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FULL PAPER

Radiation dose optimisation for conventional imaging in infants and newborns using automatic dose management software: an application of the new 2013/59 EURATOM directive

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Objective: The new 2013/59 EURATOM Directive (ED) demands dosimetric optimisation procedures without undue delay. The aim of this study was to optimise paediatric conventional radiology examinations applying the ED without compromising the clinical diagnosis.
Methods: Automatic dose management software (ADMS) was used to analyse 2678 studies of children from birth to 5 years of age, obtaining local diagnostic reference levels (DRLs) in terms of entrance surface air kerma. Given local DRL for infants and chest examinations exceeded the European Commission (EC) DRL, an optimisation was performed decreasing the kVp and applying the automatic control exposure. To assess the image quality, an analysis of high-contrast resolution (HCSR), signal-to-noise ratio (SNR) and figure of merit (FOM) was performed, as well as a blind test based on the generalised estimating equations method.
Results: For newborns and chest examinations, the local DRL exceeded the EC DRL by 113%. After the optimisation, a reduction of 54% was obtained. No significant differences were found in the image quality blind test. A decrease in SNR (−37%) and HCSR (−68%), and an increase in FOM (42%), was observed.
Conclusion: ADMS allows the fast calculation of local DRLs and the performance of optimisation procedures in babies without delay. However, physical and clinical analyses of image quality remain to be needed to ensure the diagnostic integrity after the optimisation process.
Advances in knowledge: ADMS are useful to detect radiation protection problems and to perform optimisation procedures in paediatric conventional imaging without undue delay, as ED requires.

INTRODUCTION

Plain-film radiography is the most common examination in radiology, with an estimated 129 million chest radiographs performed in the USA in 2006, including both adults and children.[1] Although in recent years there has been a debate regarding the effects of very low doses of radiation,[2] numerous reports have emphasised that even low doses can lead to increase in the risk of malignancy.[3,4] Diagnostic radiological examinations carry a higher cancer risk per unit of radiation dose in infants and children compared with adults,[5] and the average risk is also higher in infants and young children compared with older children.[6] Some authors have estimated that the average number of X-ray examinations performed on neonates weighing less than 720 g at birth in a neonatal intensive care unit is 26 acquisitions per patient.[7] Following the International Atomic Energy Agency and World Health Organisation 2012 Bonn call for action recommendations,[8] it is imperative that all radiological examinations be justified and optimised with regard to radiological protection for each paediatric patient. To perform dose optimisation, the use of diagnostic reference levels (DRLs) is necessary.[9] Local DRLs can easily be obtained using automatic dose data management software (ADMS), allowing the registration of all individual radiation doses received by patients in paediatric diagnostic imaging, which the new 2013/59 EURATOM European Directive (ED) requires.[10] In application of the ED, we used

an ADMS to obtain local DRLs for the most common examinations performed in a paediatric conventional radiology room in our hospital, focusing on infants and newborns. Because the local DRLs in some examinations and age ranges exceeded that proposed by the European Commission (EC),[11] an optimisation procedure was performed attempting to avoid compromising the diagnostic integrity of the clinical images. To assess possible reductions in image quality, both physical and clinical image quality tests were performed.

METHODS AND MATERIALS

Reference state establishment: patient dose and physical image quality

The conventional X-ray system used was a Definium™ 8000 (General Electric Healthcare Systems, Waukesha, WI), installed in-room in March 2008. According to the ED, dosimetric and demographic data from 2678 abdomen, chest and pelvis studies of [0, 5] year old children, performed in-room in 10 months period for 2014, were registered by the ADMS DoseWatch® (General Electric Healthcare Systems, Buc, France). For children under 1 year of age, data were obtained for three age ranges: (0, 3), (3, 6) and (6, 12) months. Children younger than 3 months of age were considered newborn, and the other additional age groups were selected taking into account the World Health Organisation Child Growth Standards.[12] The entrance surface air kerma ($K_{a,e}$)[13] values estimated by the equipment were verified on a polymethylmethacrylate (PMMA) phantom with a Radcal 10 × 6–60 (http://www.radcal.com) flat ionisation chamber calibrated by official calibration laboratories (energy dependence lower than 5%), building thicknesses of 4, 8, 12, 16 and 20 cm. The slab was placed on the table at 100 cm focus flat-panel distance, applying a beam field of 20 × 20 cm^2. The protocol used was Chest Posteroanterior/Anteroposterior (PA/AP) and automatic exposure control (AEC) was applied. The energy dependence of the resulting correction factor for a constant thickness of 12 cm and beams ranging from 60 to 100 kVp was also evaluated. No anti-scatter grid was used in the measurements. After the dosimetric verification, local DRLs were obtained for Abdomen (317 examinations), Chest PA/AP (2213 examinations) and AP Pelvis (148 examinations), using the 75th percentile of the population data. The local DRLs obtained were compared with the DRLs proposed by the EC. The values of the percentiles and their uncertainties were obtained through a bootstrap algorithm,[14] for a confidence interval higher than 95%.

