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ORIGINAL ARTICLE

Cumulative Radiation Dose from Radiography in Preterm Infants during Hospitalisation

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ABSTRACT

Objectives: *Preterm infants with low gestational age (GA) and very low birth weight experience high morbidity and mortality. Chest and abdominal radiographs are commonly performed in this group. The aim of this study was to estimate the trend of radiation exposure from radiographs in preterm infants.*

Methods: *In this retrospective study, 210 surviving infants were systematically reviewed. The entrance skin air kerma was measured followed by estimation of effective dose (ED) using the Monte Carlo simulation software (PCXMC 2.0). We estimated the risk of radiation-induced cancers based on referenced risk factors from the International Commission on Radiological Protection Publication 103.*

Results: *The median (interquartile range) GA, birth weight, and hospital stay of the infants was 29.2 (27.9-31.1) weeks, 1.2 (1.0-1.5) kg, and 68.5 (47.0-100.0) days, respectively. The median ED per chest and abdomen radiograph was 0.021 mSv and 0.026 mSv, respectively. Preterm infants with GA of <28 weeks received a median cumulative ED (cED) of 1.47 mSv, those of 28 to <30 weeks received a median cED of 0.84 mSv, and those of 30 to <32 weeks received a median cED of 0.39 mSv. Preterm babies with lower GA and longer hospital stay were at higher radiation risk from diagnostic radiography. Preterm infants with GA of <28 weeks and those who required surgery due to necrotising enterocolitis had the highest dose of cED.*

Conclusion: *Preterm infants were not exposed to excessive radiation during hospitalisation; dose risk for development of cancer was negligible. Nonetheless, the principle of ALARA (as low as reasonably achievable) should be applied.*

Key Words: *Infant, newborn; Radiation dosage; Radiation protection; Risk assessment*

中文摘要

住院期間早產兒在放射造影檢查過程中接觸到的累積輻射劑量

劉喬茵、許卓毅、張漢明、伍百祥、朱昭穎

目的：低胎齡和極低出生體重的早產兒一般有高發病率和死亡率，因此他們經常須要進行胸部和腹部X光檢查。本研究旨在評估早產兒在放射造影檢查過程中所接觸到的輻射劑量。

方法：本研究為210名存活嬰兒進行系統性回顧。利用Monte Carlo模擬軟件（PCXMC 2.0）估計有效

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劑量然後量度入射皮膚劑量。根據國際放射防護委員會第103號出版物中的參考風險因素估計因輻射誘發癌症的風險。

結果：本研究中嬰兒的胎齡、出生體重和住院時間的中位數（四分位距）分別為29.2（27.9-31.1）週、1.2（1.0-1.5）千克和68.5（47.0-100.0）天。胸部和腹部X光檢查的有效劑量中位數分別為0.021 mSv和0.026 mSv。胎齡少於28週的早產嬰兒所接觸到的累計有效劑量中位數為1.47 mSv，28至少於30週的嬰兒為0.84 mSv，30至少於32週的嬰兒則為0.39 mSv。低胎齡和住院時間較長的早產嬰兒從放射診斷中接觸到較高輻射風險。胎齡少於28週以及因壞死性小腸結腸炎而需接受手術的早產嬰兒有最高的累計有效劑量。

結論：早產嬰兒在住院期間沒有接觸過量輻射，因此誘發癌症風險微不足道。儘管如此，亦應實踐「最低的合理輻射量」的原則（ALARA）。

INTRODUCTION

There is increasing concern about the risk of developing cancer from exposure to ionising radiation associated with increasing use of radiological investigations and procedures. Paediatric patients warrant special attention in radiation protection, as they have higher mitotic activity, greater radiosensitivity, and a longer lifetime to manifest radiation damage than adults. In particular, preterm infants are the most vulnerable subgroup because they are smallest in size so more organs are brought to exposure within the radiographic field, resulting in a higher effective dose (ED) per radiograph.[1] Additionally, premature infants admitted to the neonatal intensive care unit (NICU) often require a longer hospital stay and more frequent radiological examinations for diagnosis, monitoring, and guiding treatments. These repetitive examinations can result in a relatively high cumulative dose. It is imperative to weigh the benefit of examination against the potential risk of performing radiological investigations for this cohort. The Oxford Survey of Childhood Cancers published in 1956[2] first demonstrated the association of prenatal irradiation and the development of childhood cancer, and this led to a paradigm shift that curtailed antenatal abdominal radiographs. Other studies also showed this association.[3-10] Nonetheless, the potential consequences of postnatal irradiation remain to be elucidated.[5,11] Over the last two decades, a few radiation dosimetric studies have been published regarding exposure to ionising radiation from radiographs by preterm infants in a neonatal unit.[12-21] The mean gestational age (GA) of subjects ranged from 25.4 to 33.0 weeks.[17,21]

