ORIGINAL ARTICLE

Establishing Pediatric Thoracic Radiography Diagnostic Reference Levels Using CALDOSE_X: A Data-Driven Approach to Optimize Radiation Safety

Ikbal Bouadel [1,2*], Morad El Kafhali [3], Marziyeh Tahmasbi [4], Soukaina Mefrah [1,2], Rajaa Sebihi [1]

[1] *High Energy Physics Laboratory Modeling and Simulation (HEPL-MS), Faculty of Sciences, Department of Physics, Mohammed V University, Rabat, Morocco*

[2] *Department of Radiology, Provincial Hospital, Ministry of Health and Social Protection, Morocco*

[3] *Physical Sciences and Engineering, Innovative Research and Applied Physics (IRAP), Faculty of Sciences, Moulay Ismail University, Meknes, Morocco*

[4] *Department of Radiology Technology, School of Allied Medical Sciences, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran*

*Corresponding Author: Ikbal Bouadel
Email: ikbal_bouadel@um5.ac.ma

Received: 16 February 2025 / Accepted: 04 March 2025

Abstract

Purpose: Disparities exist in adherence to national radiation safety standards in Morocco, particularly in pediatric conventional radiology. This cross-sectional study aims to establish Moroccan diagnostic reference levels (DRLs) for pediatric thorax radiography.

Materials and Methods: Thorax radiographs of 208 pediatric patients (newborns to 18 years old) from four Moroccan public hospitals were analyzed. Patient demographics (age, gender, weight) and scan parameters were recorded to calculate radiation doses using CALDOSE_X 5.0 software, focusing on entrance surface air kerma (ESAK, mGy) and kerma-area product (KAP, mGy·cm²). Patients were categorized into five age groups (<1 month, 1 month ≤ age < 4 years, 4 years ≤ age < 10 years, 10 years ≤ age < 14 years, and 14 years ≤ age < 18 years). The third quartile (P75) of ESAK and KAP were determined as DRLs. Statistical analyses were performed using SPSS v.21, with $p < 0.05$ indicating significance.

Results: The P75 values of ESAK and KAP across age groups were 0.61, 0.69, 0.68, 0.82, and 1.29 for ESAK and 350.25, 566.07, 499.14, 950.62, and 1816.06 for KAP. The regional DRLs exceeded those reported in some European countries, likely due to differences in imaging protocols, patient positioning, and exposure parameters. Additionally, irradiated surface area significantly influenced dose variation in patients under 10 years ($p < 0.01$).

Conclusion: Establishing Moroccan pediatric DRLs highlights the need for dose optimization in pediatric radiography. Optimizing irradiated surfaces and exposure parameters while ensuring adherence to international DRL recommendations is essential to enhance radiation safety in pediatric imaging.

Keywords: Pediatrics Thoracic Radiography; Diagnostic Reference Levels; CALDOSE_X; Radiation Safety.

DOI: https://doi.org/10.18502/fbt.v13i1.20788

1. Introduction

Ensuring radiation safety for pediatrics from the prenatal stage up to 18 years of age is crucial due to their heightened sensitivity to ionizing radiation. Pediatric patients are more susceptible to developing radiation-induced cancers [1], malformations, and the proliferation of cancerous cells due to their rapidly growing tissues [2-5]. Furthermore, radiation exposure during early development can elevate the risk of congenital malformations or birth defects [6]. Additionally, it can lead to developmental delays that may impact cognitive development.

In radiation safety, the effective dose is primarily used to assess stochastic risks, including long-term genetic effects, while the absorbed dose is more relevant for deterministic effects such as skin reactions [7]. Hence, it is important to adhere to the ALARA principle (as low as reasonably achievable), shifting the focus from "image quality as good as possible" to "image quality as good as necessary" [8, 9].

Several research endeavors extend beyond merely reducing radiation doses to optimizing and preserving the radiation safety of pediatric patients. Employing the highest kVp and the lowest mAs is recommended to achieve appropriate image quality [10]. However, this approach may affect image quality [11]. Therefore, it becomes necessary to modify and improve image quality by emphasizing the use of the highest kV, which remains the optimal solution to reduce radiation doses, and thus establish diagnostic reference levels (DRLs) for examinations in pediatric patients, especially newborns [12]. DRLs play a significant role in optimizing the doses of radiation administered to patients [13]. DRLs do not define strict radiation limits but serve as benchmarks for optimizing dose levels, and ensuring patient safety while maintaining diagnostic image quality [14]. Given pediatric patients' heightened vulnerability to ionizing radiation, establishing DRLs for thorax radiography is essential for optimizing radiation safety. Pediatric DRLs are essential benchmarks that guide radiology practices in minimizing exposure while maintaining diagnostic efficacy.