Given that local DRL for children younger than 1 year of age for the Chest PA/AP protocol exceeded that proposed by the EC (see Results section, Table 4), a dosimetric optimisation procedure was performed. The Chest PA/AP $K_{a,e}$-corrected values were considered the initial dose reference state. The initial reference state of the physical image quality was obtained using the agreed protocols of the DIMOND and SENTINEL European programs,[15] and adapted, in our case, to conventional paediatric radiological procedures. Therefore, a TOR CDR Leeds phantom (http://www.leedstestobjects.com/) was placed in the middle of the PMMA thickness during all the measurements (again, building thicknesses of 4, 8, 12, 16 and 20 cm), placing the slab on the table at a constant 100 cm focus flat-panel distance. This setup provides the optimal geometry to simulate real clinical conditions. Three acquisitions per slab thickness were performed, applying the corresponding radiographic techniques (Table 1); no anti-scatter grid was applied. The metrics used were signal-to-noise ratio (SNR) and high-contrast resolution (HCSR). A figure of merit (FOM), which indicates the necessary dose to obtain a certain image quality, was also obtained. These parameters are defined as follows:

Table 1. Chest PA/AP predefined radiographic techniques in manual mode, used in the room before the optimisation process. The focus flat-panel distance was 100 cm and no anti-scatter grid was applied

Type of paediatric patient[a]	Equivalent PMMA patient thickness (cm)	kVp	mAs	mA
Small	4	70	1.60	125
	8	70	1.60	125
Medium	12	78	2.00	160
Large	16	80	2.00	160
	20	80	2.00	160

AP, anteroposterior;PA, posteroanterior, PMMA, polymethylmethacrylate.
[a]Small and medium paediatric patient protocols were used for children under 5 years of age.

$$SNR = \frac{BG - ROI}{\sqrt{\frac{SD_{ROI}^2 + SD_{BG}^2}{2}}} \quad (1)$$

$$FOM = \frac{SNR^2}{K_{a,e}} \quad (2)$$

$$HCSR = SD_{ROI,7th} \quad (3)$$

Figure 1. TOR CDR image used to obtain the physical image metrics for a 4 cm PMMA thickness. ROIs in the first low-contrast circle, background (BG) and 7th group bar pattern ROI (ROI 7th) are shown. BG, background; PMMA, polymethylmethacrylate; ROI, region-of-interest.

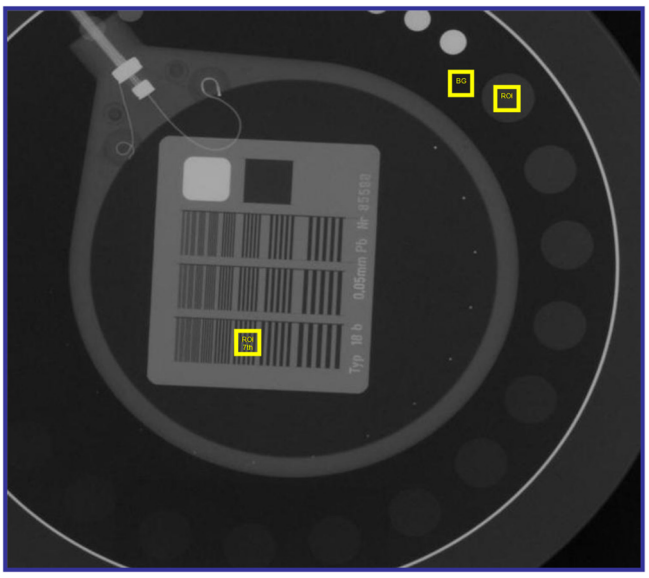


Table 2. Chest PA/AP radiographic techniques applied in AEC mode, used in the room after the optimisation process. The focus flat-panel distance was 100 cm, and no anti-scatter grid was applied

Type of paediatric patient[a]	AEC ion chamber applied	Equivalent PMMA patient thickness (cm)	kVp	mAs	*t* (ms)
Small	Centre	4	65	0.69	3.29
		8	65	1.14	5.54
Medium	Centre	12	76	1.24	4.94
		16	80	1.88	7.61
Large	2-lateral	20	80	3.61	14.60

AEC, automatic exposure control; AP, anteroposterior; PA, posteroanterior; PMMA, polymethylmethacrylate.
[a]Small and medium paediatric patient protocols were used for children under 5 years of age.

in which BG is the mean value of the pixels in the region-of-interest (ROI) in the background (Figure 1); ROI is the mean value of the pixels in the ROI placed in the first low-contrast circle; SD_{ROI} and SD_{BG} are the standard deviations (SDs) for ROI and BG; $K_{a,e}$ is the entrance surface air kerma measured with the ionisation chamber placed on the PMMA slab; and $SD_{ROI,7th}$ is the standard deviation of the pixel values of the ROI placed in the 7th group of the bar pattern.

