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Optimization of Dose and Image Quality for Computed Radiography and Digital Radiography

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The surface doses to patients during chest, abdomen and pelvis radiography were measured over a period of 3 years, during which time computed radiography (CR) and digital radiography (DR) systems were introduced to replace film–screen systems. For film–screen and CR the surface doses were measured with thermoluminescent dosimeters. For DR the surface doses were calculated from the dose–area product (DAP) meter readings. Measurements were made for each type of examination and detector type on 10 average-size patients. Measurements were made immediately after the new systems were introduced, and subsequently as adjustments were made to optimize dose and image quality. Published diagnostic reference levels were used as target values in this optimization. Initially, CR doses were the same as or higher than for film–screen, and the doses were lower for DR compared to film–screen. Subsequent clinical experience with the systems led to changes in the technique used for chest examinations both for CR and for DR. For CR, it was possible to change the algorithm and decrease the dose to one quarter of the initial value with acceptable image quality. For DR, it was decided to reduce noise by increasing the dose by a factor of two. No changes were made to abdomen or pelvic imaging techniques for either CR or DR. The final patient surface doses using CR were similar to published diagnostic reference doses; for DR, all patient doses were less than published reference levels.

KEY WORDS: Computed radiography, digital radiography, optimization, patient dose

INTRODUCTION

In developed countries, medical diagnosis results in the largest exposure to ionizing radiation from man-made sources.[1] This has led to concern from international and national bodies over the dose to patients[2,3] and to legislation regarding patient dose, at least in some countries.[4,5]

Many medical facilities are replacing screen–film radiography with filmless radiography, i.e., computed radiography (CR) or digital radiography (DR). Unlike film–screen systems, both CR and DR have a large dynamic range, so it is relatively easy to unknowingly overexpose the patient. It is therefore important to check that patient doses do not increase during the transition to digital systems. In this work, we decided to use direct patient dose measurements because of our previous experience[6] and because of the large amount of patient dose information available from many surveys using this approach.[7]

This study was undertaken to compare the patient x-ray exposures that arise from common medical imaging procedures when using screen–film radiography, computed radiography, and digital radiography. The study consisted of measurement of the exposures [entrance surface air kerma (ESAK)] received by a reference group of patients for common radiographic procedures—chest PA (chest x-ray, posterior–anterior), chest LAT (chest x-ray, lateral), abdomen AP (abdomen

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x-ray, anterior–posterior), and pelvis AP (pelvis x-ray, anterior–posterior)—using screen–film radiography, CR, or DR.

This report presents the results of the comparative study of the ESAKs obtained with CR, DR, and conventional (screen–film) radiography. It also shows how these ESAKs compare with various published diagnostic reference levels for these types of examinations. The study shows how cooperation between the radiologist, technologist, physicist, and the imaging companies can ensure that good images can be achieved at reasonable doses.

METHODS

One hundred ten patients referred for clinically indicated routine exams (chest PA, chest LAT, abdomen AP, and pelvis AP) at our hospital were entered into the study. Patients were selected only on the basis of patient weight (70 ± 10 kg). Recruitment into each exam category stopped once 10 subjects were found. Ethics approval was obtained from the local university hospital research ethics board.

For film–screen and CR exams the patient entrance dose was estimated using thermoluminescent dosimeters (TLDs) for four types of examination: chest PA, chest LAT, abdomen AP, and pelvis AP. For DR the dose was estimated from the dose–area product meter built into the collimator of the DR equipment for three types of examination: chest PA, abdomen AP and pelvis AP.[7]

The film–screen system used for chest imaging had a speed of 300 (Kodax Insight); for all other imaging 400-speed film was used (Dupont Cronex 10TL). The CR system used was the FCR XG-1 reader with STVI phosphor plates from the Fuji Corporation. Two x-ray units of the same manufacturer and model were used for all the film and CR measurements (Toshiba TOSRAD). The DR system was a Philips Diagnost DR. The x-ray units were calibrated every 6 months during the trial. Measurements were taken over a 30-month period as film was phased out and CR and DR introduced.

Film–Screen and CR

Thermoluminescent dosimeters in the form of lithium fluoride chips were sealed in plastic sachets (five TLDs per sachet). For each measurement, the dosimeter sachet was taped to the surface of the patient in the center of the x-ray light field and was not visible on the radiograph. The entrance skin exposures (ESEs) measured from the TLDs, calibrated in millirads (free-in-air), were converted to ESAK (in milligrays) by multiplying the ESE value by 0.00876.

