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Radiation exposure by digital radiographic imaging in very low birth weight infants

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Abbreviations:
BPD – bronchopulmonary dysplasia
CED – cumulative effective dose
CPAP – continuous positive airway pressure
DAP – dose-area product
DCC – dose conversion coefficients
DR – digital radiography
ED – effective dose
ELBW – extremely low birth weight
ESD – entrance skin dose
GA – gestational age
IRDS – infant respiratory distress syndrome
LHS – length of hospital stay
NBR – natural background radiation
NEC – necrotizing enterocolitis
NICU – neonatal intensive care unit
PDA – patent ductus arteriosus
SGA – small for gestational age
SIMV – synchronized intermittent mandatory ventilation
VLBW – very low birth weight

Table of Contents Summary
This study analyzes the radiation exposure of very low birth weight infants delivered by digital radiography during their stay in the neonatal intensive care unit.

What's Known on This Subject
As a result of diagnostic imaging, premature infants are repeatedly exposed to radiation during their stay in the neonatal intensive care unit. Although digital technology has the potential to reduce patient doses, it can equally lead to higher patient doses.

What This Study Adds
The cumulative effective dose delivered by digital radiographic imaging in a neonatal intensive care unit was determined and compared with previously published data that analyzed conventional radiographic imaging.

Contributors' Statements:
Dr. Ebenebe conceptualized and designed the study, collected data, carried out analyses, and drafted the initial manuscript.
Mr. Barreau conceptualized and designed the study, collected data, and carried out analyses.
Mr. Waschkewitz conceptualized and designed the study, and carried out analyses.
Dr. Schlattl assisted in conceptualizing and designing the study, performed the Monte Carlo transport calculations, and carried out analyses.
Dr. Pinnschmidt carried out statistical analyses.
Dr. Deindl assisted in conceptualizing and designing the study.
Prof. Singer assisted in conceptualizing and designing the study.
Dr. Herrmann assisted in conceptualizing and designing the study, and in drafting the initial manuscript.
All authors reviewed and revised the manuscript, approved the final manuscript as submitted, and agree to be accountable for all aspects of the work.

Abstract

Objective
The aim of this study was to determine the cumulative effective doses (CED) from digital radiographic imaging in very low birth weight infants treated in a tertiary care neonatal intensive care unit.

Methods
All preterm neonates with a birth weight <1500 g treated in our NICU between April 2011 and January 2016 were retrospectively evaluated. The effective dose for each radiographic examination was calculated with a voxel based model. CED for each infant was determined. Clinical data were retrieved by digital chart review including definition of risk factors and application of assistive devices. The results were compared with previous studies applying conventional radiography.

Results
206 preterm infants with a mean birth weight of 1108 g and a mean gestational age of 29.0 were included into this study. Neonates received a mean of 4 radiographs (range: 1-68) and a CED of 50 µSv (4-883 µSv). Independent risk factors for higher CED were low birth weight, necrotizing enterocolitis, presence of malformations, and the need for invasive ventilation. Overall mean CED was lower than in previously published data applying conventional radiography. Factors contributing to a lower radiation dose per infant in our study were a lower number of radiographs and smaller field sizes per radiographic image.

Conclusion
Applying digital technology, the mean CED from radiographic imaging in very low birth weight infants were low. Higher dosages were noted when clinical risk factors were present, emphasizing the need for close dose monitoring and the adaption of dose saving protocols in these patients.

Introduction

During their hospital stay in the neonatal intensive care unit (NICU), premature infants are repeatedly exposed to radiation as a result of diagnostic imaging. Because of their vulnerable age and a long life expectancy, young patients are particularly at high risk for delayed radiation-induced malignancies [1].

Over the last two decades the introduction of digital radiography has significantly transformed the performance of medical imaging. Obvious benefits of digital technology are improved image quality, multiple storage options, post-processing manipulation, and quick image sharing leading to better workflow management [2].

Although digital technology has the potential to reduce radiation exposure, there is also a high risk of significant increased patient doses when radiology departments switch to digital equipment [3]. Reasons that may lead clinicians to apply higher doses per image are an improved image quality and the ability to resolve overexposed images using post-processing whereas underexposed images may need to be repeated.

