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A multi institutional comparison of imaging dose and technique protocols for neonatal chest radiography

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ABSTRACT

Introduction: The focus on paediatric radiation dose reduction supports reevaluation of paediatric imaging protocols. This is particularly important in the neonates where chest radiographs are frequently requested to assess respiratory illness and line placement. This study aims to assess the impact of neonatal chest radiographic protocols on patient dose in four hospitals in different countries.
Methods: Exposure parameters, collimation, focus to skin distance (FSD) and radiation dose from 200 neonatal chest radiographs were registered prospectively. Inclusion criteria consisted of both premature and full-term neonates weighing between 1000 and 5000 g. Only data from the examinations meeting diagnostic criteria and approved for the clinical use were included. Radiation dose was assessed using dose area product (DAP).
Results: The lowest DAP value (4.58 mGy cm^2) was recorded in the Norwegian hospital, employing a high kVp, low mAs protocol using a DR system. The Canadian hospital recorded the highest DAP (9.48), using lower kVp and higher mAs with a CR system, including the addition of a lateral projection. The difference in the mean DAP, weight, field of view (FOV) and kVp between the hospitals is statistically significant ($p < 0.001$).
Conclusion: Use of non-standardised imaging protocols in neonatal chest radiography results in differences in patient dose across hospitals included in the study. Using higher kVp, lower mAs and reducing the number of lateral projections to clinically relevant indications result in a lower DAP measured in the infant sample studied. Further studies to examine image quality based on exposure factors and added filtration are recommended.
Implications for practice: Reevaluation of paediatric imaging protocols presents an opportunity to reduce patient dose in a population with increased sensitivity to ionising radiation.
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Introduction

Premature birth is the single most important cause of death in the first month of life and is a factor in over 75% of paediatric deaths in the neonatal period.[1] Neonates, especially those born prematurely, often suffer from respiratory and cardiovascular

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complications and may require hospitalisation and long periods of intensive care.[2] Chest radiographs are often used repeatedly in the first few weeks of life to assess the progress of disease and health status and to assess the placement of endotracheal tubes and lines.[3]

While being an essential diagnostic tool, the chest radiograph delivers ionising radiation with the potential to cause cell damage and is therefore associated with a radiation risk.[4] As a result, all x-rays must be justified and never used for routine monitoring of health status. Developing organs and tissues have rapid cell proliferation and therefore are more sensitive to the effects of radiation.[5] The longer life expectancy in children also allows more time for the manifestation of the harmful effects of radiation.[5] While there is some recent evidence that suggests low dose radiation such as that from medical procedures or occupational exposure may actually promote health, rather than risk, the majority of studies examine exposure in the adult population.[6] A number of studies[7–9] indicate that early exposure to ionising radiation, specifically chest x-ray exposures, may increase breast cancer risk in female patients. Studies[7–11] also indicate that many types of exposure, such as chest x-rays, chest fluoroscopy and CT that occur at a young age are associated with a higher risk of cancer. Repeated low dose exams such as chest x-rays can eventually lead to larger cumulative doses.[6]

Although the radiation dose associated with chest imaging is low and the medical benefit largely out-weighs the risk, the possibility of stochastic effects must be considered. The Image Gently campaign was established in 2007 to raise awareness about these issues and to promote that the radiation dose from these examinations be kept as low as reasonably achievable, while at the same time maintaining adequate image quality to meet diagnostic requirements.[12,13] International Council for Radiation Protection (ICRP) guidelines from 2007 also emphasised this.[14] The European Commission guidelines on radiation protection state that diagnostic reference levels (DRLs) represent powerful tools for optimisation of exposure techniques. They recommend establishment of local DRL as well as comparison with the published national and international data.[15]

Chest radiograph protocols in paediatric departments may differ from recommended practice, and a lack of reference protocols leaves the choice of exposure parameters up to individual hospitals. Furthermore, the implementation of digital imaging technology provides new opportunities for optimisation. As such, the focus on paediatric radiation dose reduction has increased and supports the need to re-evaluate paediatric imaging protocols. Several studies have examined chest image quality and the effect of various factors such as radiation spectrum, digital or computed radiography systems, x-ray tube, filtration, collimation, and grid use on patient dose.[16–21] One initial step in the optimisation process in neonatal chest radiography is to review the existing technique protocols and resulting doses for neonatal chest radiographic examinations. The authors questioned if exposure parameters were consistent for imaging this population around the world. The aim of this article is to investigate the employed imaging protocols and their impact on patient dose in four different hospitals in four different countries.

