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A survey of radiation dose associated with pediatric plain-film chest X-ray examinations

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Abstract *Background*: The effective doses delivered to pediatric patients are not well characterized for many plain-film X-ray examination techniques. The few data available on clinical doses in pediatric radiology are generally outdated because of the changes in X-ray generators and hardware that have taken place over the past decade. *Objective*: This survey characterizes X-ray examination techniques and measures effective doses delivered to a phantom representing a 1 year old in order to identify specific examination features that may result in greater than necessary doses to pediatric patients. *Materials and methods*: An anthropomorphic phantom representing a 1 year old was developed for use as a survey tool. The phantom incorporates direct reading metal oxide semiconductor field effect transistor (MOSFET) dosimeters that permit the effective dose to be measured for clinical examinations. Seventeen commonly performed examinations were characterized at ten facilities with doses determined for a chest series of exams at each facility. *Results*: The survey demonstrates that the effective dose for a given examination can vary by an order of magnitude between institutions. Distributions of examination parameters identified those that are most significant for minimizing patient dose. *Conclusion*: Efforts spent to determine pediatric specific radiographic techniques contribute more to effective imaging with low patient doses than utilizing AEC controls or high-frequency generators.

Keywords Dosimetry · Phantom · MOSFET · Diagnosis

Introduction

It is well established that diagnostic X-rays constitute the largest and most widely distributed source of man-made radiation exposure to the general population [1, 2]. While infants and children constitute only about 10% of the total number of radiographic examinations [1], they comprise the segment of the population that may be expected to be at the greatest risk for potential radiation effects for several reasons: (1) their growing tissues are more susceptible to radiation effects than mature adult tissues [3]; (2) their skeleton encompasses a greater fractional distribution of active bone marrow, an organ of high radiation sensitivity [4]; (3) the greater post-exposure lifetime of infants and children increases the possibility for any radiation-induced effects to be manifest; (4) children may be uncooperative and are frequently subject to a greater number of exposures than adult patients; (5) pediatric patients generally have a larger fraction of their anatomy located within the X-ray field compared to adults having similar examinations and projections.

The doses to pediatric patients have not been well characterized, particularly with regard to the variation in currently utilized clinical techniques and protocols associated with commonly performed radiographic examinations. In the course of their care, young patients may be exposed to a wide variety of X-ray examinations, although conventional radiographs make up three quarters of the pediatric radiological examinations performed [5]. In order to characterize the effective doses and the effect of varying clinical practice better, this study uses an anthropomorphic phantom incorporating fast-reading electronic dosimeters to measure the effective doses from a chest series of examinations at ten hospitals and clinics in the State of Florida.

Effective dose (E), as presented by the ICRP in 1991 [6], is currently considered to be the best measure for prediction of radiation detriment. The effective dose is preferred over other measures of radiation detriment because it evaluates the absorbed dose from individual organ tissues and can readily accommodate updated tissue-weighting factors. It should be noted that various sets of tissue-weighting factors were derived for children by Almén et al. and tested for use in the calculation of effective dose [7]. Almén concluded that the ICRP tissue-weighting factors were applicable to children and adolescents; therefore, the ICRP tissue weighting factors were utilized here. The effective dose is the sum of the products of the absorbed organ dose and the respective ICRP tissue-weighting factor for each specified organ.

Materials and methods

A standardized anthropomorphic phantom representing a 1-year-old patient and based on the medical internal radiation dosimetry (MIRD) anatomy [8, 9] was constructed and used to measure the doses at ten hospitals and clinics in the State of Florida. The MIRD anatomy provides a stylized anatomy that represents the standard for evaluating and comparing organ doses from a variety of radiation exposures. Site visits were made to each of these facilities where representative clinical examinations for a series of plain-film radiographs were simulated by pediatric X-ray technologists using the anthropomorphic phantom. The phantom utilizes tissue-equivalent materials representing soft tissue, lung tissue, and bone tissue and incorporates an electronic metal oxide semi-conductor field effect transistor (MOSFET) dosimeter system to provide simultaneous measurement of the radiation dose at 20 tissue locations throughout the phantom. The small physical size of the MOSFET dosimeters and the immediate readout and reuse provided by the utilization of these electronic dosimeters make them convenient for the evaluation of organ doses from clinical examinations. The complete characterization and applications of the MOSFET dosimeter system for applications in diagnostic radiology has previously been described [8, 10], The average organ doses are subsequently used to evaluate the effective dose delivered by a variety of radiological exams. Organ doses measured by the MOSFET dosimeters were used to determine the effective doses for each facility and examination, and the results permit an analysis of realistic organ doses that may be expected for this patient population.