Several studies published in the last two decades have examined the radiation exposure in neonates [4-14]. However, all these studies analyzed conventional radiographic imaging. This is, to our knowledge, the first study investigating the cumulative ionizing dose delivered to preterm neonates by digital radiography.

Patients and Methods

Patients

All preterm neonates with a birth weight <1500 g treated in our NICU (Division of Neonatology, University Children's Hospital Hamburg-Eppendorf, Germany) between April 1, 2011 and January 31, 2016 were retrospectively evaluated. Clinical patient data were obtained from a review of the digital medical chart (Soarian®, Siemens Healthcare, Erlangen, Germany). Extracted information included gestational age, birth weight, gender, length of hospital stay, small for gestational age (SGA, defined as birth weight below the 10^{th} percentile of the gestational age and sex), infectious complications, patent ductus arteriosus (PDA), necrotizing enterocolitis (NEC), malformations, and need of invasive or non-invasive ventilation (synchronized intermittent mandatory ventilation (SIMV), nasal continuous positive airway pressure (CPAP)).

The study was approved by the local ethics committee with waived informed consent.

Radiographic Device and Technical Setting

Radiographs were taken using a mobile x-ray tube (Practix 400 or Convenio, Philips, Eindhoven, The Netherlands) in combination with a computed radiography imaging system (01.04.2011 until 16.12.2013: Kodak Direct View CR 850, Eastman Kodak Company, Rochester, USA; 17.12.2013 until 31.01.2016, Agfa DX-G with needle based detector, Agfa Health Care NV, Mortsel, Belgium). The exposure settings were determined according to the infant's weight and adapted to the specific system (Table 1). A focus-to-film distance of 100 cm was applied. The dose-area product (DAP) was measured with a permanently installed DAP meter on the mobile radiographic device.

The digital radiographic images were reviewed within the local radiological information and picture archiving system (Centricity™ RIS/PACS, GE Healthcare, Solingen, Germany). For each radiographic image, the tube voltage, tube current, field size, DAP, and patient weight at the time of imaging were recorded. Radiographs were classified according to the imaged body region (chest, abdomen, combined chest/abdomen, and extremities) and further categorized by indications (verification of central venous catheter position, verification of ventilation tube position, respiratory dysfunction, abdominal symptoms, and others).

Estimation of Effective Dose

The estimation of the effective dose was calculated with help of a voxel based model (Voxel Model BABY) [15, 16], representing the dimensions of an eight week old (height of 57 cm and weight of 4200 g). The original voxel sizes were rescaled to reproduce typical dimensions of preterm babies at three different gestational ages (PT1-PT3, see Table 2) [17, 18]. The interaction of the x-ray beam with the infant's body was simulated with a user code to EGSnrc [19-21]. The imaging procedure was simulated assuming an x-ray tube potential of 72 kV and a total filtration of 0.1 mm Cu and 4.4 mm Al, which corresponds to typical parameters used in the NICU. Organ dose conversion coefficients (DCC) normalized to air-kerma free-in-air at the film position were determined following the history of 100 million initial photons for each of the 4 models and 3 examinations (combined thorax and abdomen, thorax, and abdomen radiography). Effective DCC have been computed following the definition of Publication 103 of the International Commission on Radiological Protection [22]. To deduce air-kerma free-in air of each examination, the actual DAP was divided by the actual field size. By multiplying air-kerma free-in-air with the effective DCC of that model that corresponds closest to the specific body weight of the infant at the time of examination, the ED was obtained. The ED is expressed in microsievert (μSv).

Statistical analysis

Data on patient demographics, morbidity and radiation exposure are expressed as median, minimum and maximum values or as mean and standard deviation for continuous variables and as counts and category percentages for categorical variables. The strength of associations among clinical parameters (gestational age, birth weight, length of hospital stay), number of radiographic images and CED was determined by Spearman rank correlations. Relationships among dichotomous categorical variables and continuous variables (gestational age, birth weight, length of hospital stay, cumulative effective dose) were analyzed by means of Mann-Whitney U-tests. Univariate and multivariate general linear modelling were employed to estimate the effects of categorical and continuous independent variables on the cumulative effective dose, after having log-transformed the dependent variable cumulative effective dose to normalize its distribution. General linear modelling was followed by post hoc LSD tests for group-wise comparisons. Comparison of radiation exposure with other studies was performed using One-sample T-Test.

