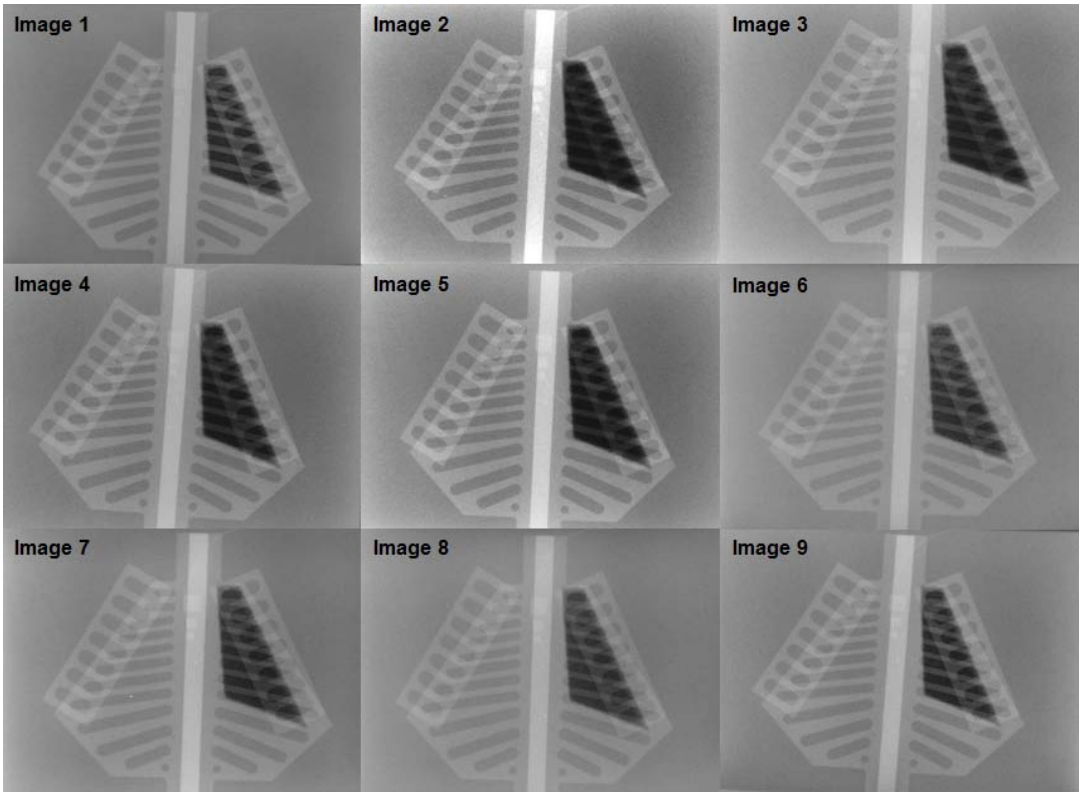

Figure 3 : Images obtained for evaluation. Image numbers correspond to those in Tables 3 and 4

V. Discussion

Exposure technique would influence the ESD and image quality. These factors thus had to be altered in combination with one another to achieve a decrease in ESD whilst image quality was maintained. Cancer induction is a stochastic risk, with no threshold dose, thus the smallest exposure to radiation has a chance of inducing cancer, e.g. leukaemia [1], in the young child. This emphasizes the importance of the ALARA principle. The risks with neonates are higher due to increased radiosensitivity and longer life expectancy. [7] Calculated relative cancer induction risks represent the risk up to the age of 15 years, but life time risks can be two to four times higher than this[18]. These risks cannot be ignored and must be reduced. [1,18]

Image 1 in Table 5 is the standard exposure image currently used for neonatal chest AP x-rays in Tygerberg Academic Hospital. Its image quality should be maintained and its ESD and relative cancer induction risk decreased in order to answer the aim of the study. The visual image quality of images 6 and 8 was comparable, image 6 was better than image 8 as it had the largest ESD reduction of about 63%. Image 7 was the best visually and had a significant ESD reduction of about 40%. The visual image quality of image 7 was about 27% better than that of the standard exposure image, image 1, as was that of image 3. Although image 3 had a slightly higher ESD than image 2, this was justified by its improved visual image quality. Image 9 was visually of lowest quality, a visual image quality that was comparable to that of image 1. However image 9 was registered a lower ESD than image 1, providing a higher overall ranking, and still answering the aim of the study. This was also the case with image 4. Image 5 performed average in the ESD and visual image quality criteria. Images 2-9 all had visual image quality comparable to or better than that of image 1, the standard exposure image, and all were obtained at reduced ESDs. Thus, all of these imaging options satisfied the aim of ESD reduction with image quality maintenance.