Several studies have established DRLs for pediatric thorax radiography examinations using incident air kerma or IAK factor and other dosimetric measures [15-19]. However, there is a lack of pediatric-specific DRLs for thorax radiography in Morocco, despite thorax imaging being one of the most frequently performed radiographic procedures in this population. This study aims to address this gap by determining regional DRLs tailored for Moroccan pediatric patients using CALDOSE_X, a Monte Carlo-based software for dose estimation in the absence of direct dosimetric measurements. Additionally, the study explores the impact of exposure factors and irradiated surface area variations across different age groups. The findings hold significant implications for enhancing radiation safety standards for pediatric patients in Morocco and fostering adherence to international guidelines on radiation safety for this susceptible group. The presented study focuses on the calculation of entrance surface air KERMA (ESAK) and KERMA-area product (KAP) in pediatrics thorax radiography (anterior-posterior and posterior-anterior (AP/PA) views) conducted at four public hospitals in the Casablanca region, Morocco and to establish DRLs accordingly.

2. Materials and Methods

This cross-sectional observational study was approved by the institutional ethics board. Informed consent was obtained from patients' guardians before inclusion in the study, and confidentiality of patient information was strictly observed throughout the study.

2.1. Study Population, Data Collection, Collected Data, and Data Collection Duration

A convenience sampling method [20] was employed, selecting pediatric patients undergoing thorax radiography based on availability rather than random selection. This approach has been widely used in radiological dose assessment studies to ensure practical feasibility while maintaining representative data collection [17, 21]. Inclusion criteria comprised pediatric patients aged newborn to 18 years who underwent thorax radiography during the study period. Patients who examined using the same DR systems across the four hospitals. Availability of complete patient demographic data (age, gender, weight) and scan parameters (kilovoltage peak (kVp), milliampere-seconds (mAs), Focus-Detector Distance (FDD)). Exclusion criteria were patients with incomplete demographic or exposure data. Cases where radiographic images were repeated due to motion artifacts or poor image quality. Patients with underlying conditions or medical devices (e.g., chest implants) that could significantly alter radiation absorption.

Based on the considered inclusion criteria, a total of 208 pediatric patients (newborns up to 18 years old) undergoing thorax radiography at four public hospitals in the Casablanca region, Morocco were included. It should be acknowledged that the study focuses on the entire thorax rather than specific anatomical structures. The patients were divided into five age categories following dosimetry guidelines [20, 22], including age <1 month, 1 month ≤ age< 4 years, 4 years ≤ age< 10 years, 10 years ≤ age< 14 years, and 14 years ≤ age < 18 years.

It is important to note that the same equipment and imaging systems (Digital Radiography (DR) imaging systems model GMM/ITALRAY) were used across all four radiology departments in hospitals where data collection took place, covering the various age groups under study. All equipment was installed within a similar timeframe, and no major repairs or modifications were reported during the study period. Routine quality control was performed on radiography systems to ensure consistency in radiation output. However, tube filtration values were not explicitly included in dose calculations, which may contribute to minor discrepancies in ESAK estimation. Future studies should incorporate direct measurements of tube filtration to enhance dose accuracy.

Four researchers collected the data using a researcher-designed checklist based on the study objectives. The data collection period was extended over nine months, from September 2022 to June 2023. The key data collected for each thorax radiography included patient demographics (gender, age, weight), estimated irradiated surface areas, and scan parameters kVp, mAs, and FDD.

It should be noted that the FDDs were determined by measuring them with a centimeter tape from the source to the detector surface, or, depending on the type of device, they could be directly viewed on the tube screen. Also, FDDs vary based on age and positioning (supine vs. standing). However, this study did not control for these variations in dose calculations, which may introduce minor inconsistencies in ESAK and KAP values.

Due to the unavailability of precise weighing equipment, the recorded patients' weights were also estimations provided by their parents upon request of hospital technologists.

The irradiated surface area was also estimated indirectly using console display data from the imaging system, as direct measurements during examinations were not available. However, variations in collimation and field selection by technologists may lead to discrepancies between the displayed radiation field and the actual irradiated area. In some cases, technologists may select a larger radiation field to ensure appropriate image quality and then crop the image post-acquisition for standardization. This practice could introduce minor inconsistencies in the estimated irradiated surface area, potentially influencing KAP and ESAK calculations. Further research should explore methods to directly measure and validate irradiated surface areas to improve dose estimation accuracy. This indirect approach was employed due to the patient load in the department and the lack of access to the desired irradiated surface area data through the control panel of imaging systems. Consequently, both irradiated surface areas in cm^2 and patient weights were estimated for this study.

2.2. The Used Software to Calculate Radiation Doses and Statistical Analysis

Calculating ESAK values directly via physical phantoms for patients undergoing X-ray examinations presents significant challenges. In this study, radiation doses were estimated using CALDOSE_X 5.0 software [23] incorporating Monte Carlo simulations.

CALDOSE_X 5.0 was used to estimate ESAK and KAP values based on recorded exposure parameters (kVp, mAs, focus-detector distance (FDD)) from digital radiography (DR) systems and patient gender, age, and specific area of interest. To ensure accuracy, the input parameters were carefully verified, and computed values were cross-checked with published DRL data where applicable.

