Dose evaluation for digital X-ray imaging of premature neonates

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DOSE EVALUATION FOR DIGITAL X-RAY IMAGING OF PREMATURE NEONATES

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X-ray radiography is a commonly used diagnostic method for premature neonates. However, because of higher radiosensitivity and young age, premature neonates are more sensitive to the detrimental effects of ionising radiation. Therefore, it is important to monitor and optimise radiation doses at the neonatal intensive care unit (NICU). The number of x-ray examinations, dose–area product (DAP) and effective doses are evaluated for three Dutch NICUs using digital flat panel detectors. Thorax, thorax–abdomen and abdomen protocols are included in this study. Median number of examinations is equal to 1 for all three hospitals. Median DAP ranges between 0.05 and 1.02 $\mu\text{Gy m}^2$ for different examination types and different weight categories. These examinations result in mean effective doses between 4 ± 4 and $30 \pm 10 \mu\text{Sv}$ per examination. Substantial differences in protocols and doses can be observed between hospitals. This emphasises the need for up-to-date reference levels formulated specifically for premature neonates.

INTRODUCTION

At the neonatal intensive care unit (NICU) x-ray imaging is used for a variety of diagnostic purposes, including diagnosing lung and bowel disease and determining the correct positioning of tubes and central lines. A substantial number of premature neonates experience one or more x-ray examinations during their stay at the NICU.

While ionising radiation doses should always be as low as reasonably achievable (ALARA-principle)⁽¹⁾, this is even more important in preterm infants. Since a tissue's sensitivity to radiation is directly proportional to its rate of proliferation, prematurely born babies are more sensitive to radiation because of the highly mitotic state of their cells⁽²⁾. Also, because of their young age premature babies are particularly vulnerable to delayed detrimental effects of ionising radiation⁽³⁾.

Moreover, due to their small size it is often a challenge to collimate correctly, in order to image only

the required area of interest. This under-collimation can lead to higher organ doses in premature babies⁽⁴⁾.

In addition, preterm infants are imaged while lying in an incubator. In order to get an acceptable image quality, a sufficient detector dose is necessary. When trying to achieve the same detector dose, placing the detector in the incubator imaging tray results in higher radiation doses for the patient when compared to placing the detector directly on the mattress⁽⁵⁾. However, using the incubator tray can have benefits in terms of hygiene and might even be necessary for unstable neonates.

To encourage good clinical practice in radiology, diagnostic reference levels (DRLs) have been determined for a variety of diagnostic procedures in radiology and nuclear medicine. The concept of DRLs was introduced by the International Commission on Radiological Protection (ICRP) in 1996 as an advisory tool⁽⁶⁾. In practice, DRLs are established by professional medical bodies, using a percentile point on

the observed patient distribution. DRLs are specific for a certain country or region.

In the last years some articles have been published regarding DRLs for premature babies^(7–9). However, no studies comparing neonatal dose–area product (DAP) values and investigating possible DRLs have been published in the Netherlands so far. Furthermore in the DRL studies mentioned before no distinction between computed radiography (CR) and flat panel digital radiography systems is made. Because of the increasing number of institutions switching to flat panel digital radiography systems, which in general allow for a substantial dose reduction, this is a major limitation.

The aim of this work is to evaluate the number of examinations and dose data in three Dutch NICUs, which all use mobile radiography systems equipped with digital flat panel x-ray detectors. The results can be used as a benchmark for radiation doses in digital neonatal x-ray imaging. Also, the results give an insight in the dose effect of using the incubator imaging tray.

MATERIALS AND METHODS

Hardware

This study is a collaboration between three Dutch NICUs with similar populations, coded A, B and C in this study. At all three NICUs mobile x-ray systems with a digital flat panel detector are being used. Hospital A uses a Carestream DRX-Revolution Mobile X-ray System (Carestream Health Inc., Rochester, NY, USA) with a digital caesium-iodide detector (Carestream DRX 2530-C). DAP is measured with a Diamentor CI (PTW, Freiburg, Germany). Hospitals B and C use a Shimadzu MobileDaRt Evolution (Shimadzu Corporation, Kyoto, Japan) with a compact Canon CXDI-80C caesium-iodide detector (Canon Inc., Tokyo, Japan). For DAP measurements a Vacudap 2004 (VacuTec Meßtechnik GmbH, Dresden, Germany) is used.