The 1-year-old phantom was used to examine radiographic techniques and organ doses from plain-film radiographic examinations at ten different institutions in the State of Florida. The radiographic examinations surveyed were a representative sample of commonly performed pediatric examinations based on an age-specific review of examination frequencies for pediatrics extracted from the Radiology Information System (RIS) at the Children's Hospital at Shands at the University of Florida, which performs approximately 10,000 pediatric examinations per year. The survey included ten institutions that were selected to provide a representative cross section of different sized facilities, ranging from small community hospitals to academic medical centers. Radiographic techniques for 17 commonly performed pediatric examinations were selected for characterization at each of the ten institutions. Imaging and dosimetry characterizations were evaluated for the chest series of examinations.

Information was collected on the relative film speed, type of generator, utilization of manual or automatic exposure control (AEC) techniques, AEC configuration (if used), whether or not scatter suppression was used, whether or not external patient-shielding devices were used, the SID, film and field sizes, focal spot selection, and the exposure details of tube potential, tube current, and exposure time. Entrance skin exposure measurements were performed using a Keithly model 96035 (15 cm) ion chamber and model 35050A electrometer(Keithley Instruments, 28775 Aurora Road, Cleveland, OH 44139, USA). These permit the normalization of organ-dose measurements in organ dose per unit entrance skin exposure for comparison with other studies.

At each institution, and for each examination, the pediatric technologist was asked to simulate each examination as if the phantom was an actual 1 year old of a size and weight equivalent to the anthropomorphic phantom. The technologist independently determined the technique factors utilized for each of the specific examinations based on individual training and institutional protocols. These techniques were used to produce images and evaluate image quality and to make exposure measurements. Phantom images for the chest examination series were obtained from each institution, using the technique factors selected by the technologist. Image quality was evaluated through a visual review of the images and a quantitative assessment of the optical density over the lung field in the phantom images. The mean lung field optical density for each projection was quantified by averaging measurements made using a digital densitometer across the lung field.

Images and dosimetry measurements were made using the 1-year-old phantom for a complete series of chest examinations at each facility. The chest series included: lateral chest, PA chest, and AP chest projections. For each of these cases, the array of MOSFET dosimeters provided a measure of absorbed doses at a number of internal organ locations. In order to minimize statistical variation in the MOSFET dosimeter measurements, higher than normal tube currents were used during dosimetry measurements, with the results subsequently rescaled, proportionally, to the clinical tube currents to determine the organ doses delivered during each clinical examination. ICRP 60 tissue-weighting factors were then applied to the absorbed organ dose and summed to determine the effective dose for each examination.

Results

Each of the facilities surveyed performed their pediatric examinations using the same X-ray equipment when possible. Many characteristics of the equipment were therefore constant for all pediatric examinations performed at that facility. All of the surveyed facilities used 400-speed film with the exception of facility 1, which used 600-speed film. The X-ray generators used for pediatric examinations in the ten institutions included seven three-phase, two high-frequency (facilities 4 and

8), and one single-phase (facility 9) generators. Grids for scatter suppression were used by all facilities for most examinations, although facilities 2, 5, and 6 occasionally performed examinations without a grid. The grid ratios employed at each facility are presented in Table 1. The half-value layers of the X-ray systems were also measured at each of the surveyed facilities, and are illustrated in Table 1.

More significant variations were observed between the different facilities and examinations for tube potential (kVp) and the product of tube current and exposure time (mAs). These specific parameters are tabulated for facility and examination in Tables 2 and 3 for the 17 commonly performed pediatric examinations.

Measurements of the mean optical density over the lung field for films of AP, PA, and lateral chest examinations of the 1-year-old phantom are tabulated in Table 4. A visual evaluation of the image quality of these films showed that all facilities produced clinically acceptable films. It was readily observed, however, that facilities 3, 4, and 7 had noticeably poorer image quality than the others.

Table 1. Measured half-value-layers and grid ratios used for pediatric examinations at the surveyed facilities

Facility ID	HVL	Grid ratio
1	3.07	10:1
2	2.89	12:1
3	3.28	12:1
4	3.72	12:1
5	2.94	10:1
6	2.66	10:1
7	3.46	10:1
8	3.16	12:1
9	2.91	12:1
10	3.44	12:1

The results from the effective doses for each of the surveyed chest examinations and facilities are presented in Table 5. Different effective doses are calculated for male and female patients owing to the different organ doses and tissue-weighting factors associated with the reproductive organs. The examination setup at the surveyed facilities was independent of patient gender.