CALDOSE_X is a Monte Carlo-based software designed for patient dose assessment in diagnostic [1] radiology. The software has been validated in several studies, demonstrating its accuracy in estimating

ESAK and KAP for pediatric and adult radiography [24]. It utilizes virtual human MAX06 and FAX06 voxel phantoms and conversion coefficients (CCs) based on ICRP 103 recommendations [25] to enhance dosimetric accuracy. By leveraging conversion coefficients CCs and aligning them with measurable quantities, this software determines organ and tissue absorbed doses along with effective doses, adhering to the standards outlined in ICRP Publication 103[25]. ESAK is calculated using the following formula [7] (Equation 1):

$$ESAK = D_{air} \times BSF \times (\frac{FDD}{FSD})^2 \quad (1)$$

where D_{air} is the absorbed dose in air, BSF is the backscatter factor, FDD is the focus detector distance, and FSD is the focus skin distance.

FSD was set based on software guidelines and BSF was provided in the software. It is important to acknowledge that specific conversion factors and calculation details may vary depending on the equipment, radiological examination type, and methodology used in different medical contexts [26].

Calculated ESAK values were further multiplied by the irradiated surface area in cm^2 to obtain the total absorbed KERMA in air product (KAP) in mGy-cm^2 (Equation 2):

$$KAP(\mathrm{mGy, cm^2}) = \mathrm{ESAK\ (mGy)} \times \mathrm{Irradiated\ Area\ (cm^2)} \quad (2)$$

Statistical analyses were performed using SPSS v. 21.0. The calculated values were reported as mean ± standard deviation or percentages. Normality was tested using Kolmogorov-Smirnov and Shapiro-Wilk tests. Due to the non-normal distribution of the data, the non-parametric Spearman and Kruskal-Wallis tests were employed to analyze correlations.

3. Results

Demographic specifications of 208 pediatric patients aged ≤ 1 month up to 18 years and the standard deviation of used exposure factors and FDDs for their thorax radiography are presented in Table 1.

Among 208 studied patients, 86 were females (41.34%) and 122 were males (58.65%). The average age and weight of studied patients were 5.04±4.86 years and 18.64±13.64 kg, respectively.

Table 2 presents the median, P75, and ranges of ESAK (mGy) and KAP (mGy.cm²) values across different pediatric age groups. Table 2 shows that ESAK values remain relatively stable in younger age groups (≤10 years), with a median dose of approximately 0.65 mGy. However, a significant increase is observed in older patients (age >10 years), likely due to increased body mass, anatomical variations, and adjustments in imaging protocols, particularly for trauma-related assessments. Table 2 also presents the median, P75, and ranges for patients' ages and irradiated surface areas. As mentioned, the

Table 1. Studied pediatric patients' age groups, mean±SD of patients' weight in each age group, along with mean±SD of scan parameters for evaluated thorax radiography examinations

Patients Demographics			Mean±SD of Scan Parameters		
Age Group	**Patients Number (%)**	**Mean±SD of Patients' Weight (Kg)**	**kVp**	**mAs**	**FDD (cm)**
1	21 (10.1)	3.85 ± 0.75	67.57±9.45	2.48± 1.21	98.33±3.93
2	76 (36.5)	9.95±3.97	69.47±9.86	2.95±1.73	102.63±7.39
3	71 (34.1)	19.27±5.83	70.00±9.21	4.12±4.87	112.42±8.80
4	26 (12.5)	33.26±8.65	72.46±9.63	5.56±4.36	117.57±9.99
5	14 (6.7)	52.00±10.97	74.42±10.58	7.02±4.92	130.00±22.18

FDD: Foucs detector distance (cm), SD: Standard Deviation
Group 1: age < 1 Month, Group 2: 1 Month ≤ age < 4 years, Group 3: 4 years ≤ age < 10 years, Group 4: 10 years ≤ age < 14 years, Group 5: 14 years ≤ age < 18 years.
Note: Mean±SD of weight and scan parameters are presented for each evaluated age group of pediatric patients.

Table 2. Regional diagnostic reference levels (RDRLs) for pediatric thorax radiography examinations, calculated by CALDOSE_X software

Age Group		1	2	3	4	5
Patient Age	Median	15.00 Days	1.00 Years	5.00 Years	11.00 Years	16.00 Years
	P75	23.50	2.00	7.00	12.00	17.00
	Range	1.00-29.00	0.20-3.50	4.00-9.00	10.00-13.00	14.00-17.00
Irradiated Surface (cm²)	Median	500.00	750.00	750.00	1068.00	1225.00
	P75	725.00	875.00	900.50	1225.00	1505.00
	Range	250.0-786.0	250.0-1250.0	350.0-1300.0	625-1350.0	1000.0-2500.0
ESAK (mGy)	Median	0.55	0.49	0.47	0.57	0.82
	P75	0.61	0.69	0.68	0.82	1.29
	Range	0.13-0.85	0.08-4.18	0.13-5.37	0.13-4.57	0.15-2.21
P-Value				0.288		
KAP (mGy.cm²)	Median	275.00	377.12	382.5	608.67	866.00
	P75	350.25	566.075	499.14	950.62	1816.06
	Range	35.00-540.00	24.00-3135.00	80.50-4027.50	156.25-5598.25	183.75-3326.05
P-Value				0.000		