It should be mentioned that in Hospital A the DAP was recorded to an accuracy of $0.01 \mu\text{Gy m}^2$, while in Hospitals B and C the resolution was equal to $0.1 \mu\text{Gy m}^2$. For both the Diamentor CI and the Vacudap 2004 DAP response in the low DAP range was verified by measurements with a Raysafe Xi Platinum (Unfors Raysafe, Billdal, Sweden) and a

Piranha 657 (RTI Group, Mölndal, Sweden), respectively. It was also found that DAP values at Hospitals B and C are always rounded down. Because of this $0.05 \mu\text{Gy m}^2$ was added to all DAP values collected at Hospitals B and C.

Data collection

All x-ray examinations performed in the NICUs over a 2-year period were retrospectively analysed. For Hospitals A and B the period ranged from November 2013 to November 2015, for Hospital C from February 2014 to February 2016. A total number of 4461 radiographs were analysed: 1356 in Hospital A, 1395 in Hospital B and 1710 in Hospital C.

All radiographs for neonates stored in the Picture Archiving and Communication System (PACS) were used for this analysis. In this study only anterior–posterior images were taken into account for DAP and effective dose analysis. To determine the cumulative number of x-rays per patient, lateral images were also taken into account.

Relevant parameters like DAP, peak tube voltage and tube current were retrieved from the DICOM headers using in house developed code written in MATLAB (MathWorks, Natick, MA, USA).

Patient weight estimation

Patient weight at the time of an x-ray examination was not registered. Therefore, the patient weight was estimated from the peak tube voltage by using the weight based imaging protocols in each hospital. To validate whether this estimation is justifiable, the settings at Hospital A were analysed. The peak tube voltage of x-rays made within two days after birth, was compared to the birth weight of the patient. Of all patients evaluated at Hospital A, 274 patients had an x-ray made within two days after birth. The relationship between peak tube voltage and birth weight of these 274 patients was compared to the imaging protocol at Hospital A.

Clinical protocol

In this study thorax, combined thorax–abdomen and abdomen examinations were studied.

The hospitals studied use different clinical protocols. The protocols for thorax examinations are given

Table 1. Imaging protocols for thorax examinations in Hospitals A, B and C.

	Focus-detector distance (cm)	Peak tube voltage (kV)	Tube current–time product (mA s)	Detector position
Hospital A	92.5	58–72	0.50–0.63	Tray
Hospital B	135–160	60–70	0.71–1.0	Under patient/tray
Hospital C	100	58–67	0.32–0.40	Under patient

in Table 1. One major difference is the position of the x-ray detector. The detector can be placed in the incubator tray, which is positioned under the mattress support structure, or directly under the patient. In Hospital B the detector position varies, depending on the stability of the patient. Furthermore, different focus to detector distances are used in the different hospitals. Finally, in each hospital x-ray tube settings are adjusted to patient weight as well as to the detector position.

Effective dose calculation

In order to gain insight into the possible health effects of the anterior–posterior x-ray examinations, mean effective doses per weight category were calculated. The effective dose was calculated using the weighting factors given in the International Commission on Radiological Protection (ICRP) 103 report⁽¹⁰⁾. Effective dose calculations were performed using the Monte Carlo program PCXMC 2.0 (STUK Radiation and Nuclear Safety Authority, Helsinki, Finland). This program calculates the effective dose according to ICRP 103 using peak tube voltage, DAP, patient height, patient weight, patient age, field of view (FOV), filtration, anode material and focus–skin distance as input. For each examination type in each hospital the mean DAP and FOV per weight category were obtained from the patient data and used as an input for PCXMC. The patient height used as input was scaled with the patient weight using preterm growth charts⁽¹¹⁾. As the phantom model in PCXMC is hermaphrodite, the average of the lengths for boys and girls was used for each weight category. Other input parameters were obtained from the machine specifications and the clinical protocols.