Action in the room

An analysis of the chest infant examinations was performed. For children who cannot stand by themselves (usually younger than 1 year of age), the Chest PA/AP protocol was applied with the patient lying supine on the table in manual mode, using the AP projection. The predefined values of kV_p and mAs were high, corresponding to children but not to infants (Table 1). Also, the ADMS showed that the radiographic techniques were typically not adjusted by radiographers before acquisition to take into account the thickness of the patients. Therefore, in the Chest PA/AP protocol for children younger than 5 years of age, the AEC was applied, activating the central ion chamber, and the predefined kVp was decreased (Table 2). The post-processing of the images was also adjusted in agreement with the radiologists and the manufacturer's engineer (varying the width and level of the grey window and enhancing the edge detection algorithm), so as not to compromise the diagnostic integrity of the clinical images.

New reference state establishment and physical image quality comparison

From March 20 to September 20, 2015, 1278 chest imaging studies of children younger than 5 years of age were performed, and local DRLs were obtained for the same age ranges, using the 75th percentile of the population data. New local DRLs were compared with the DRLs proposed by the EC and with the reference values obtained before the action in the room. Metrics used to evaluate image quality were measured again in the AEC mode and compared with the results previously obtained.

Clinical image quality analysis

To evaluate possible changes in clinical image quality in the chest examinations throughout the optimisation process, three full-time paediatric radiologists (R1, R2 and R3, with 35, 10 and 7 years' experience, respectively) performed a blind test based on the clinical image quality test published in 1996 by the EC,[11] adapted in-home for digital diagnostic images.[16–18] 80 chest images of children younger than 5 years of age were randomly selected; thus, there were 40 studies before the action in the room and 40 after (10 images for each age range considered). These images were anonymised, and the acquisition date information was removed. The images were then sent to the Picture Archiving and Communication System in three groups with a varied order (chosen randomly) so the paediatric radiologists could evaluate each group without mutual influence. Only the images that met all the following geometric prerequisites were evaluated: visualisation of the anterior ending of the first five

Table 3. Verification of the patient dose data shown by the X-ray equipment, depending on the PMMA thickness, compared with ionisation chamber dose measurements

PMMA thinness (cm)	Age range equivalent (years)	kV	mAs	$K_{a,e}$ (μGy) Definium 8000	$K_{a,e}$ (μGy) Radcal	Δ (Definium 8000–Radcal) (%)
4	(0,1)	70	0.45	40	24.69	62.01
8	(1,5)	70	0.77	70	49.56	41.24
12	(5,10)	80	0.97	120	93.16	28.81
16	(10,16)	82	1.75	230	198.00	16.16
20	(16,20)	82	3.47	450	434.50	3.57

PMMA, polymethylmethacrylate.

Table 4. Local DRLs for Abdomen AP/PA, AP Pelvis and Chest PA/AP, in terms of $K_{a,e}$, obtained applying ED 2013/59 before the optimisation process, and compared with the EC DRLs

Type of examination	Age range	Number of examinations	$K_{a,e}$ DRL EC (mGy)[a]	$K_{a,e}$ local DRL (mGy)
Abdomen AP/PA	(0, 3) months	42	–	0.67 ± 0.02
	(3, 6) months	25	1.00	0.67 ± 0.60
	(6, 12) months	41	1.00	0.67 ± 0.19
	(1, 5) years	209	1.00	0.77 ± 0.01
AP pelvis	(0, 3) months	1	0.20	Insufficient data
	(3, 6) months	19	0.90	0.38 ± 0.14
	(6, 12) months	18	0.90	0.38 ± 0.16
	(1, 5) years	110	0.90	0.45 ± 0.01
Chest PA/AP	(0, 3) months	122	0.08	0.17 ± 0.02
	(3, 6) months	99	0.10	0.16 ± 0.01
	(6, 12) months	328	0.10	0.16 ± 0.01
[1, 5) years	1664	0.10	0.049 ± 0.003	0.049 ± 0.003

AP, anteroposterior; DRLs, diagnostic reference levels; EC, European Commission; ED, EURATOM Directive, PA, posteroanterior.
The red-shaded entries highlights values higher than the EC DRLs.
[a]Children below 3 months of age were considered newborns. From 3 months to 5 years of age, EC DRLs corresponding to 5 years of age were applied.

ribs at the diaphragmatic level (inspiration prerequisite); visualisation of the bilateral ending of most ribs (rotation prerequisite); and visualisation of both lateral costophrenic angles and lung apices (field of view prerequisite). Once accepted, the analysis of the images was divided into two sections. The first, *Image Criteria Evaluation*, is a true/false (or seen/not seen) test of nine anatomic items that should be observed in all the paediatric chest digital images: vascular pattern reproduction (in the two central thirds), trachea, main bronchi, diaphragmatic contours, costophrenic angles, spine, paraspinal lines, retrocardiac lung and mediastinum. Given this is a true/false test, wherein the variable has a low probability of being false, a Poisson model was applied in the framework of generalised linear models with the generalised estimating equations (GEE) method.[19] The model includes radiologists and time point (before/after the action in the room) as primary effects, as well as their interactions. The second, *General Evaluation*, is a 3-score test (optimum, 2; acceptable, 1; and unacceptable, 0) of four general characteristics of the clinical images: contrast, noise, edge visualisation and general diagnostic acceptability. Because all the variables had three possible numerical values, a multinomial model was applied, again using a GEE-based method and including radiologists and time point. In all the tests performed, a p-value less than 0.05 was considered statistically significant.