Methods and procedure

Sample size

Four university hospitals in four different countries where universities had a previously existing relationship participated in the study. In 2018 the approximate annual birth rates in the Norwegian hospital were 2500, 4600 in the Canadian hospital, 541 and 2467 in the South African and Portuguese hospitals, respectively. Exposure parameters and radiation doses from acquired neonatal chest x-rays were collected prospectively at the four hospital sites between July 2017 and March 2018. Three university affiliated hospital sites collected data from 50 anterior–posterior (AP) chest images (one AP chest image per patient) and one collected data from 50 AP and 50 lateral chest images (one AP and one lateral chest image for the same patient). The study consisted of a total of 200 AP exposures and an additional 50 lateral exposures in the Canadian hospital.

Premature (gestational age <37 weeks) and full-term neonates (<4 weeks) weighing between 1000 and 5000 g were included. Only data from the examinations meeting the diagnostic criteria and that were reported by a radiologist at the participating hospital were included in this study.

Data acquisition

All AP images were recorded supine, with a straight tube within the incubator. The image receptor was placed directly under the patient, without anti-scatter grid or in the incubator tray. Two collection sites used digital radiography (DR) and two used computed radiography (CR) (see Table 1). The following measurements were recorded: gestational age, weight, peak kilovoltage (kVp), product of tube current and exposure time (mAs), source to image distance (SID), field of view (FOV), and dose-area product (DAP). SID was measured in cm and was 100 cm in all the participating centres.

FOV measurements were performed on the Picture Archiving and Communications System (PACS) for all hospitals. In Canada, the focus to skin distance (FSD) was calculated by measuring the infant thickness on the lateral images and infant width on the frontal image. A lead marker was used on all Canadian images to ensure that there was no magnification when measuring patient thickness. The marker size was known and measured on all resultant images to ensure images on the PACs were true to size.

DAP values were measured by DAP meter in the Norwegian and Portuguese sites, and calculated for the Canadian and South African sites using the following formula[22]:

$$\mathrm{DAP} = \frac{\mathrm{mR}}{\mathrm{mAs}} \cdot \mathrm{mAs} \cdot 0.0087 \cdot \left(\frac{\mathrm{SID}}{\mathrm{FSD}}\right)^2 \cdot \mathrm{FOV}$$

where 0.0087 (mGy/mR) is the conversion factor from exposure to absorbed dose in air; mAs used for the examination; (mR/mAs) is radiation output measured at 100 cm from the source for the kVp used in the examination. It was corrected for the focus-skin distance according to inverse square law.

The radiation output measurements are part of the routine Quality Control (QC), which also include kVp accuracy, half-value layer (HVL) measurement, mAs linearity and output reproducibility tests. This data is summarised in Table 2 for all 4 involved hospitals. Since the QC program typically follows national guidelines and regulations for radiation protection, the testing procedures may vary, e.g. in Portugal all measurements were performed only at 80 kVp.

No evaluation of image quality was performed in this study. However, data collected in this study includes only exposure parameters and patient dose for images approved by radiologists for clinical use.

Statistical analysis

Descriptive statistics were presented by centre for weight and exposure factors using R language for statistical computing version 3.4.4.

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Table 1
Equipment used in the participating hospitals.

Equipment	Norway	Portugal	South Africa	Canada
Type	DR	DR	CR	CR
Manufacturer	Carestream DRX-Revolution Mobile X-ray System	Carestream DRX-Revolution Mobile X-Ray system	Siemens Mobilette Plus	Shimadzu Mobile Art Plus MUX-100H
Filtration (inherent)	2.9 mm AL	2.7 mm AL	2.8 mm AL	2.5 mm AL
Detector	Carestream DRX 2530C	Carestream DRX-1C	CR plate	AGFA DX-M digitizer and AGFA CR MD4.0
Detector size	25 × 30 cm	35 × 43	18 × 24 cm or 24 × 30 cm	20 × 25 cm

DR = Digital Radiography; Al = Aluminium; cm = centimetre; CR = Computed Radiography.