Statistical analysis

For the number of examinations per patient the median value and interquartile ranges were used, because of the non-normal distribution. However, to compare to literature, the mean was also calculated as this is the value noted in several other studies^(8, 12–17).

To compare the distributions of the number of examinations per patient in the three hospitals a chi-square test for homogeneity was performed. To achieve a chi-square distribution the number of counts per cell has to be sufficiently high. In this case this means that a sufficiently high number of patients has to undergo some amount of x-ray examinations in order to be able to perform a chi-square test on the distribution. Because the number of patients undergoing a high amount of examinations is low, only patients undergoing 10 or fewer examinations were taken into account for the homogeneity test.

The DAP values are considered non-normally distributed and the median value and the 25th and 75th

Figure 1. Histograms of the number of examinations per patient during NICU stay for (a) Hospital A, (b) Hospital B and (c) Hospital C. The number in the top left corner gives the height of the bar at zero examinations per patient.

percentile are given. In order to facilitate an easy comparison with the literature, mean values are also given in the results section.

The reported effective dose values are mean values. To estimate the error in the effective dose, the PCXMC calculations were repeated with the same input values, except for the DAP and FOV. The positive and negative variation were estimated by using the mean DAP and FOV plus and minus the standard deviation in the data as an input for PCXMC. The number of photons simulated in PCXMC was chosen such, that the variation in DAP and FOV is much bigger than the uncertainty of the Monte Carlo simulation. The error introduced by the fact that PCXMC uses scaled mathematical phantoms was neglected, since PCXMC calculations agree with the effective dose calculated in voxel phantoms of premature neonates⁽¹⁸⁾.

RESULTS

Because of the large amount of collected data, the dose results, including figures and tables, presented in the main body of this paper only include thorax examinations. For the thorax–abdomen and abdomen examinations the results are briefly described here, while more details can be found in the Supplementary material. However, to give an insight in the total impact of x-ray examinations at the NICU, the distribution of examinations per patient shows the total of all types of examinations.

Number of examinations

The total number of examinations per patient during a NICU stay in the three hospitals is shown in Figure 1.

The median number of examinations is equal to 1 in all three cases, with an interquartile range of 4. The mean number of examinations per patient is equal to 2.2 in Hospital A, 2.6 in Hospital B and 2.7 in Hospital C. In order to gain a realistic insight in the number of radiographs for an average patient at the NICU, patients undergoing no x-ray examinations were also taken into account in these numbers. However, it should be noted that in other studies,

patients receiving no x-ray examinations are not always taken into account when calculating the mean or median number of radiographs per patient^(8, 12–16, 19). If these patients are left out when calculating the median and mean number of examinations, the medians change to two examinations per patient for each hospital and the means change to 4.0, 4.5 and 4.1 examinations per patient for Hospitals A, B and C, respectively. The maximum number of examinations observed for one patient is equal to 50.

The three histograms show some similarities and the median number of examinations and interquartile ranges are the same. However, according to a chi-square test for homogeneity the distributions are not statistically homogeneous with a probability of 0.99.

Patient weight estimation

The results in Table 2 show that for most weight categories, the actual weight agrees with the used protocol. For the two lowest weight protocols the weight in the protocol is not within the middle 50% of the actual observed patient weight. Still, it was further assumed that patient weight at the time of a radiograph can be estimated from the peak tube voltage used.

Dose–area product

Box plots depicting the median DAP and the interquartile range of the data, are presented in Figure 2. The exact values are given in Table 3. Hospitals A and C use multiple differentiated weight categories, while Hospital B uses only two weight categories. In Hospital B the protocols for imaging with the detector in the incubator tray differ from those with the detector under the patient, resulting in a higher 75th percentile of the DAP and higher DAP outliers for the same weight category. When comparing the median DAP in Hospital A, where the incubator tray is used, to Hospital C where the detector is placed directly under the patient, the same trend can be observed. It can also be observed that the interquartile range in Hospital A is relatively small.