The amount of radiation absorbed depends mainly on the number of radiographs received and the radiation dose of each radiograph. Factors such as tube potential, current, focus-skin distance (FSD), filter, and infant size were included when simulating the ED absorption by preterm infants in this study. This retrospective study sought to quantify the radiation exposure and the cumulative effective dose (cED) of preterm infants[22] who underwent radiological investigations during their stay in hospital from birth until discharge, and the relationship between the amount of ED absorption and neonatal conditions along with the risk of childhood cancer.

METHODS

Patients

The study was conducted in a regional referral and integrated neonatal unit with affiliation to the Chinese University of Hong Kong, and in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the Joint Chinese University of Hong Kong–New Territories East Cluster Clinical Research Ethics Committee. Patient consents were obtained.

Between 1 January 2010 and 31 December 2012, a total of 418 infants were admitted to NICU. Infants with GA of >32 weeks (n = 175), who died within 10 days of life (n = 13), or who had incomplete or unidentifiable medical records (n = 36) were excluded from the study; 194 infants were studied and classified into the following sub-groups: GA of 30 to <32 weeks, 28 to <30 weeks, and <28 weeks.[22]

All medical records were retrieved through the electronic Clinical Management System (CMS) of the Hong Kong Hospital Authority. The following information was collected: GA; gender; birth weight (BW); Apgar scores at 1 and 5 minutes; date of

discharge; number of chest and abdominal radiographs; number of computed tomography (CT) scans; other types of radiological investigations; and clinical conditions including respiratory distress syndrome (RDS), bronchopulmonary dysplasia, necrotising enterocolitis (NEC), and history of abdominal surgery.

Radiographs

All radiographs were taken using a portable machine Mobilett XP (Siemens AG Medical Solutions, Erlangen, Germany) routinely used for radiographic examinations in the NICU, with total filtration of 3.1-mm Aluminium equivalent thickness and an X-ray tube anode angle of 15°. All babies underwent the examinations in an incubator or on the platform lying in a supine position on top of the cassette with mean FSD and focus-receptor distance set at 98.25 cm and 108 cm for chest radiographs, respectively, and 76.67 cm and 85.33 cm for abdominal radiographs, at an anterior-posterior (AP) direction.

Pilot Study

A pilot test was conducted to measure the radiation dose of entrance skin air kerma using the Radcal Corp 6cc Ion Chamber (Radcal, Co., Monrovia, USA), from both an AP and lateral direction, delivered to a reference instrument inside the incubators at NICU. The source-to-detector distance was set at 54 cm for AP and 85 cm for lateral exposures. The entrance-skin-dose was also measured from AP using a perspex phantom, 38 cm (length) x 14 cm (width) x 7 cm (thickness) as a back scattering medium. Table 1 summarises the pilot results and the data were used as reference to calculate the input dose value for further analysis.

Table 1. ESAK and ESD measurement from pilot test.

Examination type / dose quantity	kV / mAs	SDD (cm)	Dose at SDD (μGy)
AP / ESAK	50 / 3.2	54	168
Lateral / ESAK	56 / 3.2	85	128
AP chest / ESD	50 / 3.2	67	140

Abbreviations: AP = anterior-posterior; ESAK = entrance skin air kerma; ESD = entrance skin dose; SDD = source-to-detector distance.