DR

The study was performed in a similar fashion to that for CR, except that the built-in dose–area product meter reading was recorded after the exposure of each patient. This air kerma reading in decigray square centimeters was converted to ESAK by dividing by the field size at the patient, and multiplying by the backscatter factor for the patient field size and tube potential (kVp) of the exposure.

Film Viewing

Films were viewed using a standard film alternator with a luminance of 1500 cd/m^2.

PACS

All CR and DR images were reported by radiologists on high-contrast, high-brightness CRT displays (Dome MD2P 10-bit video card, Siemens SMM) on a standard PACS system (Agfa Impax version 4.1). All displays had a contrast ratio of at least 200 and brightness of at least 250 cd/m^2 and the gray scale was calibrated to DICOM part 3.14. All examinations were of diagnostic quality.

Optimization

The optimization process for chest exams involved a change in the algorithm of the CR system and a reduction in patient dose. For DR, the noise was reduced by increasing the dose to the patient.

Effective Doses

Effective doses were estimated by using the ESAK to effective dose conversion coefficients published by Hart et al.[8]—120 kVp chest AP, 0.163 mSv/mGy; 120 kVp chest LAT, 0.103 mSv/mGy; 75 kVp abdomen AP, 0.127 mSv/mGy, and 75 kVp pelvis AP, 0.157 mSv/mGy.

Statistics

ANOVA and the two-tailed *t* test were used to determine if the differences in patient dose and tube currents were statistically significant.

RESULTS

Comparison of Patient Doses Using Film–Screen, CR, and DR

The average surface air kerma doses received by patients during the examinations are summarized in Table 1.

For chest PA, the differences in average patient doses were very significantly different ($p < 0.0001$) as shown by ANOVA. CR doses were very much higher than either film–screen ($p < 0.01$) or DR ($p < 0.01$). The patient dose from

Table 1. Comparison of patient doses for film–screen radiography, CR, and DR

	Average ESAK (mGy)		
Examination	Film–screen	CR	DR
Chest PA	0.20 ± 0.07	1.02 ± 0.63	0.07 ± 0.02
Chest LAT	1.08 ± 0.48	3.21 ± 1.16	–
Abdomen AP	5.39 ± 2.91	5.24 ± 3.03	1.75 ± 0.56
Pelvis AP	3.30 ± 1.70	4.78 ± 2.85	1.68 ± 0.65

chest PA using CR was five times higher than that from film–screen radiography. However, the chest PA patient dose from film–screen was not significantly different from DR, as shown by the Tukey HSD post hoc test.

For chest LAT, CR doses were also significantly higher than film–screen ($p < 0.0001$). The mean surface dose with CR was three times that of film–screen.

For abdomen AP, ANOVA showed significant difference in the average patient doses for film–screen, CR, and DR ($p = 0.003$). This was due to the much lower doses observed with DR compared to film–screen ($p < 0.05$) or to CR ($p < 0.01$).

No statistically significant difference was observed in the means of the three imaging technologies for pelvis AP.

Effect of Technique Factors Used for Film–Screen, CR, and DR

Slightly higher kVp (about 5% higher) was used with CR compared with film–screen for both chest PA and chest LAT. For DR, the kVp applied is slightly higher than for both film–screen and CR for all examinations studied (Table 2).

In general, the tube current (mAs) values used for DR were the lowest for all three examinations, similar for film–screen and CR for abdomen AP and pelvis AP, but much higher for CR than film–screen for chest examinations. ANOVA showed that the differences are significant for chest PA ($p < 0.0001$). Tukey HSD attributed this difference to the higher mAs used for CR than for film–screen ($p < 0.01$) or DR ($p < 0.01$); the difference in the mAs between film–screen and DR were not significant. The relatively higher the tube current (mAs) used with CR for chest x-ray is associated with the increase in ESAK observed. The difference in average mAs applied for chest PA and chest LAT between film screen and CR are somewhat proportional to the differences in dose from these examinations.

For abdomen AP, the mean mAs used for the three radiographic systems were significantly different (ANOVA, $p = 0.00026$). Tukey HSD showed that this was due to the significant difference in DR mAs compared to film–screen ($p < 0.01$) and CR ($p < 0.01$), but the mAs difference between film–screen and CR was not significantly different. This is consistent with the finding that for abdomen AP, patient doses obtained with film–screen and CR are also not significantly different.

For pelvis AP, no significant difference was observed in the mAs used for film–screen, CR or DR. This is again consistent with statistical analysis of the data of patient doses for pelvis AP and a good indication that mAs is a determining factor in resultant patient doses.