All tests were two-tailed. A p value <0.05 was considered statistically significant. Data analysis was performed using IBM SPSS Version 24 software (SPSS, Chicago, USA).

Results

Patient Demographics

During the observational period, 206 very low birth weight infants admitted to our NICU were included into this study. The median birth weight was 1108 g (410-1495 g), median gestational age was 29.0 weeks 0 (23.1-33.0 weeks), and median length of hospital stay was 65 days (18-297 days). All patients required initial ventilatory support with either nasal CPAP or SIMV. Patient demographics and morbidity data according to four birth weight categories are summarized in Table 3.

Radiographic imaging

During the hospital stay, a median number of four radiographs was performed per patient, ranging between one and 68 radiographs per patient (Table 4). The distribution of the number of radiographs per patient is illustrated in Figure 1. All patients required at least one radiograph. More than 10 and more than 20 radiographs were needed in 21.8% (45 of 206 patients), and 6.3 % (13 of 206 patients) of patients, respectively.

A lower birth weight was significantly associated with a higher number of radiographic images (birthweight < and > 750 g, median 19.7 vs. 65.9 radiographs, p value <0.001). Further independent risk factors for a higher number of radiographic images and higher CED were the diagnosis of NEC (p value <0.001), the presence of malformation (p value <0.001), and the need for SIMV (p value <0.001).

The most frequent indication for radiographic imaging was the verification of central venous catheter positions (31.2%) followed by respiratory symptoms (26.8%) and the verification of tracheal tube positions (20.0%) (Table 5). Extremely low birth weight (ELBW) infants had a higher percentage of abdominal symptoms as an indication for radiographic imaging compared to infants with a birth weight >750 g. This finding is in line with the observation that the percentage of radiographic images with higher ED (thorax/abdomen and abdomen) was considerably higher in infants with a birth weight ≤750 g compared to others (Table 6).

Organ dose conversion coefficients

Using a voxel-based models, we determined specific organ dose conversion coefficients (DCC) of each birth weight group and the potential impact on the effective dose. Calculated effective DCCs for the different preterm groups for thorax, abdomen and thorax and abdomen radiographs ranged from 0.502-0.508 mGy/mGy, 0.548-0.557 mGy/mGy, and 0.892-0.908 mGy/mGy, respectively.

Estimation of effective dose (CED)

During hospital stay, our patients received a median CED of 50.0 µSv (range: 3.6 - 882.6 µSv) (Table 3). The median CED in birth weight groups <750 g and >750 g were 210.6 µSv (range: 68.4-882.6 µSv) and 43.5 µSv (range: 3.6-537.6 µSv), respectively (p value <0.001). The median effective dose per image for thorax radiographs was 10.4 µSv (range: 1.7 - 48.5 µSv), for abdomen radiographs 12.5 µSv (range: 2.8 - 38.7 µSv), and for the combination of thorax and abdomen 18.6 µSv (range: 3.8 - 48.0 µSv).

Discussion

This work investigated radiation exposure of preterm neonates by digital radiographic imaging. Studies reporting on radiation exposure in the neonates are relatively few and, to our knowledge, included only conventional radiography [4-12]. Digital radiography has been introduced to most neonatal units and a major benefit may be the potential to reduce patient dose.

In order to be able to compare dose estimates from our data to historical collectives it is important to consider patient-related factors (e.g. age, morbidity) as they determine the clinical indication, the type of radiography ,and influence exposure settings. The distribution of the type of radiographs in our study was in accordance with findings of previous studies in VLBW and ELBW neonates [11, 13, 14]. Chest radiographs represented 69.4 % of all radiographs performed and were responsible for 61.4 % of CED. Abdominal radiography and combined imaging of chest and abdomen were less frequent (16.2 % and 13.2 %) accounting for 17.1 % and 20.2 % of the CED in our collective.