RESULTS

Dose reference state establishment

The verification of the dosimetric information provided by the equipment is shown in Table 3. For paediatric patients younger than 1 year of age, a $K_{a,e}$ correction factor of 0.62 was obtained. For patients between 1 and 5 years of age, the correction factor obtained was 0.71. No significant differences were found when varying the energies from 60 to 100 kVp (CV less than 2%). Table 4 shows local DRLs for Abdomen, Chest PA/AP and AP Pelvis compared with the DRLs proposed by the EC. Children younger than 3 months of age were considered newborn. From 3 months to 5 years of age, EC DRLs corresponding to 5 years of age were applied.

Optimisation process: patient dose and physical image quality comparison

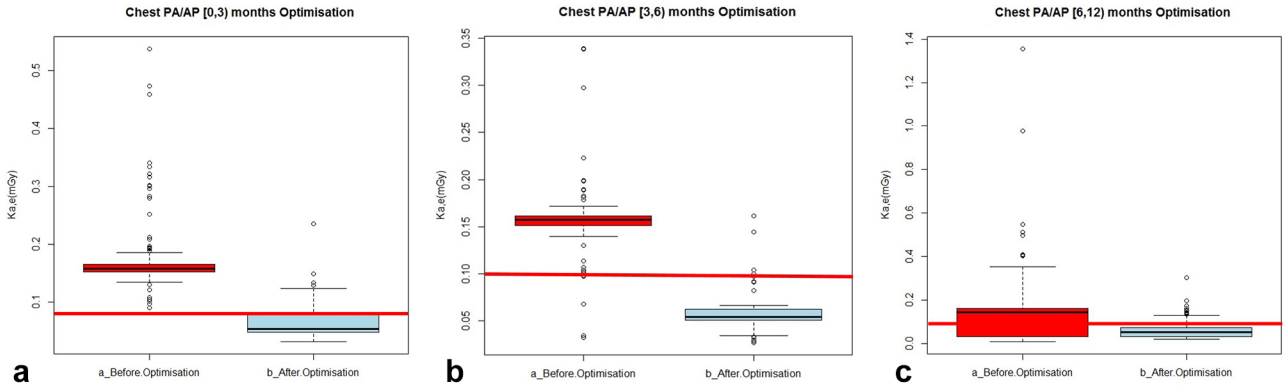
Table 5 shows the new local DRLs for Chest PA/AP examinations, obtained after the action in the room. The $K_{a,e}$ distributions for

Table 5. Local DRLs for Chest PA/AP, in terms of $K_{a,e}$, obtained after the action in the room, compared with the EC DRLs. The blue-shaded valueshighlights optimised values

Type of examination	Age range	Number of examinations	$K_{a,e}$ DRL EC (mGy)[a]	$K_{a,e}$ Local DRL (mGy)
Chest PA/AP	(0, 3) months	80	0.08	0.08 ± 0.04
	(3, 6) months	66	0.10	0.06 ± 0.04
	(6, 12) months	205	0.10	0.07 ± 0.04
	(1, 5) months	927	0.10	0.06 ± 0.02

AP, anteroposterior; DRLs, diagnostic reference levels; EC, European Commission; PA, posteroanterior.
[a]Children below 3 months of age were considered newborns. From 3 months to 5 years of age, EC DRLs corresponding to 5 years of age were applied.

Figure 2. $K_{a,e}$ distributions before (red) and after (blue) the action in the room for the Chest PA/AP examinations in the age ranges considered: (a) (0, 3) months of age, (b) (3, 6) months of age, (c) (6, 12) months of age. The red lines represent the EC DRLs. AP, anteroposterior; DRLs, diagnostic reference levels; EC, European Commission; PA, posteroanterior.



children younger than 1 year of age before and after the action in the room, compared with the DRLs proposed by the EC, are shown in Figure 2. Mean and SD dose values were also obtained for comparison purposes (see Discussion section, Table 7). Considering the (0, 1) age range, a reduction in dose of approximately 56% was found in the third quartile values, and 54% in the average values. Figure 3 shows the HCSR and SNR parameters of the physical image quality depending on the slab thickness, obtained before and after the action in the room. Figure 4 shows the relationship between physical image quality and dose to the patient, obtained in terms of FOM. A coverage factor of k = 2 was applied in the uncertainties estimation.