Table 2. Relationship between peak tube voltage, patient weight according to protocol and actual patient weight.

Peak tube voltage (kV)	Weight category according to protocol (g)	Actual patient weight (median (25th–75th percentile)) (g)	Number of patients analysed
58	450	715 (484–1034)	11
60	600	773 (634–785)	29
62	1000	991 (826–1066)	69
63	1300	1320 (1211–1401)	33
64	1700	1673 (1560–1830)	46
66	2500	2350 (2110–2530)	26
68	3200	3195 (2905–3355)	30
70	3800–4200	3750 (3630–3970)	18

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Figure 2. Box plots of the dose-area product per weight category for thorax examinations at (a) Hospital A, (b) Hospital B, with examinations with the detector in the incubator tray shown as a notched box plot and (c) Hospital C. The DAP is only given for weight categories containing more than 15 data points.

For Hospitals A and C the results for combined thorax–abdomen examinations can be found in the Supplementary material. Both graphs show an increase of DAP with growing patient size. In Hospital B no distinct thorax–abdomen protocol is being used.

In Hospital C the abdomen protocol was rarely used. In Hospital A for the abdomen protocol the trend in DAP is similar, while the values are slightly higher than those found for thorax examinations. For Hospital B, the values found for abdomen examinations are higher than those found for thorax examinations.

Effective dose

The effective doses calculated for anterior–posterior thorax examinations are shown in Figure 3. The error margins were estimated from the variation in input parameters, as explained in the Statistical analysis section. The values are also given in Table 4. It can be observed in Figure 3a that at Hospital A for weight categories bigger than 3200 g the effective dose is increased, which corresponds with an increase in tube current–time product in the protocol. In Figure 3b it can be observed that the mean effective dose is higher when using the incubator tray. Hospital C shows the lowest effective doses, the standard deviation is relatively big.

For both combined thorax–abdomen and abdomen examinations the effective doses show a trend that is similar to the thorax examinations. Mean effective doses are higher for both thorax–abdomen and abdomen examinations when compared to thorax examinations.

DISCUSSION

The main goal of this study was to evaluate x-ray doses in three Dutch NICUs using digital x-ray systems. The obtained data can be used as a benchmark for radiation doses in a vulnerable population. To facilitate a comparison between our data and literature values an overview of recent patient studies is given in Table 5.

Compared to literature values ranging between 2 and 25.9, the number of radiographs per patient in our study was relatively low, even when patients undergoing no x-ray examinations at all are not taken into account. Estimation of actual patient weight at the time of a radiographic exam was based on the peak tube voltage and the imaging protocol. For the two lowest weight protocols the weight of the imaging protocol is just outside the middle 50% of the observed patient weight. This could be caused by the fact that for smaller neonates the tube voltage is rounded down, in order to keep the radiation dose

Table 3. Median and mean DAP values and the number of examinations per weight category for thorax examinations at the three hospitals. Values based on 15 examinations or less are shown in *italics*.