Table 2. PCXMC simulation parameters.[25]

Parameter	Data
Height	Refer to Fenton and Sauve 2007[25]
Mass (birth weight)	From demographics (kg)
FSD	98.25 cm (chest), 76.67 cm (abdomen)
Beam weight	By estimation
Beam height	By estimation
Projection angle	270°
X-ray mean tube potential	52 kV
X-ray mean	3.2 mAs
X-ray tube anode angle	15°
Filter	Aluminum
Filter thickness	3.1 mm
Input dose value (AP chest)	0.0507 mGy
Input dose value (AP abdomen)	0.0833 mGy
Monte Carlo simulation parameters: maximum energy	150 keV
Monte Carlo simulation parameters: No. of photons	20,000

Abbreviations: AP = anterior-posterior; FSD = focus-skin distance.

Radiation Dose Simulation

The ED of radiation absorbed by preterm infants from radiographic examination during their hospital stay was estimated by simulations using the program PCXMC 2.0.[23] PCXMC 2.0 calculated the ED as well as the organ dose resulting from X-ray examination based on the Monte Carlo method on phantom family from Oak Ridge National Laboratory. The simulation required several parameters as shown in Table 2.[25] Some data were not available due to the limitation inherent in a retrospective study. A few estimations were made and are explained as follows.

Estimations and Limitations

Estimation of Infant Height

The length of the preterm infant was not documented in our radiology information system (RIS) or CMS, but the GA at birth was recorded. Thus, the length of the neonate could be estimated based on the GA and using the "fetal-infant growth chart for preterm infants".[24,25] A quadratic equation was formulated based on Fenton's correlation of height and GA (equation 1) that allowed us to estimate infant height from corresponding GA. With the weight and estimated height, the body surface area (BSA) in m^2 was calculated using equation 2.[26]

$$y = -0.0192*x^2 + 2.4257x - 15.219 \quad (1)$$

$$R^2 = 0.9998$$

where x = the GA at birth in weeks and y = the height of the preterm infant in centimetres

$$BSA = 0.024265*W^{0.425}*H^{0.3964} \quad (2)$$

where W = weight in kilograms and H = height in centimetres

Focus-skin Distance, Beam Weight, and Beam Height

For the geometry data of radiation beam, a mean FSD at AP direction for chest and abdomen was acquired from radiographers (see FSD in Table 2). Since the

beam width and height for each radiograph were not available from RIS or CMS, an estimation of these figures was made based on the common practice of experienced radiographers. Chest radiographs were normally taken from the shoulder to the mid-liver, and abdominal radiographs were generally taken from the liver, including a small portion of the inferior lung, to the bladder. With this assumption we manually adjusted the beam width and height on PCXMC on which the organs were shown after input of phantom height and mass.

Input Dose Value

After the simulation process in PCXMC, the input dose value was inserted as incident air kerma in milligray (mGy). Based on the results of the pilot study, we applied the inverse-square law (see equation 3) to measure the input dose value of chest and abdomen radiographs. To measure I_2, I_1 and D_1 were obtained from the pilot test, and D_2 was FSD for either chest or abdominal radiographs. The parameters for X-ray spectrum calculation are listed in Table 2.

$$I_2 = (I_1 * D_1^{\wedge 2}) / D_2^{\wedge 2} \quad (3)$$

where D_1 = distance 1 from source, D_2 = distance 2 from source, I_1 = intensity at D_1, and I_2 = intensity at D_2

Effective Dose

The program calculated and presented the ED with both tissue weighting factors from the old International Commission on Radiological Protection (ICRP) Publication 60 (1991) and the new tissue weighting factors of ICRP Publication 103 (2007). In the current study, ED from ICRP Publication 103 was adopted for analysis.

The Risk of Radiation

The risk of cancer induced by the radiograph examination was calculated by the product of accumulated dose and risk factor as follows:

Cancer induction risk =
(accumulated ED)*(risk coefficient) (4)

The accumulated dose was adopted from the median ED in our study and the risk coefficient was adopted from the ICRP-60 prenatal radiation exposure risk factor 13 x 10^{-2} per Sv. Our results indicated that risk of cancer is induced by 2.73 x 10^{-6} and 3.38 x 10^{-6} in a single chest and abdominal X-ray, respectively.