Also consistent with earlier articles, we observed a strong relationship between birth weight and the CED [6, 7, 10, 11]. Infants with a birth weight ≤750 g had a median CED that was 3.5-fold compared to infants with a birth weight of 751-1000 g and even 7-fold compared to infants with a birth weight of 1251-1500 g. The patient with the highest radiation exposure in our cohort (68 radiographic images, CED of 883 µSv) was a SGA twin with a birth weight of 609 g who suffered from infant respiratory distress syndrome (IRDS), bronchopulmonary dysplasia (BPD), respiratory candida infection, and underwent surgery for meconium ileus. All these morbidities are strongly related to extreme prematurity [23]. Also the presence of congenital malformations was significantly associated with a higher CED (mean: 245 µSv vs. 88 µSv, $p < 0.001$). Two infants with birth weights between 1200 g and 1400 g stood out with approximately 50 radiographic images and a CED > 500 µSv (Figure 2). One was born with a ruptured omphalocele and developed IRDS, pulmonary hypertension, BPD due to prolonged ventilation, as well as an ileus with peritonitis. The other one was a twin born with VACTERL association including esophageal atresia with tracheoesophageal fistula, duodenal atresia, ventricular septal defect, atrial septal defect and acquired repeated infections, particularly aspiration pneumonias.

The overall median CED during NICU hospital stay was 50 µSv (range: 4-883µSv). Previously reported cumulative radiation exposure applying conventional radiography in neonates ranged from 71.5-717 µSv [4-14]. However, the majority of these studies cannot be directly compared to our data as a number of older publications reported only entrance skin dose (ESD) [7, 8, 10, 14]. ESD reflects the radiation dose at the surface of the skin which is not equal to the effective dose (ED) as a measure of the absorbed organ doses which was used in our study [24, 25]. Other previous reports lacked detailed information of patient characteristics like gestational age or birth weight [4, 5, 9, 12].

Three studies during the last two decades met the criteria for reasonable comparison [6, 11, 13] (Table 7). In a similar patient collective comprising VLBW and ELBW infants Puch-Kapst et al. [11] and Donadieu et al. [6] reported a CED during NICU stay applying conventional radiography which were 71.5 µSv and 138 µSv and thereby 43% to 176 % higher than in our study. Infants in the study by Puch-Kapst et al. had received a similar median number of four radiographs per patient. The substantially higher CED in the study by Donadieu et al. can also be attributed to a higher number of radiographs per patients (median: 10.6 radiographs) and a higher rate combined examinations of the chest and abdomen than in our study. Wilson-Costello et al. reported only on dose exposure in children below ≤750 g birth weight [13]. The reported CED was almost threefold higher compared to children in the same weight group in our study (717 µSv vs. 272 µSv). The increased CED can partially be attributed to a higher number radiographs per infant, which was about twice as high as in our study. The ED per abdominal the combination of abdominal and chest radiographs, was more than 1.5-fold higher compared to our study.

Information regarding the applied field size was only specified in the study of Puch-Kapst et al. [11]. The exposed field size was larger compared to our study. When calculating the theoretical value of ED per cm2 a similar radiation exposure to our study could be noted (Table 8). This finding highlights the importance of attentive selection of the field to achieve notable reduction of radiation exposure. One study that analyzed chest radiographs found that in average 45% of each image consisted of unnecessarily imaged organs or tissues [26]. Substantial variations between studies regarding numbers of radiographs per infant performed in the NICU (Table 7) are not solely a reflection of inherent patient populations but strongly suggest that more standardized protocols for imaging in the NICU are necessary. In addition, alternative diagnostic approaches lacking radiation exposure are needed to reduce the number of radiographs. With improving imaging frequency and resolution, ultrasonography has shown to be an effective and reliable method for the diagnosis of neonatal respiratory distress syndrome [27], the verification of peripherally inserted central catheter position [28-30] and endotracheal tube position [31-33] in neonates. Furthermore, recent data suggest that abdominal ultrasound can identify or exclude infants with NEC who may need surgery with high sensitivity and specificity [34, 35].

Digital radiography systems have the potential of substantial patient dose reduction compared to conventional screen-film systems [36, 37]. However, lowering the radiation dose without impairment of image quality is complex and requires the optimization of the whole imaging chain (detector, acquisition, processing, and display) including sufficient training of staff [38]. Overexposure with digital radiography has been reported as this cannot be easily identified by impairment of image quality [38]. Monitoring of patient dose and adherence to diagnostic reference levels are important components to avoid dose levels that do not contribute to the clinical purpose of a medical imaging task [38].

