Radiation Protection Dosimetry (2014), Vol. 158, No. 1, pp. 43–50 doi:10.1093/rpd/nct192
Advance Access publication 28 July 2013

ESTIMATION OF DOSE–AREA PRODUCT-TO-EFFECTIVE DOSE CONVERSION FACTORS FOR NEONATAL RADIOGRAPHY USING PCXMC

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Received March 1 2013, revised July 8 2013, accepted July 10 2013

Dose–area product-to-effective dose (*E*) conversion factors for chest, abdomen and abdomen–chest neonatal radiographs were computed. Seven patient models in the Monte Carlo software, PCXMC, were defined, representing neonates ranging in weight from 0.5 to 6.0 kg. Conversion factors for a tube potential range of 50–80 kVp at two beam filtrations (3.0 mm Al and 3.0 mm Al+0.1 mm Cu) were calculated. For 133 neonatal radiographs, effective dose values determined using these conversion factors were compared with those obtained from PCXMC simulations customised for each radiograph. For a 3.0-kg newborn irradiated at 60 kVp/3.0 mm Al beam filtration, the conversion factors were 2.58, 1.90 and 1.91 μSv (mGy cm^2)$^{-1}$ for chest, chest–abdomen and abdomen radiographs, respectively. Average dose difference between the conversion factors and customised dose calculations was 16 %. Disagreement in effective dose was most strongly correlated with under-collimation in the lateral direction.

INTRODUCTION

Ionizing radiation poses a greater biological risk for children than that for adults. Children have young differentiating cells and longer life expectancy, which make them more susceptible to the stochastic effects of radiation. These effects include radiogenic cancers and leukaemia[1]. For common radiographic examinations such as chest or abdomen, the lifetime risk of cancer to young children is about twice that to adults[2]. Therefore, patient dose must be kept as low as reasonably achievable (ALARA)[3, 4].

Neonatal babies born with breathing and other disorders are hospitalised in the neonatal intensive care unit (NICU). X-ray imaging is regularly performed in the NICU, and patients can be subjected to several radiographs per day. Anterior–posterior (AP) chest and abdominal radiographs are the most common diagnostic imaging examinations[5].

Due to their smaller size, many of the sensitive organs of neonates fall within the field of exposure during a radiographic examination, which include the lungs, stomach, bladder, colon, liver, thyroid and gonads. It is typical that a patient in the NICU receives multiple radiographic examinations, where the frequency depends on the birth weight, gestational age and clinical conditions[5, 6]. Several studies have sought to document neonatal doses[5–10], employing a variety of techniques, including Monte Carlo simulations[7] and skin dose measurements or estimates[5, 8–10].

Dose–area-product (DAP) or kerma–area-product meters are now common features of radiographic or fluoroscopic imaging systems. They provide either actual readings or software estimates based on system calibration measurements, in units of gray-meter squared (Gy m^2). DAP meters offer several advantages. The DAP reading does not change with distance from the X-ray source because of the inverse relationship between X-ray beam intensity and area. This facilitates measurements and removes the need for geometric correction. Further, DAP readings account for the irradiated area. Unlike air kerma, the DAP will increase or decrease with the area of the X-ray beam. This is useful in assessing patient exposure as long as the exposure is over collimated. Once the beam extends well beyond the patient edges, DAP readings become misleading. Like incident air kerma, however, the DAP is a surrogate for dose and cannot directly be translated into an assessment of risk.

Effective dose (*E*) is the parameter often used to quantify risk. Effective dose[3] is a weighted average of the organ doses resulting from an exposure, with the weighting representing the relative susceptibility of human organs to radiation damage. Using effective dose for estimating risk in clinical settings is a controversial

concept but remains widely used[11, 12]. Several groups have used effective dose to report on the doses of their NICU populations[5, 9, 10, 13].