Discussion

Many of the parameters examined in this study affect the effective dose that is delivered to the patient. In order to minimize the patient dose while retaining the relevant diagnostic information on the image, it is necessary to develop protocols that provide an acceptable compromise between these factors. The effects of the combination of these parameters can be observed in the effective doses delivered to patients in the chest series of examinations. Figure 1 illustrates the distribution of average effective doses delivered by the series of chest exams evaluated for each facility. Figure 1 shows that the effective doses varied by nearly an order of magnitude for the ten facilities that were surveyed. A review of Table 5 also demonstrates that the doses delivered by each facility were consistent for the series of chest projections performed at that facility. By examining the individual examination parameters used by the various facilities, we can gain some insight into effective techniques for reducing patient doses while maintaining good-quality images.

All of the facilities surveyed used 400-speed film-screen combinations with the exception of facility 1, which used 600-speed film-screen combinations. In all cases these represented the standard speed film used at that institution for diagnostic examinations. Facility 1 delivered consistently low doses, which may be partially

Table 2. Tube potential (kVp) selected for a 1 year old for each of the examinations performed at the surveyed facilties

Examination facility ID	1	2	3	4	5	6	7	8	9	10
Lateral chest	74	85	75	75	75	58	70	84	90	95
AP chest	66	70	75	75	62	58	70	68	80	90
PA chest	66	72	68	75	67	58	70	68	80	90
AP abdomen	70	68	60	70	70	68	70	66	75	65
AP pelvis	70	72	60	70	70	68	70	66	75	70
AP hip	65	70	60	65	65	68	70	66	75	75
Waters sinus	75	65	70	70	65	80	70	65	75	70
Lateral sinus	68	60	70	65	65	70	70	65	70	60
AP skull	78	70	70	65	65	80	75	65	80	70
Townes skull	82	70	70	70	70	80	80	65	80	75
Lateral skull	73	60	70	65	70	70	65	65	75	70
AP cervical spine	65	65	70	65	65	68	65	65	60	66
Lateral cervical spine	70	65	70	65	67	74	70	65	70	75
AP thoracic spine	72	65	70	65	70	68	75	65	65	70
Lateral thoracic spine	75	70	70	60	70	68	70	54	60	83
AP lumbar spine	72	70	70	70	70	68	75	65	70	75
Lateral lumbar spine	75	74	70	75	70	68	70	65	70	75

Table 3. Tube current (mAs) selected for a 1 year old for each of the examinations performed at the surveyed facilties

Examination facility ID	1	2	3	4	5	6	7	8	9	10
Lateral chest	3.8	4.0	1.7	17.9	2.0	3.2	12.3	2.5	18.0	4.0
AP chest	1.8	3.2	1.7	12.9	1.3	1.6	9.3	2.0	10.0	1.6
PA chest	1.8	4.0	1.9	17.0	1.3	1.6	7.8	2.0	10.0	2.0
AP abdomen	3.8	4.0	30.0	12.6	8.5	3.2	11.0	8.1	10.0	6.4
AP pelvis	3.8	5.0	27.0	8.9	7.6	3.2	3.5	7.2	10.0	2.0
AP hip	3.8	5.0	9.0	12.1	4.5	3.2	3.5	1.8	10.0	0.8
Waters sinus	1.8	6.4	38.0	14.2	20.4	8.0	29.0	27.8	25.0	14.4
Lateral sinus	1.8	5.0	2.0	10.3	1.6	5.0	11.0	20.6	17.5	4.8
AP skull	1.3	6.4	17.0	21.0	21.7	6.4	4.5	11.7	10.0	14.4
Townes skull	1.8	6.4	46.0	20.6	11.6	8.0	3.0	17.1	22.0	4.0
Lateral skull	1.8	5.0	12.0	12.4	2.5	5.0	3.8	7.0	12.0	13.2
AP cervical spine	3.8	3.0	5.0	9.1	6.8	2.0	4.5	4.2	20.0	2.0
Lateral cervical spine	6.3	4.0	8.0	8.0	2.0	1.6	10.0	45.1	25.0	2.4
AP thoracic spine	3.8	5.0	13.0	14.0	8.4	2.0	9.8	5.4	5.4	3.6
Lateral thoracic spine	6.3	6.4	16.0	32.1	9.7	4.0	10.4	40.0	100.0	5.2
AP lumbar spine	3.8	6.4	16.0	9.8	9.0	3.2	11.8	9.4	30.0	4.0
Lateral lumbar sping	7.2	10.0	30.0	18.5	16.2	6.0	22.0	27.9	45.0	4.8