Clinical image quality analysis results

The first clinical image quality test performed, *Image Criteria Evaluation*, showed that only in the visualisation of the costophrenic angles were statistically significant differences observed before and after the action in the room (contours observed in 98% of images before and 91% after, $p = 0.045$); however, this effect was due to the existence of pulmonary diseases in the selected images (Figure 5a). The results of the second test performed, *General Evaluation* (Figure 6), were as follows: In the contrast evaluation no significant differences were found before and after the action in the room, although a different method of evaluating the contrast was observed between radiologists ($p < 0.001$). As with the physical image quality test, there was a statistically significant increase in noise perception for two radiologists after the action in the room (see an example in Figure 5b), although R3 did not find significant differences. In the edge visualisation, no significant differences were found, although the distribution was pointed towards better ratings. As with the contrast evaluation, a different method of evaluating the edges was observed between radiologists ($p < 0.001$). The results of the general diagnostic acceptability test depended on the radiologists: for R1 and R3 no significant differences were found, although poorer general diagnostic acceptability was found for R2 after the action in the room.

DISCUSSION

ADMS is useful to obtain local DRLs because all the dosimetric data estimated by the X-ray equipment can be registered; however, an ionisation chamber verification of the dosimetric information provided by the software is necessary. In Table 3, a significant variation in the dose can be observed. Given the equipment estimates the $K_{a,e}$ for a standard patient (equivalent to 20 cm PMMA), the difference regarding the dose values obtained with the ionisation chamber increases as the PMMA thickness decreases, yielding variations up to 62% for the thinner patients. Therefore, local DRLs must be obtained from dosimetric values corrected by an ionisation chamber if these data are estimated by X-ray equipment.

Figure 3. Physical image quality depending on slab thickness in terms of SNR (a) and HCSR (b), obtained before and after the in-room action. HCSR, high-contrast resolution; SNR, signal-to-noise ratio.

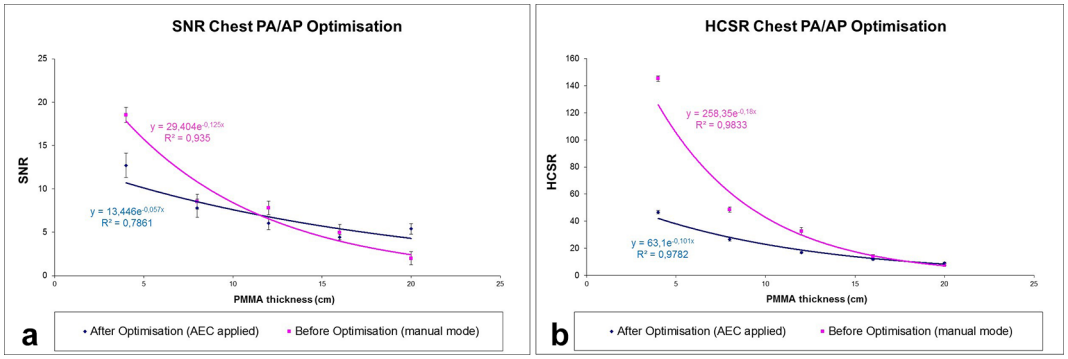
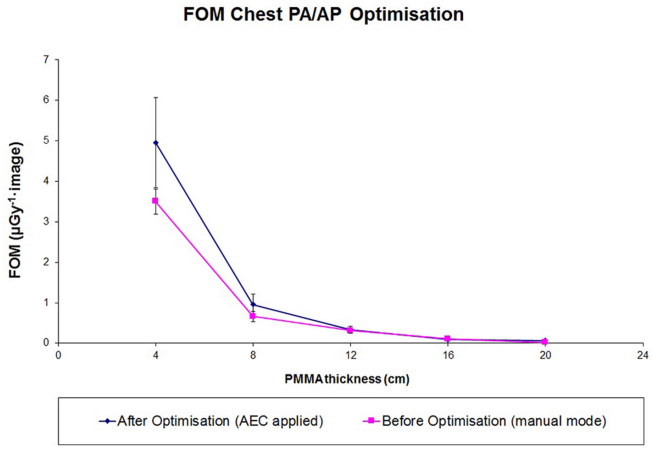


Figure 4. Relationship between physical image quality and dose to the patient, obtained in terms of FOM before and after the in-room action. FOM, figure of merit.



In this study, the local DRLs obtained through dosimetric-corrected values were lower compared with the DRLs proposed by the EC for all the examinations and age ranges considered, except in Chest PA/AP protocol for children younger than 1 year of age; here, the local DRLs were 60% higher. For the newborn babies, the local DRL obtained was 113% higher (Table 4). The analysis of the exposure data shown by ADMS revealed that the Chest PA/AP protocol was not well-defined for newborn and infant patients. The Chest PA/AP "small" protocol (Table 1) was designed by the manufacturer to work in manual mode with predefined values of kVp and mAs corresponding to (1, 5) year-old children, and the ADMS showed this was not usually adjusted by the radiographers to take into account the thickness of the infant patients. The use of manual mode is usually correct for small children because the AEC system performance can be inefficient or unsafe.[5] The handing of a kVp and mAs constant table regarding the child's weight or age was considerate,[20] but finally was discarded because in our hospital the use of exposure charts could be less safe than the use of the AEC devices. The radiographers working in the Paediatric Radiology Department have high mobility between modalities (approximately 50% of the staff combine their work in paediatrics with adult patients at the General Radiology Department), and sometimes they are not specially trained in paediatric conventional radiology. Nevertheless, care must be taken in selecting the AEC for small children. The resulting patient dose and image quality must be evaluated to ensure that the acquisition protocol is correctly designed and is working properly.