Effective dose cannot be directly measured. It can be estimated from Monte Carlo simulations or organ measurements in phantoms. Both methods can provide conversion factors (CFs) that can be used in obtaining an estimate of effective dose from a readily measurable quantity, such as entrance skin dose (ESD), incident air kerma (K_{ai}) or DAP. Makri *et al.*[7] measured ESD and then reported ESD-to-organ dose and K_{ai}-to-organ dose CFs for neonatal radiographs of the chest and abdominal regions. Karambatsakidou *et al.*[14] and Schmidt *et al.*[15] formulated dose–area product-to-effective dose (DAP-to-E) CFs for paediatric cardiology using the Monte Carlo-based dose calculation software, PCXMC[16]. Smans *et al.*[17] compared K_{ai}-to-organ dose CFs for radiographs of premature babies resulting from simulations using stylised mathematical phantom with those resulting from more representative voxelised phantoms. Damilakis *et al.*[18] reported CFs for gastrointenstinal tract contrast studies performed on infants. Hart *et al.*[19] published CFs for estimating effective doses from paediatric examinations, but these CFs were based on ICRP 60[20] and combined all neonates in a single category of age 0.

PCXMC 2.0 (STUK, Finland) (henceforth referred to as PCXMC) is a dose calculation software based on MC simulations[16]. It uses stylised mathematical hermaphrodite phantoms to represent patients from age 0 to adulthood. Some of its beneficial features include a graphical user interface and customisation of the mathematical phantom by height and weight. It has been used for neonatal dosimetry[21] and was shown to give results comparable with those from simulations based on voxelised phantoms of premature babies[17]. Similarly, earlier work by the authors' group resulted in effective dose values for neonatal radiography using PCXMC and direct organ dose measurements in a physical phantom[22] being comparable. A PCXMC simulation requires the user to enter information about the imaging geometry, exposure field, patient parameters and beam conditions and may therefore pose a challenge for a busy imaging practice or the non-technical user.

The purpose of this study is to use PCXMC to determine a set of DAP-to-E CFs for neonatal radiography. The CFs are based on patient weight and beam quality and can be easily used in look-up table or formula form to determine effective dose. To assess the accuracy of the CFs, the authors collected DAP readings from clinical radiographs in their institution's NICU and compared the effective dose obtained from the CFs with the effective dose obtained from PCXMC simulations customised for each radiograph. With the increasing interest in establishing dose records, CFs can provide a relatively simple and accurate method for recording dose and determining the risk for this susceptible population of patients.

MATERIALS AND METHODS

PCXMC model

In PCXMC, the authors defined seven patient models, with weights ranging from 500 to 6000 g. To determine the heights of these patient models, the authors collected weight and height data of 144 NICU cases and generated a logarithmic fit of height as a function of weight. To validate the weight–height relationship, the authors compared their fit with that obtained from the weight–height charts reported by Fenton[23].

For each patient model, the authors set the source-to-image receptor distance in PCXMC to 105 cm and the phantom exit to image distance to 5 cm. The latter represents the gap between the patient and the image receptor caused by the patient mattress or image receptor tray. With the input of a board-certified paediatric radiologist, the authors adjusted the X-ray field incident on the PCXMC stylised phantom so that it mimics clinical practice, allowing for typical under-collimation in NICU radiography based on the radiologist's experience. Models for AP chest, abdomen and combined chest–abdomen examinations were defined. Figure 1 shows the irradiated field of view of the PCXMC model for a 3-kg patient for AP chest, abdomen and chest–abdomen. Table 1 provides the details of the irradiated field of view for each weight and examination protocol considered. Reflecting common clinical practice, the chest field directly irradiated the thyroid partially and the abdomen field irradiated the gonads.

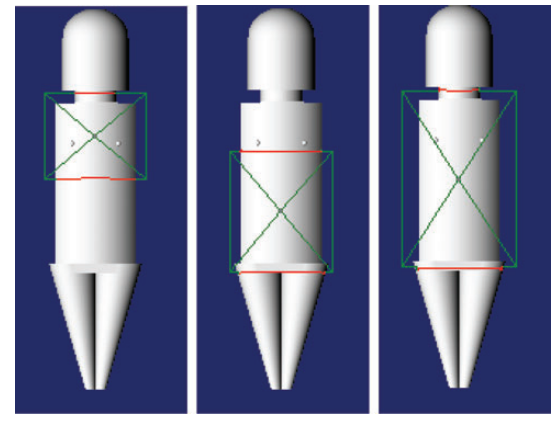

Figure 1. The irradiated field of view of the PCXCM stylised phantom used to derive DAP-to-E CFs for AP chest (left), AP abdomen (middle) and AP chest–abdomen of a 3.0 kg neonate.