Table 4. Measured repeat rate and lung-field optical density from each of the surveyed facilities. The optimal range is considered to be between 0.5 and 2.0 with the distribution centered on 1.2

Facility ID	Repeat rate (%)	Average lung OD	Average lung OD	Average lung OD
		AP chest	PA chest	Lateral chest
1	4.5	1.495	1.015	1.115
2	0.5	1.030	1.400	1.110
3	8.0	2.235	2.570	1.415
4	5.5	2.440	2.655	1.665
5	4.0	0.625	0.475	0.715
6	2.0	0.650	0.595	0.470
7	1.0	2.215	2.160	1.995
8	4.3	0.990	0.840	1.125
9	3.5	0.875	0.425	1.735
10	3.0	1.100	1.295	1.480

Table 5. Comparison of effective doses for male and female 1 year olds among facilities for chest examinations

Facility ID	AP chest Effective dose (mSv)	PA chest Effective dose (mSv)	Lateral chest Effective dose (mSv)
1	0.008	0.012	0.004
2	0.007	0.004	0.011
3	0.038	0.037	0.047
4	0.053	0.041	0.061
5	0.008	0.002	0.015
6	0.0027	0.006	0.013
7	0.059	0.024	0.061
8	0.012	0.005	0.017
9	0.021	0.007	0.062
10	0.022	0.013	0.031

attributed to the use of a relatively faster film-screen combination.

The effective radiographic voltage depends on the type and age of the X-ray generator. Considering the very short exposure times required for pediatric examinations, a nearly rectangular radiation waveform and a minimal amount of ripple are desirable for pediatric patients. One-, 2- and 6-pulse single-phase generators cannot generally provide this. Twelve-pulse three-phase, high-frequency or direct-current constant potential high voltage generators are required. High milliamperage (400–600 mA, 800 mA maximum) permits shorter exposure times, so motion blurring is minimized even in the uncooperative infant or young child, although low milliamperage settings may also be required in small infants. This means that the smallest patients need the most powerful machines. As previously discussed, the majority of surveyed facilities used three-phase generators, with two high-frequency, and one single-phase generator. Facility 9, which utilized a single-phase generator, delivered an average effective dose of 0.03 mSv (3 mrem), somewhat above the average, but less than several facilities that used three-phase

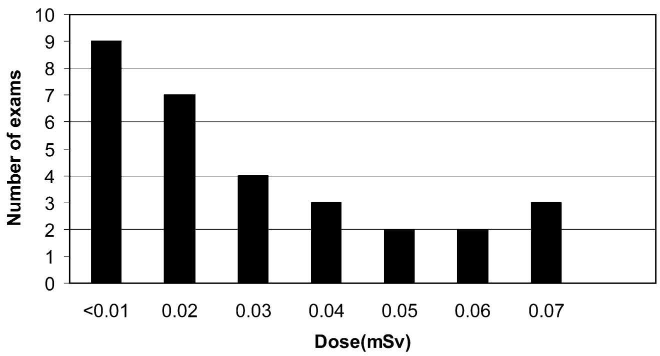

Fig. 1. Histogram distribution of the effective doses to a 1 year old measured for chest examinations at ten facilities

generators and one facility utilizing a high-frequency generator. The facilities using high-frequency units did not produce substantially lower effective doses than facilities using three-phase generators. In fact, facility 4, which used a high frequency generator had the highest average effective doses of the chest series (0.052 mSv). Facility 8 also used a high-frequency generator and delivered an average effective dose of 0.011 mSv, an effective dose, similar to that achieved by most of the facilities utilizing three-phase generators. These results suggest that the improved radiation quality provided by the high-frequency generators by itself does not realize a significant dose reduction in pediatric imaging. While the greater output of the high-frequency generators permits shorter exposure times, this did not appear to have a significant effect on motion artifacts in the resulting image since the repeat rates for facilities 4 and 8, 5.5% and 4%, respectively, are similar to those of the other facilities (Table 4).