ESAK: entrance surface air KERMA(Kinetic Energy Released per unit Mass), KAP: KERMA in air product, P75: 75th percentile.
Age Group 1: age < 1 Month, Group 2: 1 Month ≤ age < 4 years, Group 3: 4 years ≤ age < 10 years, Group 4: 10 years ≤ age < 14 years, Group 5: 14 years ≤ age < 18 years.
Note: * shows statistically significant differences

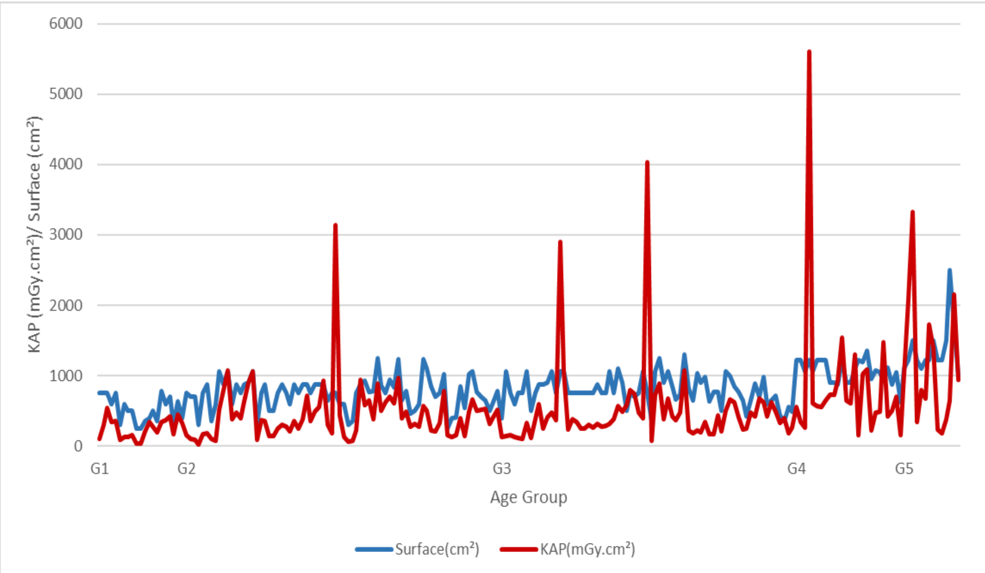

Figure 1. Variations of KAP (mGy.cm²) with irradiated surface area (cm²) across different pediatric age groups

calculated DRLs for pediatric thorax radiography are P75 of the ESAK and KAP values. It should be stated that this study did not explicitly separate AP and PA radiography techniques, which may influence the effective organ dose.

Table 3 summarizes the calculated regional DRLs based on the third quartiles of obtained KAP (mGy.cm²) values for each considered age group compared to those of selected countries [20]. The calculated regional DRL values exceeded those reported in some European countries (France, Spain, and Belgium).

Figure 1 illustrates the relationship between KAP and irradiated surface area across pediatric age groups. While a moderate correlation is observed in younger patients, Table 4 reveals that this relationship weakens in older age groups.

The normality of data for both KAP in mGy.cm² and the irradiated surface in cm² across the five age groups were evaluated using the Kolmogorov-

Table 3. The calculated regional diagnostic reference levels (DRLs) for pediatrics thorax radiography in Morocco compared to those of selected countries

Age Group	Austria	Spain	France	Lithuania	Belgium	Morocco
1	17.00	40.00	10.00	50.00	20.00	350.25
2	23.00	50.00	20.00	60.00	35.00	566.07
3	26.00	85.00	50.00	80.00	50.00	499.14
4	37.00	100.00	70.00	100.00	120.00	950.62
5	73.00	-----	-----	-----	-----	1816.06

Age Group 1: age < 1 Month, Group 2: 1 Month ≤ age < 4 years, Group 3: 4 years ≤ age < 10 years, Group 4: 10 years ≤ age < 14 years, Group 5: 14 years ≤ age < 18 years.

Table 4. The Spearman's Rho test results to evaluate the correlation of KERMA-Area product and irradiated surface in pediatrics thorax conventional radiography

	$S_1 K_1$	$S_2 K_2$	S_3K_3	$S_1 S_4$	$S_4 K_2$	$K_4 K_5$
Correlation Coefficient	0.606	0.753	0.398	0.475	-0.454	-0.753
Sig.)	0.004	0.000	0.001	0.029	0.020	0.002
N	21	76	71	21	26	14