Table 1. Patient models and X-ray beam dimensions used in all CF computations.

Patient weight (kg)	Patient height (cm)	Chest AP[a]	Abdomen AP[a]	Chest–abdomen AP[a]
0.5	26.2	7.0×6.0, 8.5	7.2×8.7, 3.5	8.2×12.0, 5.5
1.0	35.3	10.0×9.0, 11.0	8.8×12.0, 4.7	10.0×16.5, 7.0
2.0	44.5	11.0×11.0, 14.0	11.1×13.3, 5.9	12.6×20.0, 9.6
3.0	49.8	13.0×11.0, 16.5	12.9×15.5, 6.6	14.6×22.5, 10.5
4.0	53.6	16.0×12.0, 17.5	14.3×17.2, 7.1	15.4×24.5, 11.5
5.0	56.6	17.0×13.0, 18.5	14.3×18.0, 7.5	15.2×26.0, 11.5
6.0	59.0	17.0×14.0, 19.0	15.0×19.0, 8.0	15.1×27.0, 12.3

[a]The entries in each cell have units of cm and are respectively the X-ray beam width×height and *Z*ref. In PCXMC, user-specified coordinates (*X*ref, *Y*ref, *Z*ref) define the centre of the beam. The authors set *X*ref and *Y*ref to zero. *Z*ref defines the centre of the beam along the longitudinal axis of the patient. The origin point (0,0,0) places the beam centre near the gonads of a 3.0 kg neonate.

In each case, 2 million photons with a maximum energy of 150 keV were simulated, to achieve statistical uncertainty of no more than 3 %. All of the 24 organs included in the PCXMC phantom were included in the simulation, even if they were not in the direct path of the X-ray beam. The phantom arms were not included. The effective dose was calculated using the most recent tissue weighting factors[3].

As inputs to PCXMC, the authors entered tube potential, beam filtration and an incident DAP value of 1 mGy cm^2 and varied the tube potential (kV) from 50 to 80 kV in steps of 5 kV, for beam filtrations 3.0 mm Al and 3.0 mm Al plus 0.1 mm Cu.

Clinical data

The portable radiographic system (AMX4, GE HeathCare, Waukesha, WI) used in the NICU at the Winnipeg Children's Hospital was equipped with a Diamentor CX DAP meter (PTW Corp., Freiburg, Germany). The technologists recorded the DAP readings by annotating the radiographic image in the acquisition software of the computed radiography system (Agfa Healthcare, Mortsel, Belgium). For the purpose of this study, the authors retrieved the DAP readings, patient weights and heights, kVp and patient age for 133 NICU radiographs acquired over a period of two months (19 May to 20 July 2010). This set of images was different from the one used to determine the patient height–weight relationship. For each image, the effective dose was determined using the DAP-to-E CFs computed in this study. The beam filtration in the authors' NICU is estimated at 2.7 mm Al. The authors therefore used the CFs for 3.0 mm Al filtration. The effective dose resulting from each specific radiograph using a PCXMC simulation customised for that radiograph was also determined, using a beam area as close as possible to that evident in the radiograph, the actual kVp and filtration, and the actual patient weight and height.

The effective dose determined from CFs was compared with that determined directly from PCXMC by calculating their per cent relative difference, according to the following formula:

$$D = \frac{E_p - E_{\mathrm{DAP}}}{1/2 \cdot (E_p + E_{\mathrm{DAP}})} \times 100,$$

where D is the per cent difference, E_p is the patient-specific effective dose and E_{DAP} is the effective dose computed from the CFs. The average, median and standard deviation of D and its absolute value for all cases and for chest, abdomen and chest–abdomen cases were computed separately. A negative value of D indicated that the CF method over estimated effective dose.

The Pearson correlation between the absolute value of D and the differences in beam width (right-to-left of patient), beam length (craniocaudal direction), kVp and patient weight were computed. All clinical cases for which the absolute value of D was larger than the average plus one standard deviation were examined.