Optimization of Patient Dose

Table 3 presents a summary of the initial average patient doses for the three types of examinations using film–screen, CR, and DR systems.

The radiologists in our department found the diagnostic quality of the abdomen and pelvis exams with both CR and DR to be similar to film–screen. Therefore, no changes were made to

Table 2. Technique factors used for film–screen, CR, and DR

	kVp			Average mAs		
Examination	FS	CR	DR	FS	CR	DR
Chest PA	115	121	125	3.0 ± 1.2	8.7 ± 4.8	1.35 ± 0.23
Chest LAT	115	121	–	14.7 ± 6.3	27.1 ± 8.5	–
Abdomen AP	75	75	81	43.1 ± 24.0	33.0 ± 16.5	10.77 ± 2.31
Pelvis AP	75	75	77	37.3 ± 41.0	21.8 ± 12.2	10.17 ± 4.49

Table 3. Summary of initial patient doses after change to CR and DR

	Average ESAK (mGy)		
Exam/Projection	Screen–film	CR	DR
Chest PA	0.20	1.02	0.07
Abdomen AP supine	5.24	5.39	1.86
Pelvis AP	3.30	4.78	1.68

Table 5. Rando phantom chest tests for CR dose reduction

kVp	Phototimer cells	Density	mAs	CR S No.	Relative surface dose
121	Center	+2	7.45	179	1
121	Center	0	3.6	333	0.48
121	2 Outer	+2	2.59	565	0.35
121	2 Outer	0	1.82	836	0.24

the protocols used for the abdomen or pelvis exams. Radiologists also liked the CR chest exams, although the dose was high. Radiologists found the DR chest exams too noisy. Both of these problems were addressed.

Table 4 summarizes the techniques used specifically for chest PA exams and the measured doses. The last column shows the reference surface dose suggested by the European Commission.[5]

For chest PA using CR, the surface dose is five times the surface dose previously measured using the film–screen system and more than three times the European reference level. Apart from kVp, which was mentioned previously, the photocell use and density were different for the three modalities.

To further investigate the role of the photocell and density controls, an anthropomorphic phantom (Rando Phantom, Alderson Laboratories) was used to take CR radiographs. The results are summarized in Table 5.

The S number shown in column 5 is the way the CR manufacturer indicates the relative speed of the cassette. It is calculated by dividing 200 by the cassette surface exposure in mR. For the anthropomorphic phantom the mAs is slightly lower than the average mAs used for patients patients, but only the relative values are of concern here. By reducing the density control to zero the patient surface dose is halved. By reverting to the lung field photocells only, as was used for film–screen, the dose can be reduced to 24%.

To actually implement this dose reduction in the hospital, various chest CR algorithms were applied to the same raw data for a typical image taken using only the two outer lung AEC photocells. The radiologists were asked to select their preferred reconstructed image. An evaluation was made, comparing the chest radiographs on 12 patients who had had a previous radiograph within 3 weeks using the higher dose setting with a subsequent radiograph using the lower dose and smoother algorithm. The two lung fields were used with no density correction reducing the dose to 24% or approximately 0.25 mGy (1.02×0.24). Two radiologists blinded to the dose information simultaneously viewed the two chest PA radiographs of the same patient obtained within 3 weeks and chose the best quality image. They specifically were directed to assess the visualization of peripheral vessels, minor fissures, and retrocardiac structures. In 60% of the cases, the lower-dose image with the new algorithm was preferred. This lower-dose technique was subsequently adopted as the routine technique for chest radiography using CR.

Using DR, the surface doses were found to be less than one quarter of the EC reference dose. As the radiologists became adjusted to the digital techniques, it was decided to reduce the noise in the DR images. This was achieved by doubling the dose (halving the set speed on the system) and by using a slightly higher smoothing algorithm. The final patient dose was about half the reference dose. The final doses are shown in Table 6.

Table 4. Chest PA: measured doses and AEC settings

Type	kVp	AEC cells	Density	mAs	Surface air kerma[a] (mGy)	EC reference dose (mGy)[5]
Film	115	Lung fields	0	3.0	0.2	0.3
CR	121	Center	+2	8.7	1.02	0.3
DR	125	All 3	0	1.1	0.07	0.3

[a]Includes backscatter.