S_1K_1 : The correlation between S_1 and K_1 S_1S_4: The correlation between S_1 and S_4
S_2K_2 : The correlation between S_2 and K_2 S_4K_2: The correlation between S_4 and K_2
S_3K_3 : The correlation between S_3 and K_3 K_4K_5 : The correlation between K_4 and K_5
K_1, S_1 : THE KERMA-AREA PRODUCT and THE IRRADIATION SURFACE for the Group 1
K_2, S_2 : THE KERMA-AREA PRODUCT and THE IRRADIATION SURFACE for the Group 2
K_3, S_3 : THE KERMA-AREA PRODUCT and THE IRRADIATION SURFACE for the Group 3
K_4, S_4 : THE KERMA-AREA PRODUCT and THE IRRADIATION SURFACE for the Group 4
K_5, S_5 : THE KERMA-AREA PRODUCT and THE IRRADIATION SURFACE for the Group 5

Smirnov and Shapiro-Wilk tests in SPSS. The KAP values for age groups 2, 3, and 4, as well as the irradiated surface values for age groups 4 and 5, did not conform to a normal distribution. Consequently, the non-parametric Spearman test was employed to analyze the correlations.

Table 4 summarizes the Spearman's Rho test results. The Spearman correlation analysis (Table 4) confirms a statistically significant but moderate correlation at 0.01 significance level, between KAP in mGy.cm² and the irradiated surface in cm² for younger age groups (age groups 1 to 3), whereas, in older groups (age groups 4 and 5), the dependence on irradiated surface diminishes. This suggests that additional factors such as patient positioning, exposure settings, and anatomical variations play a more significant role in dose distribution.

It should be acknowledged that to make the graph easier to read, the five groups of pediatric patients are numbered as follows: group 1 (patients number 1 to 21), group 2 (patients numbers 22 to 97), and group 3 (patients numbers 98 to 168), group 4 (patients numbers 169 to 194), and group 5 (patients numbers 195 to 208). Notably, several outliers (patients 98, 99, 108, 128, 170, 175, 184, and 190) deviate from the expected trend, suggesting variations in exposure conditions, positioning errors, or protocol inconsistencies. This highlights the need for stricter standardization of imaging techniques in older pediatric groups.

Further analysis of Table 4 reveals that irradiated surface areas in groups 1 and 4 (S1, S4) were similar**,** and dose values in age groups 4 and 5 (K4, K5) were nearly identical. Additionally, KAP values in age group 2 closely matched irradiated surfaces in group 4 (S4)**.** This complex interplay suggests that irradiation surface is not the sole determinant of dose and other exposure factors must be optimized for better dose control.

4. Discussion

This study established regional DRLs for pediatric thorax radiography in Morocco, addressing the need for optimized radiation safety in pediatric imaging.

The Moroccan regional DRLs for pediatric thorax examinations in conventional radiology for five evaluated groups of patients aged from newborns up to

18 years old, were calculated as 350.25, 566.07, 499.14, 950.62, and 1816.06, respectively. The regional DRLs exceeded those reported in some European countries (France, Spain, Belgium), which may be attributed to differences in imaging protocols and patient positioning, variations in X-ray equipment, exposure settings (kVp, mAs), and detector sensitivity, and differences in dose estimation methods, such as Monte Carlo simulations versus direct dosimetric measurements.

Interestingly, DRLs for age groups 2 and 3 do not follow a strict increasing trend. This could be due to variations in sample size across age groups, differences in scan acquisition parameters (e.g., kVp, mAs), and irradiated surface inconsistencies, as observed in Figure 1.

Based on the findings (Table 1), it is evident that the age group of less than one month has the shortest distance from the X-ray tube, closely followed by the second age group, featuring a progression of values that rises with age, along with corresponding average distances of 98.33±3.93, 102.63±7.39, 112.42±8.80, 117.57±9.99, and 130.00±22.18 cm, respectively. The variation in FDD between supine (≤120 cm) and standing (≥180 cm) radiography may contribute to dose variations across age groups. While our study documented FDD values for different pediatric groups (Table 1), it did not explicitly analyze them as confounding factors. Future studies should assess the extent to which FDD differences influence dose estimates and whether standardizing FDD protocols could enhance dose optimization. This provision elucidates the ascending dosage sequence concerning ESAK and KAP, where the dose increases as the distance decreases. This principle aligns with the inverse square law, emphasizing the direct influence of distance on radiation dose [27].

Moreover, the Kruskal-Wallis test results indicated no statistically significant differences among the applied KVps for the various age groups (P-value = 0.171). However, there were statistically significant differences in the used mAs for different age groups (P-value = 0.00).

A noteworthy observation is the remarkable difference between the average dose for adult patients in thoracic examinations, which is approximately 0.29 mGy [28], and the average doses for pediatric patients respectively for the five groups studied, which obtained as 0.61, 0.69, 0.68, 0.82 and 1.29 mGy as presented in Table 2. In this scenario, the findings indicate that the regional DRLs for the ESAK value are exceeded, surpassing even the DRLs recommended for adults. This underscores the need for comprehensive training of radiographers in radiation safety to safeguard the pediatrics undergoing imaging examinations.

Based on the findings, ESAK increases with age, with the highest values observed in age groups 4 and 5. This pattern aligns with increased patient size and variations in imaging protocols, particularly for trauma-related assessments. However, the Kruskal-Wallis test revealed no significant differences in ESAK values among the age groups ($p = 0.288$).