Table 2
Quality control results.

kVp	Norway		South Africa		Canada	
	kVp accuracy	HVL, mm Al	kVp accuracy	HVL, mm Al	kVp accuracy	HVL, mm Al
40	1.6%	1.3	N/A	N/A	4.6%	1.3
50	1.0%	1.8	0.2%	2.2	3.9%	2.0
60	1.7%	2.1	0.2%	2.6	4.2%	2.2
70	0.7%	2.4	3.9%	3.1	2.8%	2.6
80	N/A	N/A	5.7%	3.5	N/A	N/A
kVp repeatability[a]	0.25%		0.28%		0.12%	

**In Portugal all exposures were performed at 80 kVp with accuracy of 0.1% and repeatability of 0.2%.
***All units demonstrated a linear correlation between mAs and radiation exposure with $R^2 = 1$.
[a] The repeatability was calculated as STD/mean, where STD is standard deviation.

Boxplots and scatterplots were used to show the relationship between DAP and weight, as well as DAP and other exposure factors.

One-way ANOVA was used to evaluate the differences between means of exposure factors by centre, and p-values <0.001 indicated differences statistical significantly different than 0.

Pearson correlation coefficients (R) were used to demonstrate strength of the linear relationship between dose and weight, and p-values <0.001 indicated R-values statistically significantly different than 0.

Ethics

The study was performed with institutional review board approval from the hospital research ethics board in Canada, Norway, Portugal and South Africa. Where required, written informed consent was obtained.

All recorded patient data was anonymous, each patient was assigned a numerical identifier and no images were stored or transferred outside of the participating hospitals for the purpose of the study. None of the examinations deviated from normal protocol.

Results

The median infant weight measurement in grams was higher in Norway compared to South Africa with the lowest median infant weight measurement (Table 3). A model of dose by country was performed, and a model of dose by country controlling for weight. Adding weight to the model confirmed that the difference in dose between the two countries does not affect the observed dose difference between countries.

The results showing collected exposure factors, DAP values and FOV utilised are summarized by country in Table 4 and Figs. 1–3. Both CR systems in Canada and South Africa used the same median kVp and similar median mAs values (Table 4). A higher kVp was used in the x-ray unit equipped with DR systems compared to the ones with CR which were using higher mAs (Fig. 1a,d). The lowest median DAP is in Norwegian hospital (DR) where the median weight of the patient sample was the highest. The South African hospital (CR) has the second lowest median DAP, followed by the Portuguese hospital (DR). For the AP projection the median DAP value in Portugal is the highest with a large range in values. The Pearson Correlation Coefficients (R) and associated p-values are shown on Fig. 3, demonstrating strong correlation between the dose and weight in Norway (R = 0.698) and Canada (R = 0.555) and weak correlation for South Africa (R = 0.277) and Portugal (R = 0.219). The total DAP from the examination is the highest in the Canadian hospital (CR) because of the additional lateral projection (Fig. 2).

The FOV median and range was the largest in Portugal (Fig. 1b) when compared to infants of the same weight in Norway (Fig. 1c). The FOV in the Canadian and South African hospitals was also larger than the FOV recorded in the Norwegian hospital. The difference in the mean DAP, weight, FOV and kVp between countries is statistically significant ($p < 0.001$).

The mean estimated entrance skin dose (ESD) in μGy was the highest at the hospital in Portugal at 81.4 ± 58.4, followed by Canada (AP projection) at 57.7 ± 5.9, South Africa at 55.3 ± 18.4 and lowest in Norway at 35.3 ± 10.7 (Table 4).

Table 3
Infant weight, premature and full-term infants.

	Norway	Portugal	South Africa	Canada
Median infant weight in grams	2550 g	1760 g	1600 g	1704 g
Weight range (g)	800–4600	1102–2990	1000–3000	1000–2850
Premature infants %	56%	78%	84%	86%
Full term infants %	44%	22%	16%	14%

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Table 4
Exposure factors, ESD, DAP values and FOV for participating hospitals.