Data Analysis

The correlations among cED, GA, BW, BSA, length of hospital stay, and number of radiographs taken were analysed by Spearman correlation for non-parametric analysis using the Statistical Package for the Social Sciences (Windows version 20.0; SPSS Inc, Chicago [IL], USA). Medians were used for data in normal distribution, Mann-Whitney test was used to compare variables between two groups, and Kruskal-Wallis test was applied for independent measures with more than two groups. Statistical significance was set at $p < 0.05$.

RESULTS

The median (interquartile range [IQR]) number of chest and abdominal radiographs taken per infant was 10 (4-26) and 17 (9-25), respectively. The median (IQR) ED of chest and abdominal radiographs was 0.021 mSv (0.020-0.023 mSV) and 0.026 mSv (0.024-0.027 mSv), respectively. The median (IQR) duration of hospital stay was 68.5 days (47.0-100.0 days), and the data indicated that preterm infants underwent at least one chest or abdominal radiograph every 2.5 days. Linear regression model indicated that cED was significantly correlated with GA, BW, BSA, length of hospital stay, and number of radiographs taken ($p < 0.001$). Tables 3 and 4 summarise the full demographics and radiological details.

Infants with the following three conditions were compared:

(1) cED in non-NEC infants with surgery vs. those without surgery:
Mann-Whitney test was carried out to analyse the

Table 3. Demographic data of studied patients (n = 194).

Demographics	Data*
Sex	
Female	83 (43)
Male	111 (57)
Inborn vs. outborn†	
Inborn	168 (87)
Outborn	26 (13)
Birth weight (kg)	1.2 (1.0-1.5)
Estimated height (cm)	39.26 (37.51-41.70)
Body surface area (m^2)	0.12 (0.10-0.13)
Gestational age (weeks)	29.2 (27.9-31.1)
Hospital stay (days)	68.5 (47.0-100.0)
Apgar score at 1 min	7 (5-8)
Apgar score at 5 mins	8 (7-9)
No. of radiographs per patient	27 (15-52.75)

* Data are shown as No. (%) or median (interquartile range).
† Inborn refers to preterm newborns delivered in a tertiary care centre, and outborn are those transferred to a tertiary centre after birth.

cED difference between non-NEC infants with and without abdominal surgery. Results indicated that the cED was significantly different between them (p = 0.025). The median (IQR) cED of non-NEC infants with surgery was 1.29 mSv (0.82-2.31 mSv) compared with 0.98 mSv (0.39-1.21 mSv) in infants without surgery (Table 5).

(2) cED in infants with surgery due to NEC vs. no surgery and no NEC:
The median (IQR) cED in infants with surgery due to NEC and those without surgery or NEC was 1.90 mSv (1.47-2.29 mSv) and 1.27 mSv (0.50-1.63 mSv), respectively. cED was significantly different (p = 0.024) in a Mann-Whitney test (Table 6).

(3) cED between non-surgical infants with and without NEC:
The median (IQR) cED of non-surgical infants with and without NEC was 1.37 mSv (0.86-2.13 mSv) and 0.84 mSv (0.84-1.19 mSv), respectively. The cED was significantly different (p = 0.022) in a Mann-Whitney test (Table 7).

The cED difference was not significant using Mann-Whitney test in the following comparisons: (1) NEC patients with and without surgery; (2) surgical infants

Table 4. Measurement of X-ray and effective dose received per infant.

	Median (interquartile range)
No. of CXRs per infant	10 (4-26)
No. of AXRs per infant	17 (9-25)
Total No. of radiographs	27 (15-52.75)
ED per CXR (mSv)	0.021 (0.020-0.023)
Total ED of CXRs (mSv)	0.197 (0.093-0.564)
ED per AXR (mSv)	0.026 (0.024-0.027)
Total ED of AXRs (mSv)	0.440 (0.234-0.684)
Total ED	0.668 (0.355-1.288)

Abbreviations: AXR = abdominal X-ray; CXR = chest X-ray; ED = effective dose.

Table 5. Comparison of non-NEC infants with surgery and those without surgery.