After performing the action in the room, the new local DRLs obtained were similar or lower compared with the DRLs

Figure 5. (a) Two images of patients (7-month-old to the left, 3-month-old to the right) obtained after the action in the room with no visualisation of the costophrenic angles (score 0) due to pulmonary diseases (red arrows). All the radiologists scored these images in the same manner; (b) Two images of patients obtained after the action in the room with the poorest evaluation of noise (score 0). The image on the left (3-month-old) was scored with null value by all the radiologists. The image on the right (4-month-old) was scored with null value only by radiologist 3.

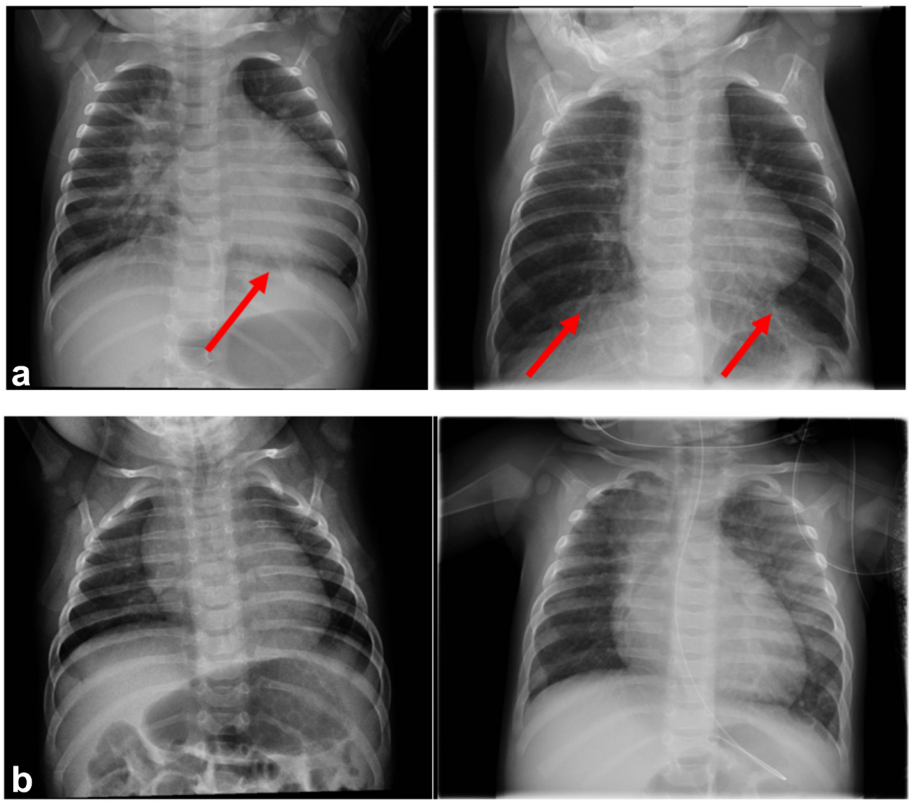
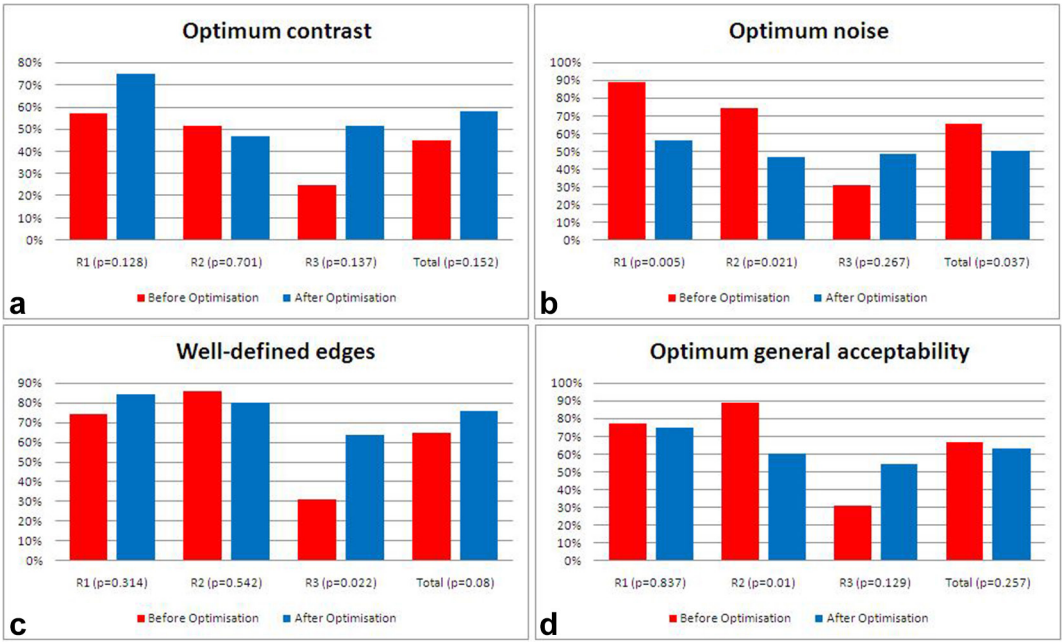