Exposures	Canada		Norway	Portugal	South Africa
	AP	LAT	AP	AP	AP
kVp					
Mean, ±std	54.76 ± 1.91	55.06 ± 1.95	66.80 ± 4.94	64.02 ± 5.43	54.38 ± 1.38
Median	55.0	55.0	68.5	65.0	55.0
Range (min–max)	50–58	50–60	59–73	50–75	50–55
mAs					
Mean, ±std	1.61 ± 0.05	1.61 ± 0.05	0.69 ± 0.04	1.19 ± 0.46	2.05 ± 0.59
Median	1.60	1.60	0.71	1.10	1.80
Range (min–max)	1.60–1.80	1.60–1.80	0.56–0.71	0.56–2.20	1.25–3.20
DAP (mGy cm^2)					
Mean, ±std	9.48 ± 2.42	9.58 ± 2.52	4.58 ± 1.87	17.48 ± 12.87	10.40 ± 6.21
Median	8.87	9.07	4.20	13.65	8.86
Range (min–max)	5.18–15.96 Median total DAP[a]: 17.75	4.92–15.58	1.10–8.50	3.10–52.80	3.40–30.89
Field-of-view (cm^2)					
Mean, ±std	221.01 ± 45.36	217.96 ± 45.05	172.74 ± 46.51	319.64 ± 159.04	249.50 ± 100.56
Median	216.49	214.89	174.10	273.25	235.13
Range (min–max)	138.47–323.08	127.14–316.22	90.60–296.70	89.99–890.46	105.00–561.00
ESD (μGy)					
Mean, ±std	57.65 ± 5.90	43.07 ± 5.17	35.35 ± 10.71	81.43 ± 58.40	55.33 ± 18.36
Median	57.44	43.63	34.76	61.98	47.79
Range (min–max)	44.47–74.47	30.00–54.27	13.56–64.90	18.42–298.86	18.36–102.09

[a] Total DAP includes AP and LAT projections.

Discussion

The results of this multi-centre study showed the lowest DAP value and lowest ESD was recorded in the Norwegian hospital, which employed a high kVp, low mAs protocol using a DR system. This hospital also had babies with the highest median infant weight. The Canadian hospital recorded the highest DAP, using lower kVp and higher mAs in a CR system, along with the addition of a lateral projection. Collimation varied in all four hospitals and the larger FOV contributes to patient dose, While an increase in patient dose that corresponds with an increase in weight is not unexpected, the hospital with the highest median infant weight recorded the lowest DAP value. This study shows significant differences in patient dose in chest radiography in the four hospitals involved.

The available QC data demonstrated that x-ray beams from three units had similar quality with a slightly harder beam (i.e. higher HVL) in South Africa, as demonstrated in Table 2. There were no sufficient radiation measurement data from the hospital in Portugal due to variability in the QC requirements in different countries. Based on the provided information, the most probable reason for the difference in patient dose is variations in the acquisition for the same examination and not the equipment.

Optimisation of protocols for neonatal chest imaging according to image quality and radiation dose is essential.[3] Exposure parameters should be adequately tailored for paediatric patients, and DRLs should be implemented to assist in the optimisation and dose reduction.[5] When exposure parameters are chosen manually, often for portable chest radiography or paediatric chest examinations, radiographers tend to favour overexposure over underexposure. The resulting 'dose creep' can cause a gradual increase in exposure parameters over time.[23] Transition from film screen systems to digital receptors without a change in protocol results in low noise images produced by overexposed image receptors.[24] Without standardization of protocols in routine practice, a wide variation of doses may be received by the same neonate during hospitalisation.[2] Radiation dose can be increased without visible change in the final image and therefore different hospitals, using different imaging parameters can show variation in radiation dose.[25] These results show a wide range in DAP values in a couple of participating hospitals (Table 3). Both the dose and range of DAP values can be reduced if a more common and standardised protocol will be used, as suggested by earlier studies carried out by Frayre et al.[2] and Stollfuss et al.[25]

Furthermore, these results show that the standard projection is not solely the AP, as the Canadian hospital included both AP and lateral images of the chest in the daily examination. This additional image, with a median DAP of 9.07 when combined with the median DAP of 8.87 from the AP projection, shown in Figs. 2 and 3 results in a higher dose to the Canadian sample. Inclusion of the lateral DAP is an important factor in assessing the actual dose received. Reasons to perform a lateral radiograph could be to more accurately assess the extent of cardiac or respiratory disease or the position of lines and tubes. However, the lateral images appear to not be part of protocols elsewhere in the world. It appears from the results that reduction of the number of lateral projections to clinically relevant indications would reduce the total radiation dose to the patient sample.