Weight category (g)	Hospital A			Weight category [g]	Hospital B			Weight category (g)	Hospital C		
	DAP (median (25th–75th percentile)) (μGy m ²)	DAP (mean ± SD) (μGy m ²)	Number of exams		DAP (median (25th–75th percentile)) (μGy m ²)	DAP (mean ± SD) (μGy m ²)	Number of exams		DAP (median (25 th –75 th percentile)) (μGy m ²)	DAP (mean ± SD) (μGy m ²)	Number of exams
450	0.18 (0.16–0.23)	0.19 ± 0.05	12					500	0.05 (0.05–0.05)	0.1 ± 0.2	25
600	0.20 (0.16–0.23)	0.19 ± 0.05	51					750	0.05 (0.05–0.05)	0.05 ± 0.05	134
600–1000	0.20 (0.18–0.22)	0.20 ± 0.02	10	0–2000	0.45 (0.30–0.55)	0.4 ± 0.2	340	1000	0.05 (0.05–0.05)	0.1 ± 0.1	290
1000	0.21 (0.20–0.24)	0.22 ± 0.04	106					1250	0.05 (0.05–0.15)	0.2 ± 0.2	149
1300	0.25 (0.22–0.28)	0.26 ± 0.06	58	0–2000 ^a	0.45 (0.35–0.65)	0.5 ± 0.3	554	1500	0.15 (0.05–0.15)	0.2 ± 0.2	125
1700	0.31 (0.26–0.36)	0.32 ± 0.07	63					1750–2000	0.15 (0.05–0.55)	0.3 ± 0.4	143
2500	0.37 (0.30–0.41)	0.37 ± 0.09	46	2000–5000	0.55 (0.45–0.85)	0.6 ± 0.3	42	2500	0.15 (0.05–0.55)	0.3 ± 0.3	79
3200	0.55 (0.50–0.66)	0.6 ± 0.1	34					3000–3500	0.25 (0.15–0.55)	0.4 ± 0.5	210
3800–4200	0.69 (0.57–0.84)	0.7 ± 0.2	24					>3500	0.25 (0.25–0.40)	0.4 ± 0.3	13
								≥3500	0.40 (0.25–0.55)	0.6 ± 0.8	14

^aImages acquired with detector in incubator tray.

Figure 3. The effective dose according to ICRP 103 for thorax examinations in (a) Hospital A, (b) Hospital B and (c) Hospital C.

low. Because the number of patients taken into account in these weight categories and the deviation from the protocols are relatively small, the patient weight estimation based on tube voltage was not rejected.

Median DAP as well as the interquartile range varies substantially between the three hospitals. These variations are caused by differences in tube

Table 4. Field of view (FOV) at the focus-skin distance, mean effective doses and the number of examinations per weight category for thorax examinations at the three hospitals. The FOV is given as width $\times$ height. For the effective dose (D_{eff}) the largest error is shown. For weight categories with <15 examinations the effective dose was not calculated.

Weight category (g)	Hospital A			Number of exams	Weight category (g)	Hospital B			Number of exams	Hospital C			Number of exams
	FOV (mean $\pm$ SD) (cm)	D_{eff} (mean $\pm$ SD) (μSv)				FOV (mean $\pm$ SD) (cm)	D_{eff} (mean $\pm$ SD) (μSv)			FOV (mean $\pm$ SD) (cm)	D_{eff} (mean $\pm$ SD) (μSv)		
600	9 $\pm$ 1 $\times$ 9 $\pm$ 2	11 $\pm$ 1		51	0-2000	13 $\pm$ 3 $\times$ 12 $\pm$ 3	14 $\pm$ 3		340	9 $\pm$ 1 $\times$ 9 $\pm$ 3	7 $\pm$ 7		25
1000	9 $\pm$ 1 $\times$ 9 $\pm$ 1	11.0 $\pm$ 0.1		106						9 $\pm$ 1 $\times$ 13 $\pm$ 3	4 $\pm$ 4		134
1300	10 $\pm$ 1 $\times$ 10 $\pm$ 1	11 $\pm$ 1		58						10 $\pm$ 2 $\times$ 14 $\pm$ 4	4 $\pm$ 4		290
1700	10 $\pm$ 1 $\times$ 11 $\pm$ 2	12 $\pm$ 2		63	0-2000 ^a	11 $\pm$ 3 $\times$ 11 $\pm$ 3	20 $\pm$ 8		554	11 $\pm$ 2 $\times$ 15 $\pm$ 5	7 $\pm$ 7		149
2500	11 $\pm$ 1 $\times$ 11 $\pm$ 2	11 $\pm$ 2		46						11 $\pm$ 2 $\times$ 15 $\pm$ 5	7 $\pm$ 7		125
3200	12 $\pm$ 1 $\times$ 12 $\pm$ 2	15 $\pm$ 2		34	2000-5000	13 $\pm$ 3 $\times$ 15 $\pm$ 6	15 $\pm$ 4		42	12 $\pm$ 1 $\times$ 17 $\pm$ 4	11 $\pm$ 11		143
3800-4200	12 $\pm$ 2 $\times$ 13 $\pm$ 2	16 $\pm$ 2		24						12 $\pm$ 1 $\times$ 20 $\pm$ 3	9 $\pm$ 9		79
										13 $\pm$ 3 $\times$ 20 $\pm$ 5	11 $\pm$ 11		210