Figure 6. Clinical image quality analysis results corresponding to the general evaluation. Optimum contrast (a), noise (b), well-defined edges (c) and optimum general acceptability (d) evaluations are shown before and after the action in the room (*Total* columns), including the evaluation performed by each radiologist separately (R1, R2 and R3). All the *p*-values are shown.



proposed by the EC (Table 5). The reduction in dose obtained for children younger than 1 year of age was approximately 56% (third quartile values). In terms of the $K_{a,e}$ distributions, the reduction in the patient doses is also clear: 50% of the $K_{a,e}$ values were now below the EC DRLs in all the age ranges considered (Figure 2). More outliers were observed before the action in the room, perhaps due to unusual changes in the predefined kVp and mAs performed by the radiographers in manual mode. In terms of statistical dispersion, no effect of the AEC applied after the action in the room was clearly observed for children younger than 1 year of age: in children (0, 3) months, the dispersion was high; however, in children (6, 12) months of age, the dispersion was lower. A weight-based boxplot study could represent this effect, if there is one.

In terms of physical image quality, a good correlation was observed in the exponential fit of both parameters, especially for HCSR in manual mode ($R^2 > 0.98$). However, a poorer correlation was observed after the action in the room because the AEC system attempts to keep the image quality constant (Figure 3). For a 4 cm PMMA thickness, equivalent to neonates, poorer image parameter values were found after the action in the room. This was an expected result, because after the activation of the AEC, the patient doses involved were lower. Otherwise, despite the poorer image quality observed, the FOM is higher for a 4 cm PMMA thickness because the patient doses involved are much lower. The FOM had shrunk, however, from 8 cm PMMA thickness, yielding values near zero. This feature could be due to the high noise obtained in large thicknesses because no anti-scatter grid was used in the measurements.

Table 6. $K_{a,e}$ of 10 patients for abdomen, pelvis and chest examinations, obtained in application of 97/43 ED, and compared with EC DRLs. Age, weight and thickness means are also shown

Type of examination	Age (years)	Weight (kg)	Thickness (cm)	$K_{a,e}$ DRL EC (mGy)		
				Ka,e(mGy)		
				Average	Median	P75
				1		
Abdomen AP/PA	10.3	48.9	13.5	0.94	0.8	0.85
				0.9		
AP Pelvis	8.3	35.4	9.4	0.49	0.48	0.5
				0.1		
Chest PA/AP	4.7	15.2	7.2	0.05	0.05	0.06

AP, anteroposterior; DRLs, diagnostic reference levels; EC, European Commission; PA, posteroanterior.
All the dose values obtained were below the EC DRLs; therefore, no radiation protection issue was detected.

Table 7. Comparison between the average dose values obtained in this study with others of recent studies. The corresponding percentage of reduction is also shown. The studied age group is indicated, as well as the number of patients involved and the parameters applied in the final stage of the optimisation process. A brief summary of the methods and materials used are shown in the observations column

Author	Age group (years)	*n*	Tube potential (kV)	mAs ± SD	$K_{a,e}$ ± SD (mGy)	Reduction in $K_{a,e}$ (%)	Observations
This study	0–1	351	65 (small)	1.21 ± 0.57	0.06 ± 0.03	54	Digital radiography; central AEC chamber used; ADMS used; anti-scattering grid not used; three paediatric radiologists performed blind image quality test; physical image quality test performed
			76 (medium)				
Kostova-Lefterova *et al*[23]	0–1	Not referred (109 patients 0–15 y)	65	1.60	0.03 ± 0.02	≈ 79	Screen-film radiography; exposure chart used; questionnaire used; anti-scattering grid not used; one paediatric radiologist performed image quality test
Martin *et al*[24]	0–1	Not referred	65	Not referred	0.05	18	Computed radiography; exposure chart used; questionnaire used; anti-scattering grid not used; one paediatric radiologist performed blind image quality test
Paulo et al[25]	0–18	80	70 (< 5 kg)	2.54	0.08 ± 0.05	63.6	Computed radiography; central AEC chamber used (lateral in patients above 5 kg); questionnaire used; anti-scattering grid used; three paediatric radiologists performed blind image quality test
			77 (5–10 kg)				
			81 (10–20 kg)				

ADMS, automatic dose data management software; AEC, automatic exposure control; SD, standard deviation.