Collimation plays an important role in reducing scatter radiation, increasing image quality and decreasing patient exposure.[25] Wide transverse collimation boundaries risk upper arm exposure and the irradiation of red bone marrow,[25] and under-collimation can lead to higher organ doses in premature babies.[4] Close collimation reduces dose and reduces the amount of scatter, although the effect in neonates is relatively small compared to adults.[25] Morrison et al.[26] found that many radiographers widen their collimation to counter possible patient motion and repeated image acquisition. This increased FOV results in increased patient dose.[26] Careful collimation can reduce patient exposure by limiting the x-ray field to the area of interest. In this study, the size of the collimation is much smaller in Norway where the median patient weight is highest (Fig. 1b) showing no reasonable correlation between the size of the patient and employed collimation in the remaining involved hospitals. Consultation and collaboration

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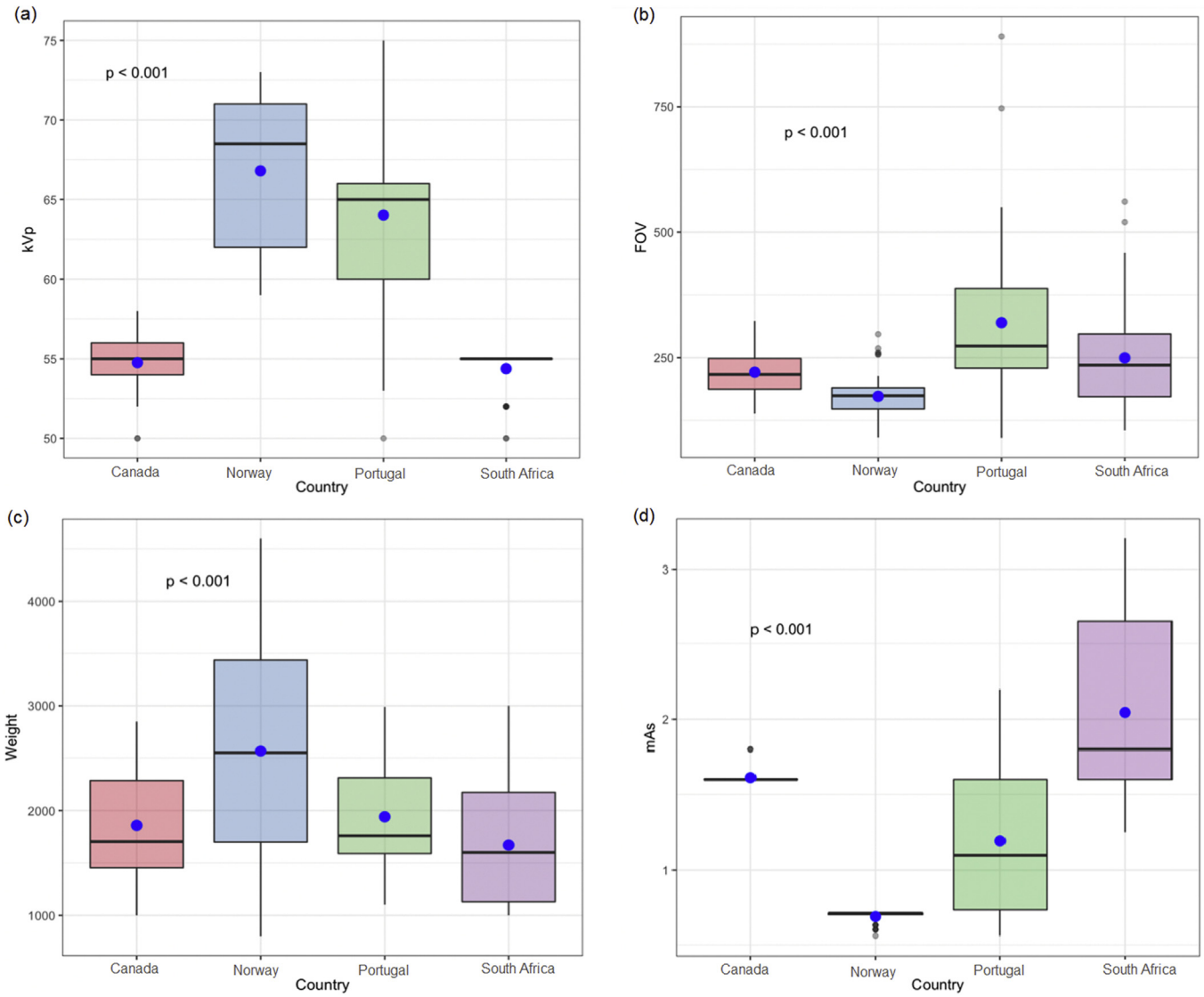