	Median (IQR)		p Value*
	Non-NEC infants with surgery (n = 18)	Matched non-NEC infants without surgery (n = 18)	
No. of radiographs per infant	55.5	39.5	0.025
cED per infant (mSv)	1.29 (0.82-2.31)	0.98 (0.39-1.21)	0.025
Gestational age (weeks)	27.43 (25.75-29.71)	27.93 (27.03-29.57)	0.401
Birth weight (kg)	0.973 (0.80-1.04)	1.013 (0.966-1.122)	0.125

Abbreviations: cED = cumulative effective dose; IQR = interquartile range; NEC = necrotising enterocolitis.
* Mann-Whitney test.

Table 6. Comparison of infants with surgery due to NEC and those with no surgery and no NEC.

	Median (IQR)		p Value*
	Surgery due to NEC (n = 9)	Matched cases with no surgery and no NEC (n = 9)	
No. of radiographs per infant	77	55	0.019
cED per infant (mSv)	1.90 (1.47-2.29)	1.27 (0.50-1.63)	0.024
Gestational age (weeks)	27.14 (26.43-28.00)	28.0 (26.29-28.86)	0.929
Birth weight (kg)	0.86 (0.71-1.18)	0.89 (0.82-1.09)	0.627

Abbreviations: cED = cumulative effective dose; IQR = interquartile range; NEC = necrotising enterocolitis.
* Mann-Whitney test.

Table 7. Comparison of non-surgical infants with and without NEC.

	Median (IQR)		p Value*
	Non-surgical NEC cases (n = 13)	Matched non-surgical cases without NEC (n = 13)	
No. of radiographs per infant	57	39	0.026
cED per infant (mSv)	1.37 (0.86-2.13)	0.84 (0.84-1.19)	0.022
Gestational age (weeks)	28 (27.57-28.00)	28 (27.00-28.86)	0.959
Birth weight (kg)	1.15 (0.89-1.39)	1.13 (0.95-1.36)	0.898

Abbreviations: cED = cumulative effective dose; IQR = interquartile range; NEC = necrotising enterocolitis.
* Mann-Whitney test.

with and without NEC; and (3) surgical infants without NEC and non-surgical infants with NEC.

Difference of Cumulative Effective Dose between Very Preterm and Extremely Preterm Infants

Preterm infants were categorised into three groups: group 1 (GA of <28 weeks), group 2 (GA of 28 to <30 weeks), and group 3 (GA of 30 to <32 weeks). Results from Kruskal-Wallis test indicated that the cED of three groups independent measures were all significantly different ($p < 0.001$) [Table 8].

DISCUSSION

Prematurity is a risk factor for various short- and long-term health complications. Chest and abdominal radiographs are commonly performed as diagnostic procedures to evaluate significant complications such as NEC. Compared with CT, radiological interventions and nuclear medicine examinations, the mean ED of a plain radiograph is thousand-fold less. Nevertheless, the dose of ionising radiation from frequent radiographs on infants is cumulative and arguably more deleterious when their radiosensitivity, body size, and longer life expectancy are taken into account.

The mean ED from chest and abdominal radiographs was measured by simulation using a PC-based Monte Carlo program in this study. Results were comparable with other publications as shown in Table 9. Results obtained from sub-group analysis revealed that preterm infants with smaller GA and longer hospital stay have a higher radiation risk due to a higher frequency of radiographs. Regression analysis indicates that these two variables are significant predictors ($p < 0.001$) of higher cED. Preterm infants born at younger GA and lower BW are more likely to have RDS. Data from a landmark study reported 78%, 63%, 44%, and 26% of preterm infants with BW of 501-750 g, 751-1000 g, 1001-1250 g, and 1251-1500 g respectively had RDS and inverse risk in infants with more advanced GA.[27]

Chronic lung disease (CLD) occurs frequently in preterm infants. One study reported that 23% of infants with BW of 501-1500 g had CLD, demonstrating that low BW is related to increased risk of developing CLD.[27] A similar trend was also observed in our study wherein up to 82% of infants with GA of <28 weeks (median weight, 0.88 kg) had CLD compared with only 10% of those with GA of 30 to <32 weeks (median weight, 1.49 kg). Small GA and longer hospital stay were significant risk factors for having more radiological investigations performed due to the increased risk of developing these conditions associated with extreme prematurity. The number of chest radiographs taken in preterm infants with GA of <28 (median, 35) was significantly more compared with the number taken in infants with GA of 30 to <32 weeks (median, 5).