The relative cancer induction risk for image 1, the standard exposure image, was 1.8 – 8.3 per million for an average of 15 chest AP exposures. This risk had to be reduced to answer the aim of the study. The risk for image 3 was 1.7 – 7.9 and for image 7 it was 1.8 – 8.1 per million for 15 exposures. This was very comparable to the risk for image 1, although these images were obtained at ESDs 48% and 40% less than that of image 1. The risks for the remaining exposures in Table 5 were lower than that of image 1. It was decided that images 2, 4, 5, 6, 8 and 9 were more optimal options, with a greater relative cancer induction risk reductions than images 3 and 7. The ESD and relative cancer induction risk could be reduced, with maintenance or improvement of visual image quality, compared to the standard exposure.

This method of cancer induction risk calculation, although suggested in literature [7], did

have limitations. The NRPB tables did not make provision for the actual inherent, i.e. 1.5 mm Al, and total filtration with additional filtration of 0.1 mm Cu and 1 mm Al, i.e. 6 mm Al equivalent, filtrations used, thus the closest available values were used in approximation, i.e. the values for 2 mm and 5 mm Al filtrations. The coefficient for 1.5 mm Al filtration was expected to be lower than the one at 2 mm Al filtration, therefore the risk with such an exposure was also expected to be lower. Similarly, the coefficient for 6 mm Al filtration was anticipated to be larger than that of 5 mm Al filtration, which would result in a higher risk. The tables considered a narrow range of kV values only, so linear interpolation was used to derive the coefficients at the experimentally used kV settings. The coefficients were based on ICRP 60, quoting data applicable to adults, and not ICRP 103, which would have been more ideal. The science committee of International Organization for Medical Physics (IOMP) has expressed caution in the use of effective dose for estimation of cancer induction risks. [19] These considerations introduced uncertainties in the calculated risks. The risks in Table 5 are thus not absolute risks, but were used for quantitative relative comparison of the images in Table 5. As the results in Table 5 were used to relatively compare different exposures obtained in the same dose range this method was deemed acceptable for this study. Other options for cancer induction risk calculation include programs like Child Dose. [20]

Recommended images 6, 8 and 2 required additional filtration of 0.1 mm Cu and 1 mm Al, or a total filtration of 0.1 mm Cu and 2.5 mm Al. This was equivalent to 6 mm Al filtration. Additional filtration was not available on the mobile units used for neonatal chest x-rays. Additional filtration plates thus had to be stuck to the exit window of the tube after set-up, as these plates obstruct the light field. This can lead to retakes. Current mobile units can be fitted with commercially available filter assemblies that do not obstruct the light beam. Alternatively new mobile units, with additional filtration on a selection dial, could be acquired.

Images could be obtained as raw or processed. Raw images are more grainy. Raw mode can be selected at image readout. Images 5, 2 and 4 were obtained with raw image readout. In raw mode no inherent image processing occurred with the readout process. Processed images are the standard with the equipment used. Inherent image processing occurs with readout, making the images smoother and easier to look at.Images 6, 8 and 9 were processed images. All six of these images were recommendable options.

VI. Conclusion

Use of a self-developed phantom allowed derivation of optimised exposure protocols that decreased the ESD and relative cancer induction risk, while maintaining or even improving visual image quality. A total of six optimised exposure protocols were derived as images 6, 5, 8, 2, 9 and 4 in Table 4 and Fig 3. The most optimal protocol, giving the best relationship between ESD and image quality maintenance, was image 6 obtained as a processed image at 57 kV, 2 mAs, 100 cm FFD, fine focus and with additional filtration of 0.1 mm Cu and 1 mm Al (or total filtration equivalent to 6 mm Al). These protocols were recommended to the radiology department for implementation on real neonatal patients, which would clinically evaluate its acceptability and usability. Neonates are more sensitive to radiation, experience rapid cell division and growth, have a smaller body size and longer life expectancies. The ALARA principle must be honoured in order to minimise the stochastic risk of cancer induction in the young child, due to the care given to him or her as a neonate.

VII. Acknowledgements

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