Figure 1. (a–d): Box–whisker plots of kVp, collimation (cm^2), weight (g), and mAs distributions for AP chest images at participating hospitals. Boxes and whiskers represent 100% of the data distribution. The two boxes in the middle represent a total of 50% of the data distribution and all data beyond the boxes represent 25% of the data distribution on either side (for a total of 50%). The points at the ends of the box plot whiskers are the extreme values at either end of the distribution of values. The blue dots in the boxes represent the mean, and the lines represent the median for each figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

amongst practitioners with regards to the impact of collimation on dose and image quality would be of benefit.

At lower kVp images show higher contrast, and possibly increased quality due to an improved signal to noise ratio (SNR).[23] However, employing higher kVp (and resulting lower mAs) technique is considered best practice in digital imaging in order to reduce radiation dose.[27] The goal is to produce an optimum exposure with acceptable noise level without unnecessary exposure to the infant.[2] As hospitals move to DR systems with higher detective quantum efficiency, it is important to modify parameters that decrease patient dose so as not to miss an opportunity for dose reduction. Both hospitals using CR systems (South Africa/Canada) employed low kVp and higher mAs for imaging and as a result have higher DAP values than the Norwegian hospital despite having babies of lower weight. While having a higher mean kVp and lower mean mAs values than the CR counterparts, the Portuguese hospital did not have a similar total DAP reduction and this may indicate that there is a potential for dose reduction in this site.

European guidelines[28] recommend the addition of up to 1 mm of aluminium (Al) or 0.1–0.2 mm of copper (Cu) filtration. The addition of copper filtration shows considerable reduction in dose to superficial organs such as the breast, and filters of up to 0.2 mm have been shown to decrease entrance skin dose (ESD) by up to 39%.[28] This is achieved with no decrease in image quality.[29] However, none of the centres involved in this multi-institutional study employed the use of added filtration as the units did not have a filter wheel to allow additional filtration.

Hinojos-Armendariz et al.[30] tested two different exposure protocols. The standard used low kVp, higher mAs and no filtration and

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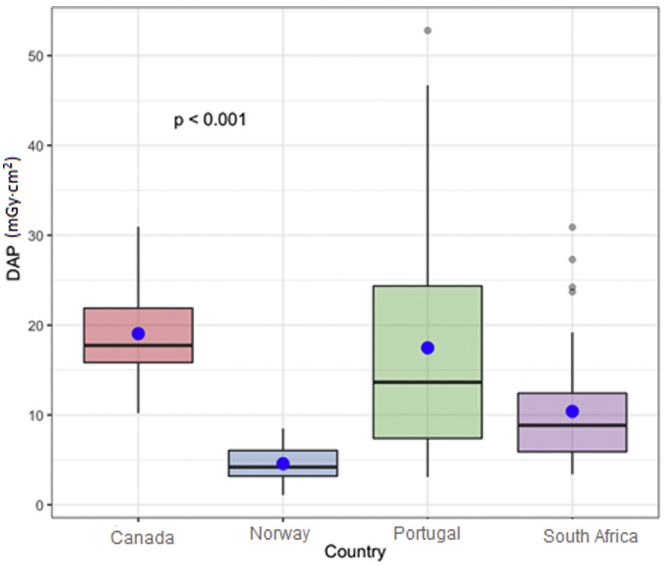

Figure 2. Box–whisker plots of DAP (mGy cm^2) values distribution for participating hospitals. Both AP and LAT projections are included for Canada. Boxes and whiskers represent 100% of the data distribution. The two boxes in the middle represent a total of 50% of the data distribution and all data beyond the boxes represent 25% of the data distribution on either side (for a total of 50%). The points at the ends of the box plot whiskers are the extreme values at either end of the distribution of values. The blue dots in the boxes represent the mean, and the lines represent the median for each figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the experimental used higher kVp, lower mAs and the addition of 2 mm of Al filtration. Despite differences in radiologist ratings, there was no significant difference between the two imaging acquisition techniques, supporting they were perceived as equivalent. An increase in tube potential and addition of filtration resulted in a reduction of radiation dose by more than 40% with negligible effects on image quality.[30] Similar effects are observed in this study. The hospital employing the highest kVp, inherent filtration and lowest mAs recorded the lowest DAP.