Our study has the following limitations: (1) The study design is retrospective, and is therefore dependent on medical documentation and principally prone to selection bias. (2) The three voxel-based newborn models used in our study were obtained by a geometrical scaling of the model of an 8-week old infant [15, 39]. Thus, the organ sizes and positions of the preterm models do not necessarily agree with those of actual preterm babies, particularly for the lightest weight group. However, the difference in effective DCC between the models is in all cases very small (<5%) and it can be therefore assumed that the classification into the patient weight groups provides sufficiently reliable effective dose estimates.

Conclusion

To our knowledge, this is the first study that analyzes radiation exposure of VLBW infants during their NICU stay by digital radiographic imaging. Compared with historical collectives applying conventional radiography, lower cumulative effective doses were noted. Main factors for a lower dose exposure were a reduced number of radiographs per patient and minimization of field size. Our study emphasizes the necessity of effective dose monitoring protocols in young infants as significantly increased radiation exposure was noted with very low birth weight and the presence of comorbidities.

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Tables and Figures (Titles and legends)

TABLE 1. Exposure settings for thorax and abdomen radiography adjusted to patient's weight

*Kodak Direct View CR 850 system was used in combination with Kodak GP plates (18 x 24 cm and 24 x 30 cm)
**Agfa DX-G was used in combination with a CR HD 5.0 general needle based detector (18 x 24 cm).

TABLE 2. Defined dimensions of preterm (PT) at three different gestational ages for estimation of the effective dose

TABLE 3. Patient Demographics and Morbidity
Abbreviations: GA, gestational age; LHS, length of hospital stay; SGA, small for gestational age; PDA, patent ductus arteriosus; NEC, necrotizing enterocolitis.

TABLE 4. Radiation exposure according to birth weight

Numbers are medians (ranges).

FIGURE 1 Distribution of number of radiographs per patient (median: 4).

TABLE 5. Indications for radiographic imaging

TABLE 6. Distribution of type of radiographs

FIGURE 2. Scatterplot showing the distribution of cumulative effective dose (logarithmic scale) according to birth weight.
Solid line represents the fit line across all patients.

TABLE 7. Radiation exposure by radiographic imaging in different studies

All numbers are medians (ranges) unless otherwise indicated (*mean ± standard deviations).
Abbreviations: NA, not available.

TABLE 8. Comparison of effective doses according to field size

Abbreviations: SD, standard deviation; NA, not available.

Infant weight, g	Exposure settings	
	01.04.2011 - 16.12.2013*	17.12.2013 - 31.01.2016**
< 500	65 kV, 0.64 mAs	65 kV, 0.4 mAs
500 - 700	68 kV, 0.64 mAs	68 kV, 0.4 mAs
701 - 1400	72 kV, 0.64 mAs	72 kV, 0.4 mAs
1401 - 4000	75 kV, 0.64 mAs	75 kV, 0.4 mAs

Characteristics	PT1	PT2	PT3
Gestational age, weeks	24	27	30
Weight, g	700	1000	1400
Length, cm	31.5	35.5	40.0
Chest diameter, cm	5.5	6.0	7.0
Abdomen diameter, cm	6.0	7.0	8.0

Characteristics	**Birth weight categories, g**				**All patients**
	≤750	**751-1000**	**1001-1250**	**1251-1500**	
Number of patients (%)	27 (13.1)	62 (30.1)	53 (25.7)	64 (31.1)	206 (100.0)
Demographics					
Female, No. (%)	18 (66.6)	32 (51.6)	26 (49.1)	32 (50.0)	108 (52.4)
Birth weight, median (range), g	640.0 (410-743)	923.5 (760-996)	1180.0 (1010-1245)	1414.0 (1263-1495)	1108.0 (410-1495)
GA, median (range), weeks	25.0 (23.1-32.4)	27.9 (24.6-32.0)	29.0 (26.6-33.0)	30.3 (28.4-32.1)	29.0 (23.1-33.0)
LHS, median (range), days	118.0 (57-195)	75 (42-124)	60 (29-233)	48 (18-297)	65 (18-297)
Morbidity, No. (%)					
SGA	10 (37.0)	9 (14.5)	6 (11.3)	3 (4.7)	28 (13.6)
Infection	16 (59.2)	29 (46.8)	18 (34.0)	15 (23.4)	78 (37.9)
PDA	17 (63.0)	26 (41.9)	14 (26.4)	10 (15.6)	67 (32.5)
NEC	7 (25.9)	3 (4.8)	3 (5.7)	1 (1.6)	14 (6.8)
Malformation	0 (0.0)	2 (3.2)	3 (5.7)	1 (1.6)	6 (2.9)