Table 8. Demographics, common neonatal conditions, and surgeries in neonates stratified by gestational age.

	Median (IQR) or No. (%)			p Value*
	Gestational age (weeks)			
	<28 (n=49)	28 to <30 (n=58)	30 to <32 (n=87)	
Demographics				
Median GA (weeks)	26 (25-27)	28 (28-29)	31 (30-31)	<0.001
Birth weight (kg)	0.88 (0.78-0.98)	1.14 (1.00-1.34)	1.49 (1.37-1.65)	<0.001
Body surface area (m^2)	0.10 (0.09-0.10)	0.12 (0.11-0.13)	0.14 (0.13-0.15)	<0.001
Duration of hospital stay (days)	110 (97-127)	71 (58-88)	47 (40-61)	<0.001
Neonatal conditions				
RDS	49 (100%)	58 (100%)	77 (89%)	-
CLD/BPD	40 (82%)	24 (41%)	9 (10%)	-
NEC	11 (22%)	8 (14%)	3 (3%)	-
Abdominal surgeries	15 (31%)	6 (10%)	6 (7%)	-
Abdominal surgeries due to NEC	5 (10%)	3 (5%)	1 (1%)	-
No. of chest radiographs per infant	35 (25-51)	11 (7-19)	5 (3-9)	<0.001
No. of abdominal radiographs per infant	26 (19-39)	20 (13-30)	11 (5-17)	<0.001
cED per infant (mSv)	1.47 (1.21-2.21)	0.84 (0.51-1.21)	0.39 (0.23-0.61)	<0.001

Abbreviations: BPD = bronchopulmonary dysplasia; cED = cumulative effective dose; CLD = chronic lung disease; GA = gestational age; IQR = interquartile range; NEC = necrotising enterocolitis; RDS = respiratory distress syndrome.
* Kruskal-Wallis test.

Table 9. Comparison of the measurement of X-ray and effective dose with other studies.

Study (year)	kVp / mAs (CXR)	ED (μSv) per CXR	kVp / mAs (AXR)	ED (μSv) per AXR	Sample size	Birth weight (g)	Gestational age (weeks)	Length of hospital stay (days)	No. of conventional radiographs per patient	Risk of childhood cancer induction
Present study (2016)	52 / 3.2	21.0	52 / 3.2	26.0	194	Median: 1235 IQR: 960-1480	Median: 29.2 IQR: 27.90-31.14	Median: 68.5 IQR: 47-99.75	Median: 27 IQR: 15-52.75	CXR: 2.73×10^{-6} AXR: 3.38×10^{-6}
Armpilia et al[12] (2002)	53 / 2.0	7.8	53 / 2.1	10.2	30	-	-	-	Mean: 3.2	$(0.3\text{-}1.3) \times 10^{-6}$ From a single radiograph
Brindhaban and Al-Khalifah[13] (2004)	57 / 1.6	26.0	57 / 1.6	32.0	-	Water phantom	Water phantom	Water phantom	Total: 20-25	$(9\text{-}117) \times 10^{-6}$
Donadieu et al[14] (2006)	-	13.3	-	13.5	450	Median: 1250 IQR: 520-2760	Median: 30.1 IQR: 24.1-33.9	Median: 16 IQR: 1-246	Median: 10.6 IQR: 0-95	-
Jones et al[16] (2001)	62 / 2.0	15.4	62 / 2.5	21.9	-	Anthropomorphic phantom	Anthropomorphic phantom	Anthropomorphic phantom	-	4.8×10^{-6}
Makri et al[17] (2006)	50 / 1.5	10.2	-	-	60	2003	33.0	-	-	1.7×10^{-6}
Olgar et al[18] (2008)	49 / 1.9	16.0	48 / 2.0	27.0	23	Mean: 1500	-	Mean: 50 Range: 6-112	Mean: 14 (CXR), 5 (AXR)	CXR: $(0.4\text{-}2) \times 10^{-6}$ AXR: $(0.6\text{-}2.9) \times 10^{-6}$
Puch-Kapst et al[19] (2009)	60 / -	14.4	60 / -	17.8	212	Median: 1100 Range: 445-1500	Median: 29.5 Range: 24-36	Median: 38	Median: 4 Range: 1-62	17.5×10^{-6} (1:60,000)
Sutton et al[20] (1998)	60-65 / 20.9-27.8	40 (overall mean)	60-65 / 20.9-27.8	40 (overall mean)	55	Median: 1110 IQR: 540-1480	Mean: 28.8 Range: 24-34	Mean: 60 Range: 4-239	Mean: 9.1	1:60,000
Wilson-Costello et al[21] (1996)	65 / 1.5	10-20	65 / 1.5	20-40	25	Mean: 671	Mean: 25.4	Mean: 115	Mean: 31	1:10,000 (1×10^{-4}) Based on UNSCEAR[29] risk factor 16×10^{-2}