RESULTS

Weight–height model

The logarithmic fit for weight and height data obtained from clinical cases is shown in Figure 2. The following is the fit equation:

$$H = 13.20 \times \ln(W) + 35.33,$$

where H is the height of the infant in cm, and W is the weight of the infant in kg. The average difference between the fit and actual height values is 4 % and that between the fit and the median height data reported by Fenton[23] is 10 %. The height values used for the PCXMC patient models are listed in Table 1.

Conversion factors

Tables 2–7 list the CFs as a function of weight for each beam filtration considered. The tables also provide the mean and standard deviation of the CFs averaged over kVp.

Figures 3–5 illustrate kVp-averaged CFs as a function of weight, for each beam filtration. The results show that the CFs decrease as the weight increases. In other words, for the same DAP reading, a larger patient will have a smaller effective dose than a smaller patient, which is expected. The results also show that, relative to the mean, the standard deviation of the CFs increases with patient weight, suggesting that the relative variation with kVp is greater for bigger children. This is the case for all three types of examinations, with the largest variations observed in the case of the abdomen.

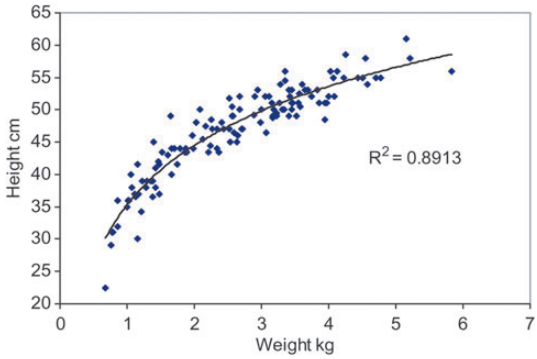

Figure 2. Patient height as a function of patient weight obtained from 144 neonatal cases. The data were used to derive patient height using the fitted equation $H = 13.20 \times \ln(W) + 35.33$.

Of the 133 patient radiographs considered, there were 16 abdomens, 63 chests and 54 combined chest–abdomen radiographs. Patient weights ranged from 1.0 to 5.9 kg. The average DAP reading was 3.5 mGy cm^2 with a range of 1.1 to 14.3 mGy cm^2. The average kVp was 62.7, and the range was 58–70. Table 8 provides DAP ranges and averages and average kVp for four patient weight groups.

The overall average relative difference in effective dose between the CFs method and the customised simulations methods was −7.7 %, with a standard deviation of 19.5 % and a median of −7.0 %. For the absolute value of the relative difference, the average was 16.0 %; the standard deviation, 13.5 %; and the median, 11.7 %. For chest radiographs, the average relative difference was −9.0 % (absolute value, 17.6 %). For abdomen radiographs, the difference was similar, −9.0 % (absolute value, 14.6 %).

Table 2. CFs (μSv/mGy cm^2) for AP chest with 3.0 mm Al filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	9.68	10.04	10.33	10.57	10.77	10.96	11.12	10.49 ± 0.51
1.0	4.89	5.09	5.26	5.40	5.53	5.64	5.75	5.37 ± 0.31
2.0	3.25	3.41	3.54	3.65	3.75	3.85	3.94	3.63 ± 0.25
3.0	2.35	2.47	2.58	2.66	2.74	2.82	2.88	2.64 ± 0.19
4.0	1.71	1.80	1.88	1.95	2.01	2.07	2.13	1.93 ± 0.15
5.0	1.49	1.57	1.65	1.71	1.77	1.82	1.87	1.70 ± 0.14
6.0	1.38	1.46	1.54	1.61	1.67	1.73	1.78	1.60 ± 0.15

The CFs were obtained from PCXMC using the parameters in Table 1.

Table 3. CFs (μSv/mGy cm^2) for chest AP with 3.0 mm Al + 0.1 mm Cu filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	10.95	11.34	11.63	11.84	12.00	12.14	12.26	11.74 ± 0.47
1.0	5.62	5.84	6.01	6.14	6.25	6.34	6.42	6.09 ± 0.28
2.0	3.80	3.97	4.11	4.22	4.31	4.40	4.47	4.18 ± 0.24
3.0	2.78	2.91	3.02	3.10	3.18	3.24	3.30	3.07 ± 0.19
4.0	2.01	2.12	2.21	2.28	2.34	2.40	2.45	2.26 ± 0.16
5.0	1.77	1.87	1.95	2.01	2.07	2.12	2.17	1.99 ± 0.14
6.0	1.64	1.75	1.84	1.92	1.98	2.04	2.09	1.90 ± 0.16

The CFs were obtained from PCXMC using the parameters in Table 1.