The majority of the dedicated pediatric facilities either had grids that were removable from their chestboard or used cross-table X-ray projections if the examination was performed on the table and the grid was not preferred. In pediatric patients, radiography should be performed without grids, as the tissue volume irradiated is small and there is little scatter, and large-grid ratios require increased patient exposure to achieve the desired optical density of film. The radiation dose to the pediatric patient can be significantly reduced by omitting the grid. The survey showed that all chest examinations were performed without a grid, except in facilities where it was impossible to remove the grid. The abdomen, pelvis, spine, and skull examinations were all performed with a grid. Grids with 10:1 ratios were found in most of the facilities. Facilities that used a general-purpose X-ray room for their pediatric studies, in which kilovoltages of more than 100 kV were commonly used, had 12:1 linear grids installed.

Adult patients vary in size, but their relative variation is small compared to the range encountered in pediatric patients. Most facilities accommodate this range by utilizing manual techniques, yet one may expect that an automatic exposure control (AEC) device would be helpful in this situation. We observed that the four facilities (facilities 4, 7, 9, and 10) that used AEC during chest examinations delivered the largest effective doses with one exception. Facility 3 was the only facility that used manual techniques that had doses as large as those using AEC. The higher doses delivered using AEC result from the fact that most AEC systems are not designed to accommodate pediatric patients adequately. They have relatively large and fixed ionization chambers and neither their size, shape, or position can compensate for the many variations of body size and body proportion in pediatric patients. In addition, the usual ionization chambers of AECs are built in behind the grid. Consequently, AEC use may be associated with the use of the grid where the grid is not removable. Specially designed pediatric AECs have been tested that utilize a small mobile ion chamber for use behind a lead-free cassette. The position of the detector can be selected with respect to the most important region of interest. Such positioning needs to be performed extremely carefully, as even minor patient movement could disturb the detector's reading. Since the high speed of modern screens requires a minimal dose at the front of the cassette, the detector behind the cassette would be required to work in a range at a fraction of the entrance dose. It has proven difficult to ensure reproducibility in this range and is an area for future development.

Manual techniques are the preferred method of radiographing pediatric patients. The majority of facilities that utilized manual techniques had generated their technique charts either through experience or through the utilization of a variety of sizes of frozen game birds as test phantoms. For example, game hens have been used since they mimic a neonate in size.

The radiologic techniques of kVp and mAs were examined for all of the surveyed examinations. For the facilities that were surveyed, it was observed that the distribution of kVp spanned a relatively narrow range, 70 ± 3 kVp, which is illustrated in Fig. 2. The kVp is observed to vary much more from facility to facility than it does for the 17 examinations surveyed at each facility. The largest deviation of kVp for examinations occurs within the chest series of exams. Table 2 shows that the PA and AP projections utilize very similar kVp at each facility, but a significant variation is observed between facilities. As expected, lateral projection chest examinations used a consistently greater kVp than the PA/AP projections.

The mAs used by the facilities and for different examinations varied over a much greater range than did tube potential. The variation in mAs was greater between facilities than between the surveyed examinations performed at each facility. The distribution of mAs is illustrated in Fig. 3 with an average of 10.2 ± 11.5 mAs.

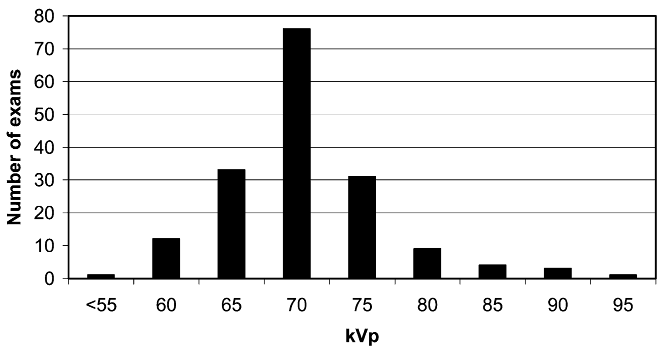

Fig. 2. Histogram distribution of the kVp observed for the surveyed pediatric examinations at ten facilities

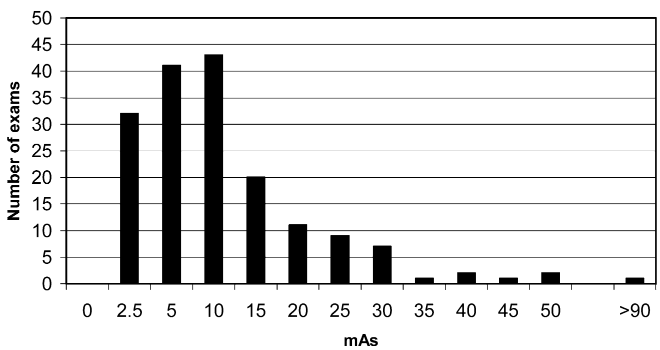

Fig. 3. Histogram distribution of the mAs observed for the surveyed pediatric examinations at ten facilities