^aImages acquired with detector in incubator tray.

settings and detector placement. The variation in interquartile range is partly caused by the accuracy of the DAP meters. In Hospitals B and C the DAP meter had a step size of $0.1 \mu\text{Gy m}^2$. Because the measured doses are close to this value, doses get

rounded off, presumably increasing the standard deviation. Also, for Hospital B and Hospital C a relatively large standard deviation can be observed in the FOV size. This indicates inconsistent collimation, which can lead to a larger variation in DAP.

Table 5. Overview of the mean entrance skin doses (ESD), dose–area products (DAP) and effective doses (D_{eff}) per examination type and per weight category for premature neonates, published in the last 15 years. Belgian diagnostic reference levels are underlined. Effective dose calculations are based on conversion coefficients determined by the National Radiological Protection Board (NRPB) unless indicated otherwise.

Study	Examination type	Patient weight (g)	ESD (μGy)	DAP ($\mu\text{Gy m}^2$)	D_{eff} (μSv)	Mean number of examinations per patient
Aramesh <i>et al.</i> ⁽¹⁹⁾	Thorax	1951	80			2 ^a
Dabin <i>et al.</i> ⁽⁸⁾ and Dabin <i>et al.</i> ⁽⁹⁾	Thorax	<1000	<u>41^b</u>	<u>0.41^b</u>		7.9 ^c
		1000–2000	45 ^b	0.72 ^b		
		>2000	<u>46^b</u>	<u>0.61^b</u>		
	Thorax–abdomen	<1000	47 ^b			
		1000–2000	51 ^b			
		>2000	58 ^b			
Toossi <i>et al.</i> ⁽²⁰⁾	Thorax	2650	76.3			
	Abdomen	2650	61.5			
Puch-Kapst <i>et al.</i> ⁽²¹⁾	Thorax	1100			14.4	8 ^c / 4 ^a
	Thorax–abdomen	1100			23.8	
	Abdomen	1100			17.8	
Olgar <i>et al.</i> ⁽¹²⁾	Thorax	1500			15 ^d	14
	Abdomen	1500			22 ^d	5
Lacerda <i>et al.</i> ⁽²²⁾	All	2260	75			3.9 / 2.0 ^a
Smans <i>et al.</i> ⁽¹³⁾	Thorax	<1000	28 ^a			9.6 ^c
		1000–2500	33 ^a			
		>2500	52 ^a			
Dougeni <i>et al.</i> ⁽¹⁴⁾	All	<1000	29.8	0.41		3 ^c
		1000–1500	32.4	0.54		
		1500–2500	37.5	0.75		
		>2500	45.4	0.92		
Donadieu <i>et al.</i> ⁽²⁶⁾		1250			13.0 ^d	10.6 ^a
Makri <i>et al.</i> ⁽¹⁵⁾	Thorax	650–4250	44		10.2 ^e	8.9
	Thorax–abdomen	650–4250	43		Male: 14.7 ^e	
					Female: 17.2 ^e	
Thierry <i>et al.</i> ⁽²³⁾	Thorax	All			22.8 ^d	
	Thorax–abdomen	All			38.6 ^d	
	All	1000	61.3			
		2000	64.5			
		3000	88.3			
Ono <i>et al.</i> ⁽¹⁶⁾	All	<750	17			25.9
		750–1000	19			18.6
		1000–1500	24			8.6
		1500–2500	33			3.3
		>2500	34			2.6
Armpilia <i>et al.</i> ⁽¹⁷⁾	Thorax	All	36		7.8	3.2

^aMedian value.