Table 4. CFs (μSv/mGy cm^2) for abdomen AP with 3.0 mm Al filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	7.21	7.58	7.88	8.14	8.37	8.58	8.76	8.07 ± 0.56
1.0	4.02	4.26	4.46	4.64	4.79	4.93	5.07	4.59 ± 0.37
2.0	2.36	2.54	2.68	2.81	2.93	3.03	3.13	2.78 ± 0.28
3.0	1.65	1.79	1.91	2.01	2.10	2.19	2.27	1.99 ± 0.22
4.0	1.32	1.44	1.55	1.64	1.72	1.80	1.87	1.62 ± 0.20
5.0	1.18	1.29	1.39	1.48	1.56	1.64	1.71	1.47 ± 0.19
6.0	0.99	1.09	1.17	1.25	1.32	1.38	1.45	1.24 ± 0.16

The CFs were obtained from PCXMC using the parameters in Table 1.

Table 5. CFs (μSv/mGy cm^2) for abdomen AP with 3.0 mm Al + 0.1 mm Cu filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	8.59	8.96	9.26	9.50	9.69	9.85	9.99	9.41 ± 0.50
1.0	4.89	5.14	5.35	5.52	5.66	5.78	5.89	5.46 ± 0.36
2.0	2.96	3.15	3.31	3.44	3.55	3.65	3.73	3.40 ± 0.28
3.0	2.11	2.27	2.39	2.50	2.59	2.67	2.75	2.47 ± 0.23
4.0	1.71	1.85	1.97	2.06	2.15	2.22	2.29	2.03 ± 0.21
5.0	1.54	1.67	1.79	1.88	1.97	2.05	2.11	1.86 ± 0.21
6.0	1.30	1.42	1.51	1.60	1.67	1.73	1.79	1.57 ± 0.18

The CFs were obtained from PCXMC using the parameters in Table 1.

Table 6. CFs (μSv/mGy cm^2) for abdomen–chest AP 3.0 mm Al filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	7.13	7.43	7.68	7.89	8.07	8.23	8.39	7.83 ± 0.45
1.0	3.96	4.16	4.32	4.45	4.57	4.68	4.79	4.42 ± 0.29
2.0	2.36	2.50	2.62	2.72	2.81	2.89	2.97	2.70 ± 0.22
3.0	1.70	1.81	1.90	1.99	2.06	2.13	2.19	1.97 ± 0.17
4.0	1.45	1.55	1.63	1.71	1.77	1.84	1.90	1.69 ± 0.16
5.0	1.30	1.39	1.47	1.55	1.61	1.67	1.73	1.53 ± 0.15
6.0	1.29	1.38	1.45	1.52	1.58	1.64	1.69	1.50 ± 0.14

The CFs were obtained from PCXMC using the parameters in Table 1.

Table 7. CFs (μSv/mGy cm^2) for abdomen–chest AP with 3.0 mm Al + 0.1 mm Cu filtration.

kV kg	50	55	60	65	70	75	80	Average ± SD
0.5	8.22	8.53	8.78	8.97	9.12	9.26	9.37	8.89 ± 0.41
1.0	4.67	4.88	5.04	5.17	5.27	5.36	5.44	5.12 ± 0.27
2.0	2.83	2.98	3.11	3.21	3.30	3.38	3.44	3.18 ± 0.22
3.0	2.06	2.18	2.29	2.37	2.45	2.51	2.57	2.35 ± 0.18
4.0	1.78	1.89	1.98	2.06	2.12	2.19	2.22	2.03 ± 0.16
5.0	1.60	1.71	1.80	1.88	1.94	2.00	2.06	1.86 ± 0.16
6.0	1.59	1.68	1.76	1.83	1.89	1.95	2.01	1.82 ± 0.15

The CFs were obtained from PCXMC using the parameters in Table 1.