Table 6. Summary of final patient doses after optimization

	Final average patient surface dose (mGy)		
Exam/Projection	Screen–film	CR	DR
Chest PA	0.20	0.24	0.14
Abdomen AP supine	5.24	5.39	1.86
Pelvis AP	3.30	4.78	1.68

Table 7. Final mean patient effective dose

Exam/Projection	Patient effective dose (mSv)		
	Screen–film	CR	DR
Chest PA	0.033	0.039	0.023
Abdomen AP	0.67	0.68	0.24
Pelvis AP	0.52	0.75	0.26

Patient Effective Doses

Using the conversion coefficients of Hart et al,[8] Table 7 shows the effective doses corresponding to the mean surface doses measured.

DISCUSSION

The need to optimize protection of patients without compromising the clinical value associated with the exposure was espoused in ICRP Report 60.[9] Hitherto, the philosophy had always been that the clinical benefit of the diagnostic procedure to the patient outweighed the associated radiation risk, and, thus, the practice was clearly justified. Although this philosophy still holds true, there is now emphasis on optimization of protection of the patient, not within the concept of a restrictive dose limit, but within the concept of a reference level of exposure, to allow an appropriate degree of flexibility. ICRP Report 73[2] introduced the term "diagnostic reference level" or DRL, which is a form of investigational level. It can serve as a quality assurance tool for diagnostic radiology to provide a trigger for local review if consistently exceeded. Different organizations have recommended some form of DRLs for the common types of diagnostic examinations included in this study (Table 8).[5,7,10–13] Note, however, that these reference levels are, in general, based on experience with screen–film radiography.

Before changing to filmless radiography, patient doses from screen–film radiography were all below the reference levels recommended by advisory bodies. This was not the case after the introduction of CR. The initial doses received by patients undergoing chest PA or chest LAT were significantly higher with CR than with screen–film radiography. For chest PA, the CR doses were five times higher, whereas for chest LAT, three times higher than screen–film doses. The reason for this difference was the change of the phototimer cells used to terminate the exposure and the increase in the AEC density control. With film–screen systems the lung field photocells were used; with CR the center (mediastinum) cell was used plus an increase in density of +2. This was done because of dissatisfaction with the chest images taken with the same parameters as film–screen. We feel this was mainly due to the continued printing of film from CR examinations before the PACS system was able to distribute the images throughout the facility. It was also partly due to the comfort level of radiologists with the new digital images.

Patient doses for abdomen AP or pelvis AP, at about 5 mGy, were below the reference levels of 10 mGy recommended by most advisory bodies and similar to the recent recommendations of the National Radiological Protection Board (NRPB).[10] There was no statistically significant difference between CR and screen–film radiography for abdomen AP and pelvis AP examinations. In the case of abdomen and pelvis studies, there was also no change to the photocells used for radiography.

Using DR, the surface doses were found to be less than one quarter of the European-Commission-recommended DRLs; using CR, the surface dose was three times the DRL. As the radiologists became adjusted to the digital techniques, it was decided to reduce the noise in the DR images. This was achieved by doubling the dose (halving the set speed on the system) and by using a slightly higher smoothing algorithm. The final patient surface dose was about 0.7 of the lowest reference value shown in Table 8.

Caution is necessary if phantoms alone are used as the basis for patient dose comparisons. For example, had the chest radiography measurements only been estimated with a phantom such as the NEXT chest phantom,[14,15] the patient doses measured for CR would have been underestimated by 65%. This is because the NEXT chest phantom is of uniform attenuation (it has no mediastinum),

Table 8. Reference levels (in milligrays) recommended by various advisory groups

Examination	IAEA[12]	EC[5]	IPEM[7]	NRPB[10]	AAPM[13a]
Chest PA	0.4	0.3	0.3	0.2	0.25
Chest LAT	1.5	1.5	1.5	1	1.5
Abdomen AP	10		10	6	4.5
Pelvis AP	10	10	10	4	

[a]All include backscatter except the AAPM values.

and any change in the use of the AEC photocells would have had no effect on the measured dose using the phantom. In this work, the error would be the difference between the dose measured using the center photocell (over the mediastinum) and the dose measured using the outer photocells, given by rows 1 and 3 in Table 7 or $[(1.00 - 0.35)/1.00] \times 100 = 65\%$. On the other hand, the NEXT abdomen phantom would have given a better comparison, as the phantom is more anthropomorphic.

To provide clinical justification for dose reduction we employed the expert opinion of two subspecialty trained chest radiologists with a range of clinical experience [7 years (PD), 20 years (JRM)]. Because the relationship between radiation dose level and diagnostic performance is extremely difficult to quantify, we used subjective image quality based on observer experience and preference as a surrogate measure. We acknowledge that further dose reduction may be possible with a more rigorous measure of diagnostic image performance.

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