^b75th percentile.

^cThe mean number of examinations is not given per examination type.

^dEffective dose calculated with PCXMC.

^eEffective dose calculated with MCNP-4C2.

The median DAP values found in Hospital C are low when compared to the literature and are lower than the DRLs formulated in Germany and Belgium, which are based on a 75th percentile of multi-centre studies^(7, 8). German DRLs for thorax examinations are equal to $0.3 \mu\text{Gy m}^2$ for neonates smaller than 3 kg and $0.5 \mu\text{Gy m}^2$ for 3–5 kg newborns, Belgian DRLs are underlined in Table 5. For abdomen examinations the German DRL is equal to $2 \mu\text{Gy m}^2$ for 3–5 kg newborns. In Hospitals A and B some median DAP values for thorax examinations are just above the German DRL. For abdomen examinations the DAP values are below the German DRL. The DAP found in Hospitals A and B for thorax examinations is comparable to values found in recent literature. However, because in the literature mostly CR and film-screen detectors are being reported, the DAP in hospitals using digital flat panel detectors would be expected to be below average^(24, 25). For all weight categories the median DAP in Hospital C is lower than those in Hospitals A and B. However, it can also be observed that the inter-quartile range in Hospital C is relatively large, which is also reflected in the relatively large variation in FOV. These considerable differences between the hospitals indicate that standardising procedures in all three hospitals can lead to dose reduction.

An explanation why DAP values at Hospital A were mostly higher than the ones at Hospital C, is the fact that neonates are imaged with the detector in the incubator tray. This indicates an option for dose reduction, but possibly at the cost of increased hygiene risks. Also, using the incubator tray causes less disturbance to the preterm infant's sleep.

It can be observed that the error bars for the effective dose are asymmetrical. This is caused by the fact that changing the input parameters does not have a linear effect on the simulation outcome. It must be mentioned that calculation of the variation in effective dose, based on the standard deviation of the input parameters is only a rough estimation. However, it does give an insight in the order of magnitude of the possible effective dose variations. Most effective doses found are comparable with those found in literature, while especially in Hospital C some mean effective doses are lower, but again with a larger variation.

Our study has some limitations. First of all, only three out of 10 Dutch NICUs were included in this study. However, the number of radiographs included in this study is higher than in any of the studies mentioned in Table 5. Therefore we assume the amount of data to be sufficient for benchmarking.

Secondly, the estimation of patient weight based on the peak tube voltage and the imaging protocol, is only verified in Hospital A and only for part of the patients, due to the limited availability of patient weight data.

Another limitation of this study is the lack of assessment of the image quality. Parameters like signal-to-noise ratio and contrast-to-noise ratio have been investigated in order to quantify image quality, but no good relationship between these parameters and radiologist scoring was found. Therefore this method was discarded. However, the fact that the images used in the study were all used in a clinical practice gives an indication of the acceptability of the images.

CONCLUSION

In this study the number of examinations and the dose data per imaging protocol for three Dutch NICUs using flat panel digital radiography systems were evaluated. The three hospitals showed a relatively low number of examinations per patient compared to the literature. Also, DAP values and effective doses are average or low when compared to values published in literature.

Differences in tube settings and detector placement can be observed between the three hospitals, resulting in differences in mean dose. The increase in radiation risk by using the incubator tray should be weighed against other risk factors, like risk of infection.

From the variation in DAP and effective dose values between the three hospitals and the comparison with literature it can be deduced that standardisation of protocols could lead to further dose reductions. Also, formulation of a specific DRL for x-ray examinations using a flat panel detector at the NICU could lead to an increased awareness of optimisation possibilities.

SUPPLEMENTARY MATERIAL

Supplementary material can be found at *RADIATION PROTECTION DOSIMETRY* online.

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