Additionally, a moderate correlation was observed between the KAP values (Figure 1 and Table 2) and irradiated surface areas in younger age groups ($p < 0.01$). This finding aligns with expectations since radiation dose generally increases with larger exposure fields. However, in older age groups, this relationship is less pronounced, likely due to other confounding factors such as variations in patient positioning, radiographic technique (AP vs. PA), and exposure parameters such as kVp and mAs likely contribute to fluctuations in dose. The presence of multiple outliers further suggests inconsistencies in technologist practices or patient-specific factors affecting radiation dose. These findings highlight the importance of individualized dose optimization and the need for better adherence to radiation safety protocols to minimize unnecessary radiation exposure while maintaining diagnostic image quality. A notable concern in pediatric thorax radiography is unintentional radiation exposure beyond the target area. In many cases, the abdominal region is also irradiated, particularly in younger patients. This highlights the importance of precise collimation and technologist training to minimize unnecessary exposure.

The doses calculated in this study have already surpassed the recommended levels for adults. Furthermore, the results underscore the presence of extreme values associated with heightened exposure factors (kVp and mAs) necessary for thorax trauma examinations in pediatric patients. A closer examination of this observation prompts the necessity to optimize doses delivered to pediatric patients.

According to the findings, the inclusion of the irradiated surface area in cm^2 plays a crucial role in modifying the dose quantity. One potential limitation of our irradiated surface area estimation method is that technologists may have cropped images post-acquisition for quality control purposes, which could lead to discrepancies between the recorded radiation field size and the actual irradiated area. This variability may introduce minor inconsistencies in dose calculations, particularly in KAP and ESAK estimations. Future studies should consider direct measurement methods or alternative validation approaches, such as automated field size recognition algorithms or direct dosimetric assessments, to improve accuracy in radiation dose estimation.

It is also evident that technologists consistently employ uniform irradiation surfaces, regardless of individual patient specifications. This pattern is observable for both age groups 2 and 3, where 50% of these groups share the same average KAP values. It is important to note that a direct relationship is primarily observed in children from newborns to those under 10 years of age concerning their irradiated surface area. For other age groups, optimizing doses should take into account various parameters that affect received doses and the radiosafety of pediatric patients. It is also crucial to emphasize that there is no individualized adaptation for each pediatric patient. This means that pediatric patients with different individual characteristics, such as weight, age, etc., may receive the same dose without considering these specific factors. Consequently, ensuring the radiation safety of pediatric patients necessitates optimizing the irradiation surface since the irradiated surface area impacts the pediatric received doses in conventional radiology.

Based on the findings, an exemplary approach is suggested for addressing various factors influencing the received dose to patients, to establish optimized values for pediatric thorax imaging using a conventional radiography unit (DR system) with a 2.5mm Al filter. The proposed approach aligns with international standards to ensure adherence to specifications for each age group of pediatric patients. For ease of reference, the suggested optimized exposure factors, SSDs, and irradiation surfaces for each age group of pediatrics, along with the corresponding ESAK and KAP values, are documented in Table 5.

The suggested recommendation faces a constraint related to the FDDs for the age groups 1 and 2 (age <1 month and 1 month ≤ age < 4 years). Challenges arise due to the immobility of patients in these groups, compounded by the lack of means of restraint. This limitation led to the adoption of the "prone thorax (AP)" protocol for these age categories in hospitals within the study region, where tables for this protocol are fixed at a maximum height of 100cm. Given these circumstances, our approach shifts towards manipulating other pivotal factors, including kVp, mAs, and irradiation surface, to skillfully optimize the dose and adhere to the specific requirements for pediatric patients.

The significance of this study lies in its potential to enhance dose optimization efforts across pediatric radiology services, addressing the need for localized DRLs that reflect the unique demographic and technological context of Moroccan healthcare. By providing these benchmarks, this study also promotes broader awareness among radiologists and technologists regarding the importance of adapting radiation practices for pediatric care, ultimately supporting safer imaging practices and better health outcomes for children. However, the study does have several limitations. Due to the restricted timeframe required to complete the Ph.D. thesis, as well as the limited number of pediatric thoracic radiography cases available in the evaluated centers, the study included a relatively small sample of 208 pediatric patients. Patient weights, essential for dose estimation,

Table 5. A summary of proposed exposure factors, FDDs, irradiation surface area, and the corresponding ESAK, and KAP values for pediatrics thorax conventional radiography examinations

Age Group	kVp	mAs	FDD (cm)	Irradiation Surface (cm²)	ESAK (mGy)	KAP (mGy.cm²)
1	60.00	1.60	100.00	150.00	0.24	36.00
2	60.00	2.00	105.00	195.00	0.26	50.70
3	70.00	2.50	120.00	255.00	0.31	79.05
4	70.00	2.50	130.00	400.00	0.26	104.00
5	80.00	2.50	150.00	600.00	0.23	138.00

Group 1: age < 1 Month, Group 2: 1 Month ≤ age < 4 years, Group 3: 4 years ≤ age < 10 years, Group 4: 10 years ≤ age < 14 years, Group 5: 14 years ≤ age < 18 years.