Likewise, as focus flat-panel distance was always constant and the PMMA thickness was increasing, the TOR phantom placed in the middle of the slab was moving away from the image detector, causing a loss of image quality.

In terms of the clinical image quality, the analysis performed was able to detect the action in the room, with a higher noise perception (same conclusion as the physical image quality test) and a possible decrease in the general acceptability of images. However, the evaluation of the image criteria, the optimum contrast and the visualisation of well-defined edges showed that the clinical image quality was not compromised after the action in the room. To properly evaluate the diagnostic ability of the clinical images, further multireader and multicase receiver operating characteristic studies might be necessary to account for a binary "diseased" or "not diseased" decision.

In compliance with the 2013/59 ED, ADMS allows the rapid implementation of optimisation procedures without delay, as well as allowing the detection of radiation protection problems that might otherwise pass unnoticed. Indeed, the routine quality control procedure performed to comply with current legislation in Spain, the Real Decreto de Calidad en Radiodiagnóstico 1976/1999 (RD),[21] based on the repealed 97/43 ED[22] (the 2013/59 ED must be transposed to national legislation before February 2018), did not detect the radiation protection problem in infant and newborn chest acquisitions because RD 1976/1999 only requires 10 dose estimations in standard patients. This sample can be insufficient, and the use of age or weight-based ranges is recommended in paediatric conventional imaging instead of using the parameters for standard-sized patients.[5] In Table 6, $K_{a,e}$ values for 10 patients receiving abdomen, chest and pelvis examinations, obtained in application of the 97/43 ED, are compared with the EC DRLs. All the dose values were below the EC DRLs.

A comparison between the values obtained in this study with others of recent studies is shown in Table 7. The major reduction in dose is reported by Kostova-Lefterova *et al*[23] using an exposure chart for radiographers. The final dose obtained is also the lowest, probably due to the low kV and mAs applied in manual mode for the entire age range. Although Kostova-Lefterova et al used screen-film radiography, their parameters are similar to that shown in the body exposure chart (part 1) by Knight *et al.* (2013) for DR systems,[20] and the optimised-kV reported by Martin et al[24] for CR systems, shown in the third row of Table 7. Although "small" Chest PA/AP is the preferred protocol in our room for newborns and infants, very often the radiographers use the "medium" protocol in thick patients younger than 1 year of age, defined with a tube potential of 76 kV. This kilovoltage was recommended by GE technical support and is in agreement with the literature[25,26] and with the EC European Guidelines.[11] The last row of Table 7 shows the tube potential selected by Paulo et al[25] to optimise the dose in a CR system with the AEC activated, choosing 77 kV for children 5–10 kg in weight. Children above 5 kg are common up to 1 year of age.[12] Moreover, Guo et al have shown in a DR system, working in the AEC mode, that imaging at 70 kV

provides a better dose efficiency than the 60 kV protocol for newborn patients.[27] The clinical image quality is confirmed in Paulo et al and in this study, with a blind image quality test performed by three paediatric radiologists (in our study the clinical image quality was supported by the performing of a physical image quality test). However, the other studies suggest that final average dose obtained could be reduced by applying a chart exposure in manual mode with well-optimised parameters. Indeed, recent Monte Carlo simulation studies indicate that copper filtration in combination with low-kV settings can be useful for reducing patient dose, maintaining image quality in neonate chest imaging.[28,29] All data used in the studies shown in Table 7 were recorded using a questionnaire, which can be time consuming and a source of errors. In this study, ADMS allowed the fast and secure implementation of the optimisation process.

The local DRLs obtained in this study were compared with the EC DRLs published in 1996 for screen-film radiography, based on age ranges and air surface Kerma. However, new DRLs were announced in the "European Workshop on DRLs in Paediatric Imaging", which took place in Lisbon in October 2015;[30] these DRLs were recently approved by the EC in March, 2016 (European Society of Radiology communication). Taking into account the new EC DRLs, another optimisation procedure is necessary for abdomen in children aged (1, 5) years because the abdomen DRL (0.75 mGy) is slightly lower than the local DRL obtained in our survey (0.77 ± 0.01 mGy).

The main limitation of this study is related to the absence of weight-based local DRLs because patient weight data were not usually available for the ADMS. However, recent surveys in paediatric CT examinations suggest that using age groups is realistic and pragmatic for the establishment of DRLs, and the accuracy of results is ensured for data > 30 patients in a particular age group if patient weight is unknown.[31]

CONCLUSION

ADMS is useful for meeting the requirements of the new ED, allowing the establishment of statistically well-defined local DRLs and the performance of dosimetric optimisation procedures in paediatric radiology without undue delay. Using this software, important radiation protection problems can be detected that might otherwise go unnoticed. However, an ionisation chamber verification of the dosimetric information provided by the equipment and shown by the software is necessary because significant variations in the dose are possible. To ensure that the optimisation process has not compromised the diagnostic integrity of the images, it is advisable to perform at least a physical and clinical analysis of the image quality.

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