It is clear from Fig. 3 that several facilities used very large values of milliampere-seconds, approximately an order of magnitude greater than the mean. As evidenced by Table 3, there were occasional examinations that utilized uncharacteristically large milliampere-seconds compared to other examinations performed using the same equipment. These examinations undoubtedly result in a larger patient dose than necessary to achieve the desired diagnostic information.

While the personal preferences of individual radiologists introduce subjective variations in the evaluation of image quality, the optimal range of optical density is normally considered to be between 0.5 and 2.0 with the distribution centered on an optical density of 1.2 [11, 12]. Films with optical density over the lung field outside of this range usually possess inferior information content. The lung-field optical densities for AP chest, PA chest and lateral chest films in Table 4 show that facilities 3, 4, and 7 consistently produced images with high optical density, frequently outside of the optimum range. A quantitative ranking of the magnitude of the difference from an optimum optical density of 1.2 for all of the facilities surveyed shows that these three facilities produced the poorest image quality, a result consistent with the more subjective visual evaluation of image quality. Facilities 4 and 7 utilized AEC, which resulted in the selection of some relatively large values of milliampere-seconds that is likely the biggest contributor to producing images having high optical density and large patient doses. The X-ray generators at these three facilities were among those facilities with the largest values of half-value layer (Table 1). The increased penetrating ability of high-quality radiation is also likely to be a contributing factor to increased optical density and greater patient dose for the small patient size encountered in pediatric radiology.

Conversely, facilities 1 and 2 produced images nearest the optimum optical density of 1.2 and also provided the smallest patient doses, even though four other facilities produced images with smaller optical densities. Some of the contributing factors to the good performance at these facilities includes the use of manual techniques, 600-speed film at facility 1, and aggressive collimation to achieve a small field size. No significant trends in performance were observed as a function of the size of the different facilities that participated in this survey.

In conclusion, this study has provided a detailed characterization of pediatric techniques for 17 commonly performed diagnostic examinations at ten facilities and provides the only direct measurements of effective dose for clinical pediatric chest examinations. The study demonstrates that the effective dose can vary by an order of magnitude for examinations performed for the same standard patient that was represented by an anthropomorphic dosimetry phantom representing a 1-year-old patient. The observed variation for a series of chest examinations demonstrates that 53% of the examinations provided clinically useful examinations delivering effective doses less than 0.02 mSv, but hardware and technique factors can produce substantially higher doses. In several instances these doses approached those commonly attributed to adult chest examinations, 0.08 mSv.

In all of the surveyed facilities, manual technique settings were observed to provide lower patient doses than AEC controls. As expected, single-phase generators result in greater patient dose than more modern generators, but little difference was detectable between three-phase and high-frequency generators. Most importantly, careful attention to minimizing milliampere-second settings, and using the minimum acceptable optical density that provides the required diagnostic information can provide substantially lower pediatric patient doses. The results of the study show that good image quality should not require high doses. In fact, we observed a negative correlation between image quality and patient dose, with the best quality images being obtained with the smallest doses and the poorest quality images associated with the highest patient doses. This underscores the benefits of carefully selecting pediatric-specific equipment and image-acquisition parameters to maximize the overall performance of pediatric radiological examinations.

The data collected in this study focused on facilities using film-based radiography, although one facility performed the majority of their imaging using digital imaging. As digital imaging techniques become the standard in pediatric radiography, this study will continue to provide important reference values for radiographic imaging. Current computed radiography (CR) and digital radiography (DR) systems have image receptors roughly comparable to the 400-speed film-screen combinations used by the majority of facilities surveyed. The large dynamic range of digital systems are theoretically capable of producing comparable diagnostic images with smaller exposures, and effective doses, than film-based systems; in practice, this is not always observed. The phenomenon of "exposure creep" is sometimes observed, where the dynamic range of the digital system permits what would have traditionally been an overexposed examination, to be adjusted to provide a diagnostically acceptable image, but with excessive patient dose. The quantitative parameters surveyed in this study will provide a basic data set that can be referenced to ensure consistent imaging performance.

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