FDD: Foucs detector distance (cm), ESAK: entrance surface air KERMA (Kinetic Energy Released per unit Mass), KAP: KERMA in air product were based on information provided by parents rather than direct measurements, as precise weighing equipment was not available. Additionally, irradiation surface areas were estimated indirectly from console data, as direct measurement during examinations was unfeasible. Comparisons with other studies were also constrained due to the limited number of published DRLs for pediatric thoracic radiography. Furthermore, the absence of dosimetry equipment, such as phantoms, direct dosimeters, or ionization chambers, prevented validation through direct measurement of radiation doses. Future research should aim to address these limitations, enabling more comprehensive and precise evaluations. Also, this study did not explicitly separate AP and PA radiography techniques, which may influence the effective organ dose. Future studies should evaluate the impact of the projection technique on dose variation.

5. Conclusion

This study established Moroccan regional DRLs for pediatric thorax radiography, with values of 0.61, 0.69, 0.68, 0.82, and 1.29 mGy based on ESAK values and 350.25, 566.07, 499.14, 950.62, and 1816.06 mGy.cm² based on the KAP values across five evaluated age groups. These DRLs were higher than those reported in some European countries. These discrepancies highlight the influence of differences in imaging protocols, exposure settings, radiographic equipment, and patient characteristics. Further studies with larger sample sizes and standardized protocol assessments are necessary to refine these DRLs and improve pediatric radiation safety in Morocco. While an association between irradiated surface area and KAP values was observed in some pediatric groups, this relationship was not consistently strong across all age categories. This highlights the complexity of dose variation in pediatric radiography. Multiple factors beyond field size, such as exposure settings, patient positioning, and imaging techniques significantly determine radiation dose, necessitating a comprehensive approach to optimizing pediatric radiation safety.

These findings highlight a critical gap in radiation safety for pediatric thorax examinations in Morocco, emphasizing the need to optimize irradiation surface areas, enhance technologist training in pediatric radiation safety and dose management, and ensure compliance with auditing, quality control measures, and international safety regulations. Addressing these gaps will help align Moroccan pediatric radiology practices with global radiation safety standards, ultimately improving patient care and minimizing radiation risks for children. A holistic approach to radiation safety is essential, incorporating protocol optimization, equipment standardization, and exposure control to enhance diagnostic imaging while minimizing unnecessary radiation exposure. Strengthening technologist training, particularly in the effective management of irradiation surfaces, is crucial for implementing optimized imaging protocols and improving overall pediatric radiological care. Commitment to these measures will contribute to continual advancements in pediatric radiation safety, ensuring the highest standards of radiological practice and patient well-being in Morocco.

Acknowledgments

We express our sincere appreciation to the committed technologists from the four public hospitals who wholeheartedly contributed to this study. This collaboration was made possible with the support of Mr. EL Achari Adil, the official representative of the Moroccan Ministry of Health and Social Protection in Sidi Bennour city, and Ms. Sabri Amina, the RH of the delegation of the Ministry of Health and Social Protection in the same city. Special acknowledgment goes to Ms. Fajri Chaimaa for her steadfast dedication and invaluable contributions throughout the entire research process.

The authors have no conflicts of interest.

The author(s) did not obtain financial support for conducting the research, authoring, and publishing this article. Nevertheless, we wish to convey our appreciation for the assistance rendered by the Ministry of Health, Government of Morocco.

References

1- D. P. Frush, L. F. Donnelly, and N. S. Rosen, "Computed tomography and radiation risks: what pediatric health care providers should know." *Pediatrics,* Vol. 112 (No. 4), pp. 951-7, Oct (2003).

2- H. Nahangi and A. Chaparian, "Assessment of radiation risk to pediatric patients undergoing conventional X-ray examinations." *Radioprotection,* Vol. 50 (No. 1), pp. 19-25, (2015).

3- Karen M. Wieseler, Puneet Bhargava, Kalpana M. Kanal, Sandeep Vaidya, Brent K. Stewart, and Manjiri K. Dighe, "Imaging in Pregnant Patients: Examination Appropriateness." *RadioGraphics,* Vol. 30 (No. 5), pp. 1215-29, (2010).

4- A. Chaparian and M. Aghabagheri, "Fetal radiation doses and subsequent risks from X-ray examinations: Should we be concerned?" *Iran J Reprod Med,* Vol. 11 (No. 11), pp. 899-904, Nov (2013).

5- J. Valentin, "Biological effects after prenatal irradiation (embryo and fetus)." *Annals of the ICRP,* Vol. 33 (No. 1-2), pp. 1-206, (2003).

6- R. Kumar and O. De Jesus, "Radiation Effects On The Fetus." in *StatPearls*. Treasure Island (FL), (2024).

7- Mohammed Khalil Saeed, Yousif Abdallah, Ibrahim Y. Hakeem, and Fawaz F. Alqahtani, "Patient radiation dose estimation during pelvis, hip joint and lumber spine radiography in Majmaah city, Saudi Arabia hospital." *Radiation Physics and Chemistry,* Vol. 209p. 110990, (2023).