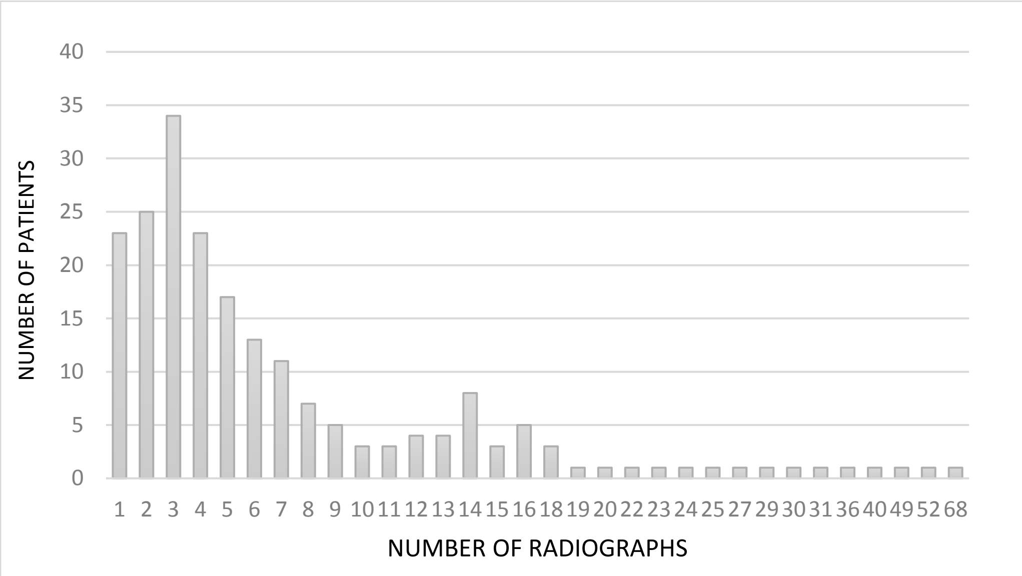
	Birth weight categories, g				All patients
	≤750	751-1000	1001-1250	1251-1500	
Number of radiographs	16 (5-68)	5 (1-29)	5 (1-49)	3 (1-52)	4 (1-68)
Cumulative effective dose, μSv	210.6 (68.4-882.6)	60.2 (9.9-304.7)	49.7 (8.2-537.6)	29.7 (3.6-534.4)	50.0 (3.6-882.6)

Indications, %	Birth weight, g		
	<750	751 -1500	all
Verification of central venous catheter	25.1	34.3	31.2
Verification of tracheal tube	18.9	20.4	20.0
Respiratory symptoms	21.8	30.1	26.8
Abdominal symptoms	27.8	10.6	16.8
Other	6.4	4.7	5.1

Type of radiograph, %	Birth weigh, g		
	<750	751 -1500	all
Thorax	59.1	75.7	69.4
Abdomen	22.9	12.2	16.2
Thorax and Abdomen	15.8	11.6	13.2
Extremities	2.3	0.5	1.1

Reference (type of radiographic imaging)	Number of infants	Birth weight, g	Radiographs per infant	Cummulative effective dose, µSv	Effective dose per radiograph, µSv			
					Thorax	Abdomen	Thorax and Abdomen	All
Puch-Kapst et al, 2009 (conventional)	212	1100 (445-1500)	4 (1-62)	71.5 (8.5-1424.0)	14.4* (±NA)	17.8* (±NA)	23.8* (±NA)	16.1* (±NA)
Dondieu et al, 2006 (conventional)	450	1250 (520-2760)	10.6 (0-95)	138 (0-1450.0)	13.3 (11.6-14.2)	13.5 (12.8-14.9)	21.3 (18.7-21.2)	NA
Wilson-Costello et al, 1996 (conventional)	25	671 (490-745)	30.8 (12-59)	717* (±340)	16.7* (±6.6)	33.7* (±32.2)	32.8* (±13.0)	23.3* (±11.0)
This study (digital)	206	1108 (410-1495)	4 (1-68)	50.0 (3.6-882.6)	10.4 (1.7-48.5)	12.5 (2.8-38.3)	18.6 (3.8-48.0)	11.34 (5.3-41.5)