Abbreviations: AXR = abdominal X-ray; CXR = chest X-ray; ED = effective dose; IQR = interquartile range.

NEC is another common but serious complication that occurs in preterm infants. Abdominal radiographs are essential to diagnose this condition along with clinical suspicion. Data from our study indicated that 22% of infants with GA of <28 weeks, including newborns from other hospitals, had NEC. In comparison, 3% of infants with GA of 30 to <32 weeks had NEC. Infants with lower GA and BW are at a higher risk of developing NEC. The median number of abdominal radiographs was 26 for infants with GA of <28 weeks, compared with only 11 for infants with GA of 30 to <32 weeks.

GA, BW, BSA, and length of hospital stay were significant factors associated with the number of chest and abdominal radiographs taken. Three GA groups (<28, 28 to <30, and 30 to <32 weeks) have presented significant difference of cEDs ($p < 0.001$). The median total cED in the extremely preterm group was 1.47 mSv, 3.8 times higher than the very preterm group of 30 to <32 weeks and 1.8 times higher than the group of 28 to <30 weeks. To further investigate the risk of radiation in different sub-groups, infants who underwent abdominal surgery and had NEC were extracted for analysis (Tables 5 to 7). Preterm infants who underwent abdominal surgery and/or were diagnosed with NEC had significantly higher radiation exposure than other subgroups in the analysis. Infants with the highest

Table 10. Cancer risk due to radiation exposure.

Median effective dose per radiograph (μSv)	Calculated cancer induction risk	Cancer risk as ratio
21	2.73×10^{-6}	1:370,000
26	3.38×10^{-6}	1:300,000

radiation exposure were those who received surgical intervention for NEC with a cED of 1.90 mSv.

The induced cancer risk can be estimated from radiation exposure as shown in Table 10. Abdominal X-ray poses a greater risk than chest X-ray as the abdominal region contains many organs that are sensitive to radiation. Although the radiation dose of a single radiograph is relatively low compared with CT scans and other radiological interventions, radiologists and paediatricians have an obligation to balance the risks and benefits of accumulative radiological procedures such as routine radiograph in premature infants. The radiation exposure of preterm infants should be compliant with the ALARA (as low as reasonably achievable) principle.

One major limitation of the proposed study is the lack of documentation of the length of preterm infants. As many preterm neonates are small for GA as well as preterm, estimation using 'fetal-infant growth chart for preterm infants' based on GA is far from ideal.

CONCLUSION

Preterm infants with low BW, low GA, and longer hospital stay underwent more radiographic examinations. Such result confirms previous findings.[28] Extremely preterm infants (GA <28 weeks) and preterm infants who underwent surgery for NEC had the highest ionising radiation dose. Given that a mean exposure from natural background radiation is 2.4 mSv annually (0.2 mSv per month),[29] the cED in these two specific groups is equivalent to more than half a year of background radiation for adults. Although epidemiological studies suggest that a protracted exposure of approximately 50 to 100 mSv is considered to be alarming for cancer risk, it is not appropriate to compare such a figure for preterm infants.[29] The results of the Oxford study on antenatal abdominal radiographs and increased risk for childhood malignancies suggest that this cohort has a unique risk.[30] There is no consensus on what is considered a safe radiation dose for preterm infants. Nonetheless, it is pivotal in clinical practice to apply the ALARA principle until more data are available.

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