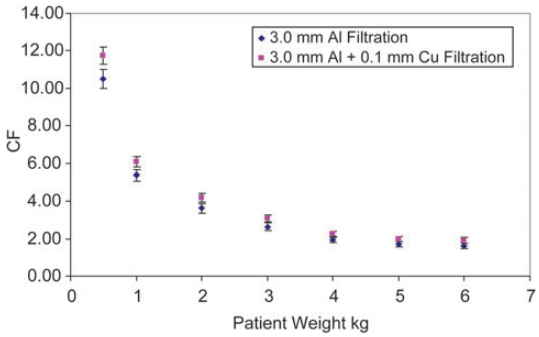

Figure 3. DAP-to-E CFs averaged over all kVp values for the beam filtrations considered in this study for the AP chest protocol. The error bars represent ±1 standard deviation.

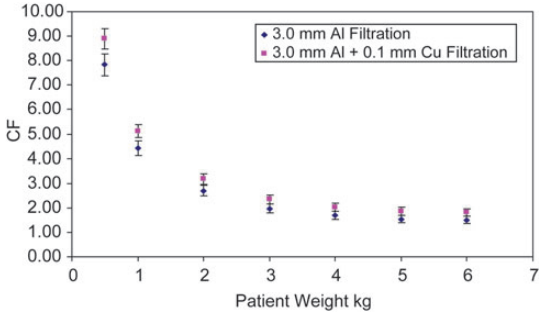

Figure 4. DAP-to-E conversion factors averaged over all kVp values for the beam filtrations considered in this study for the AP chest–abdomen protocol. The error bars represent ±1 standard deviation.

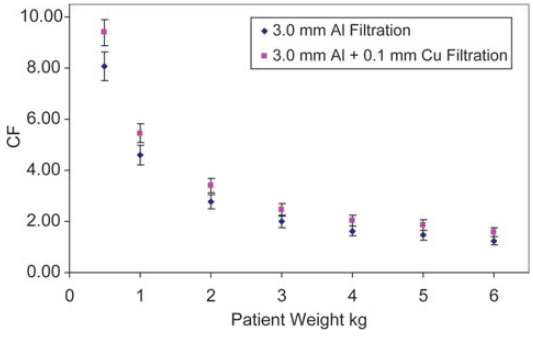

Figure 5. DAP-to-E CFs averaged over all kVp values for the beam filtrations considered in this study for the AP abdomen protocol. The error bars represent ±1 standard deviation.

Agreement was slightly better for chest–abdomen radiographs, with average relative differences of −5.8 % (absolute value, 14.5 %).

Table 8. Range of DAP values and corresponding mean values for four patient weight groups.

Weight (kg)	DAP range (mGy cm^2)	DAP mean (mGy cm^2)	Average (kVp)
0.5–1.5	1.1–12.0	2.9	60.3
1.5–2.5	1.3–14.3	3.1	62.4
2.5–3.5	1.4–6.5	3.1	62.6
3.5–4.5	3.5–8.3	5.3	59.4

The authors illustrate the comparison between the CFs methods and the customised method with an example. An abdomen examination case has a DAP reading of 3.2 mGy·m^2, patient weight of 2.9 kg, 62 kVp, beam filtration of 2.7 mm Al, and beam width and height of 15.13 and 15.44 cm, respectively. Entering these parameters in PCXMC and visually matching the PCXCM radiation field with the one evident from the image, the authors arrive at an effective dose of 5.8 μSv. This is what the authors refer to as a customised PCXCM dose calculation. The CF closest to the actual parameters of this case is the CF for 60 kVp, patient weight of 3.0 kg and beam filtration of 3.0 mm Al. The value of the CF is 1.91 μSv/mGy·m^2. Multiplying the CF with the DAP reading of 3.2 mGy·m^2 yields an effective dose of 6.1 μSv.

The per cent difference in effective dose was positively correlated with the differences in beam width and length with Pearson correlations of 0.54 and 0.36, respectively. The correlation was very weak between weight and dose differences (<0.01). The correlation between kVp and dose differences was −0.27.

There were 22 images (16 %) where the difference in case-specific effective dose and CF effective dose was larger in magnitude than the average difference plus one standard deviation (∼30 %). Visual examination of these cases revealed the cause for large differences to be, in order of importance, under-collimation in the lateral direction, under-collimation in the craniocaudal direction and patient positioning.