Characteristics	Type of Radiograph	This study	Puch-Kapst	p-value
Effective dose, mean (SD), µSv	Thorax	10.9 (5.3)	14.4 (NA)	<0.01
	Abdomen	12.9 (4.8)	17.8 (NA)	<0.01
	Thorax and Abdomen	18.8 (7.2)	23.8 (NA)	<0.01
Field size, mean (SD), cm2	Thorax	88 (39)	115 (44)	<0.01
	Abdomen	101 (38)	162 (50)	<0.01
	Thorax and Abdomen	121 (41)	132 (48)	<0.01
Mean effective dose per mean field size, µSv/cm2	Thorax	0.124	0.125	0.886
	Abdomen	0.128	0.110	<0.01
	Thorax and Abdomen	0.155	0.180	<0.01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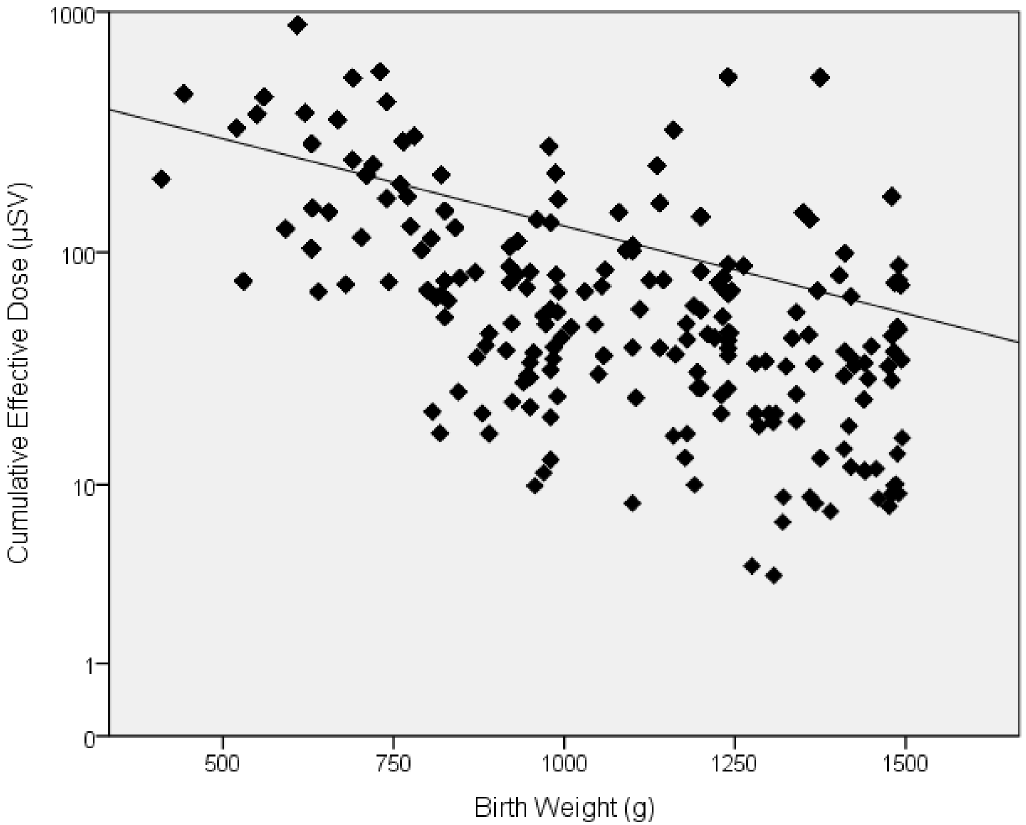
1000
100
10
1
0
500
750
1000
1250
1500
Birth Weight (g)
Cumulative Effective Dose (µSV)