8- Emily Ashworth, Liam Woods, and J. Valmai Cook, "Diagnostic reference levels in paediatric fluoroscopy: how does a secondary referral centre compare with 2018 European guidelines?" *The British Journal of Radiology,* Vol. 94 (No. 1123), p. 20201269, (2021).

9- Martin Uffmann and Cornelia Schaefer-Prokop, "Digital radiography: The balance between image quality and required radiation dose." *European Journal of Radiology,* Vol. 72 (No. 2), pp. 202-08, (2009).

10- D. N. DeMaio *et al.*, "Best Practices in Digital Radiography." *Radiol Technol,* Vol. 91 (No. 2), pp. 198-201, Nov (2019).

11- C. Martin, "The importance of radiation quality for optimisation in radiology." *Biomed Imaging Interv J,* Vol. 3 (No. 2), p. e38, Apr (2007).

12- W. Elshami, M. M. Abuzaid, M. M. Gibril, A. Sulieman, and D. A. Bradley, "Impact of high kilo-voltage peak technique on radiation dose for neonates undergoing chest radiography: Experimental study." *Radiation Physics and Chemistry,* Vol. 199p. 110327, (2022).

13- INTERNATIONAL ATOMIC ENERGY AGENCY, Dosimetry in Diagnostic Radiology for Paediatric Patients. Vienna: *IAEA Human Health Series* (2014).

14- E. Vañó *et al.*, "ICRP Publication 135: Diagnostic Reference Levels in Medical Imaging." *Annals of the ICRP,* Vol. 46 (No. 1), pp. 1-144, (2017).

15- P. Roch, D. Célier, C. Dessaud, and C. Etard, "Les niveaux de référence diagnostiques en France : une perception contrastée face à un dispositif perfectible mais efficace." *Radioprotection,* Vol. 53 (No. 1), pp. 13-19, (2018).

16- Yasuki Asada and Takuma Ichikawa, "Consideration of diagnostic reference levels for pediatric chest X-ray examinations." *Radiological Physics and Technology,* Vol. 12 (No. 4), pp. 382-87, (2019).

17- Jochen Billinger, Robert Nowotny, and Peter Homolka, "Diagnostic reference levels in pediatric radiology in Austria." *European Radiology,* Vol. 20 (No. 7), pp. 1572-79, (2010).

18- Barry F. Wall, "Diagnostic reference levels in the X–ray department." *European Radiology Supplements,* Vol. 14 (No. S1), pp. 66-73, (2004).

19- T. Kiljunen, H. Järvinen, and S. Savolainen, "Diagnostic reference levels for thorax X-ray examinations of paediatric patients." *The British Journal of Radiology,* Vol. 80 (No. 954), pp. 452-59, (2007).

20- European Commission and Directorate-General for Energy, European guidelines on diagnostic reference levels for paediatric imaging. *Publications Office*, (2018).

21- I. G. Shatskiy, A. Yu. Gryaznov, and Yu. N. Potrakhov, "Assessment of models of diagnostic reference levels for children on radiography." *AIP Conference Proceedings,* Vol. 2726 (No. 1), p. 020022, (2023).

22- A. Almen, J. Guethjonsdottir, N. Heimland, B. Hojgaard, H. Waltenburg, and A. Widmark, "Paediatric diagnostic reference levels for common radiological examinations using the European guidelines." *Br J Radiol,* Vol. 95 (No. 1130), p. 20210700, Feb 1 (2022).

23- R. Kramer, H. J. Khoury, and J. W. Vieira, "CALDose_X—a software tool for the assessment of organ and tissue absorbed doses, effective dose and cancer risks in diagnostic radiology." *Physics in Medicine and Biology,* Vol. 53 (No. 22), pp. 6437-59, (2008).

24- M. K. Saeed and Y. Almalki, "Assessment of the radiation dose associated with X-ray examinations using the DoseCal and CALDose_X software packages." *International Journal of Radiation Research,* Vol. 20 (No. 1), pp. 191-97, (2022).

25- ICRP, "Preface, Executive Summary and Glossary." *Annals of the ICRP,* Vol. 37 (No. 2-4), pp. 9-34, (2007).

26- G. Paulo, E. Vaño, and A. Rodrigues, "Diagnostic reference levels in plain radiography for paediatric imaging: A Portuguese study." *Radiography,* Vol. 22 (No. 1), pp. e34-e39, (2016).

27- Libby Brateman, "The AAPM/RSNA Physics Tutorial for Residents." *RadioGraphics,* Vol. 19 (No. 4), pp. 1037-55, (1999).

28- Suhaib Alameen, Fatima A. A. Badrey, Abdulrahman S. Abdullateef, and Abdelfatah M. Ahmed, "Assessment of ESAK and ED for Adult's Patients Examined by Computed Radiography." *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology,* Vol. 05 (No. 04), pp. 281-87, (2016).