DISCUSSION

Strictly speaking, a CF is most accurate when applied to the same conditions used to derive it. Every patient image is different and unique, and therefore this is seldom met in practice. However, CFs remain a useful tool for estimating effective dose. The accuracy of the method is demonstrated by the low average difference between effective dose determined using CFs and that using case-specific simulations. Non-physics experts can also easily apply the CFs formulated in this work and knowledge of the patient weight, kVp and beam filtration is sufficient. Patient weight and kVp are readily available to clinicians. Beam filtration can

usually be obtained from the system specifications, tube labelling or from service personnel. With portable radiography, additional filtration is not usually used and the 3.0 mm Al CFs can be used. Application of the CFs in practice may be further simplified by using the values averaged over all kVps. Given the inaccuracy inherent in the estimation of effective dose[11], this is a defensible approach.

Generally, the CFs increase with beam hardening. For example, for the 3.0 kg model, the CFs increase by 10–18 % as the kVp increases from 60 to 80. Also, the CFs increase by 17–25 % when Copper is introduced for the 3.0 kg model. This suggests that for a fixed incident dose–area product (or air kerma), the dose will increase with beam hardening. This is consistent with prior results reported in the literature[24]. Dose savings can be achieved with the use of hardened beams when the image detector dose is kept constant. The hardened beams are more penetrating. They can deliver the required detector dose and result in an acceptable level of image noise with less overall radiation absorption in the patient. With harder beams, there is an overall reduction in subject contrast. This can be mitigated through contrast enhancement image processing algorithms.

DAP-to-E CFs are sensitive to the accuracy of the collimation assumed in their calculation. As comparison with clinical data shows, the CFs are fairly accurate in predicting effective dose, with the largest errors resulting from lateral under-collimation of the beam. The effect of under-collimation in the craniocaudal direction on the accuracy of dose calculation is not as pronounced. This is reasonable given that lateral under-collimation beyond the left and right sides of the patient will change the DAP reading without subjecting the patient to a significant amount of additional radiation. The accuracy of the method can be improved by ensuring proper collimation is practiced. Examination of clinical cases with large errors further demonstrates the sensitivity of the method to collimation differences and identifies beam centring/patient positioning as important factors as well. The issue of collimation is important not for dose calculation accuracy only, but also for practicing proper radiographic technique, applying the ALARA principle and protecting sensitive organs from unnecessary irradiation.

Hart *et al.*[19] provided DAP CFs for chest and abdomen examinations for patients of age 0 based on ICRP 60[20]. Comparing the authors' method with finer weight stratification with that of Hart *et al*. was of interest. The authors conducted a study, the results of which are not reported here in detail, for chest–abdomen examinations. As reported earlier, the authors' method resulted in an average difference of −5.8 %, whereas the average difference from the method of Hart *et al.* was 41 %. This comparison demonstrates the potential value of the finer stratification by weight for more accurately assessing the risk arising from neonatal radiography. Others have similarly used a fine stratification of patient thickness in determining ESD normalizing factors for newborns[25].

It is noteworthy that the DAP values obtained from the clinical neonatal images considered in this study are comparable with those reported in other studies[21, 26]. This suggests that the CFs presented herein will be applicable in other neonatal imaging practices.

CONCLUSIONS

DAP-to-E CFs have been determined for neonatal radiography of AP chest, AP abdomen and combined AP chest–abdomen examinations using the PCXMC Monte Carlo dose calculation software. The CFs are based on patient weight, kVp and beam filtration. They represent a simple and fairly accurate method for calculating effective dose for a population of neonates. The average agreement between CF-based effective dose calculation and simulations customised for each radiograph is within 16 %. CFs can be useful in assessing the dosimetric impact of changes to the radiographic techniques, in providing data for patient dose records and in assessing the radiographic practices of neonatal intensive care units.

ACKNOWLEDGEMENTS

The author is thankful to Dr Martin Reed of the Pediatric Radiology Department at the Winnipeg Children's Hospital for assistance with defining the beam area in the PCXM models.

FUNDING

This work was supported in part by grants from the Manitoba Institute of Child Health and the Manitoba Medical Services Foundation.

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