These findings suggest the potential benefit of possible future studies, including surveying neonatal chest imaging protocols in many diagnostic imaging centres in each country of interest to develop a standard or reference protocol. Analysis of equipment type, as well as examining the impact of added aluminium or copper filtration and exposure parameters on image quality may determine trends or define protocols for dose reduction in future neonatal chest imaging. Transition to DR systems for the centres involved also may also provide an opportunity for dose reduction.

Study limitations

There are several limitations to this study as performed.

DAP meters in countries involved were not tested for consistency, however it is assumed each would provide the same measure if a "standard" amount of radiation was used. As a result, some variance between hospitals could be due to variations of DAP outputs.

The study did not include data describing the image quality other than that the images were considered to be acceptable for the reporting radiologists. Different thresholds for what was an acceptable image in the different sites would have an impact on the protocols. To evaluate the resulting image quality when using the different protocols, further study (e.g. a phantom study) would be appropriate. The phantom study is being performed in one the participating hospitals in the current study.

The Norwegian study participants had a wider weight range. If the study only included smaller neonates (1000–3000 g) only 25 neonates from Norway would be included in that category. However, the correlation analysis showed the same results for the Norwegian neonates' weight between 1000 and 3000 g as for the weight between 1000 and 5000 g (Fig. 3).

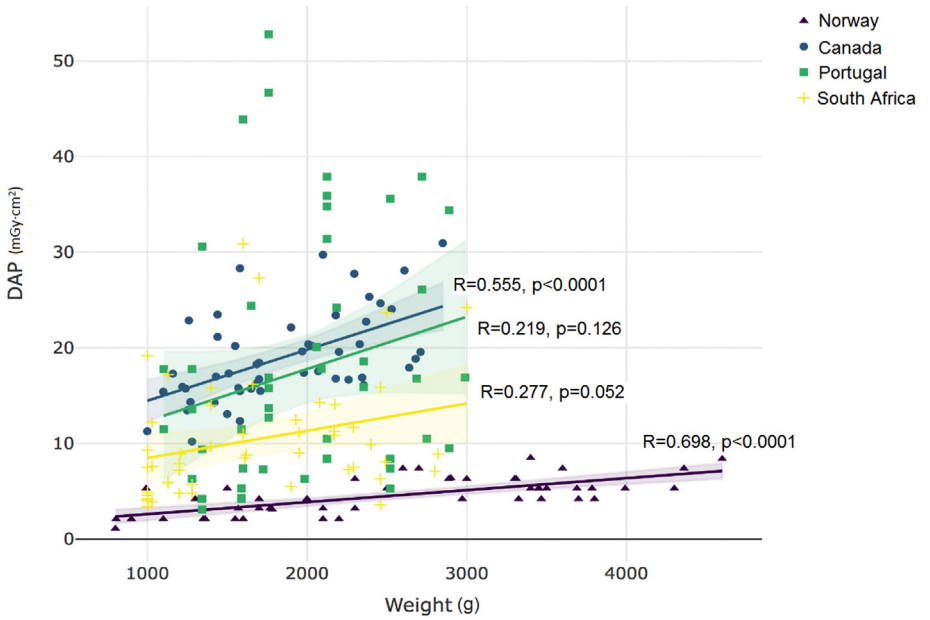

Figure 3. DAP (mGy cm^2) distribution vs. patient weight (g). The DAP value from Canada includes both AP and LAT projections, all other hospitals show only AP view.

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Conclusion

The study has highlighted a number of potential areas for standardisation of exposure parameters and recommendations for modification of neonatal chest radiograph protocols. Neonatal chest radiograph protocols, in particular the non-standardised exposure parameters and collimation, seem to have impact on patient dose and exposure variation across the four different hospitals worldwide. This study has shown that using higher kVp, lower mAs and reducing the number of lateral projections to clinically relevant indications result in a lower DAP measured in the infant sample studied.

The centres evaluated in Canada, South Africa, and Portugal exhibited higher DAP on babies of lower weight than did the Norwegian centre. Further studies examining the impact of exposure factors on image quality as well as the addition of copper filtration on image quality and dose are recommended.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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