Optimization of the Radiological Protection of Patients Undergoing Digital Radiography

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Abstract Because of a much higher dynamic range of flat panel detectors, patient dose can vary without change of image quality being perceived by radiologists. This condition makes optimization (OT) of radiation protection undergoing digital radiography (DR) more complex, while a chance to reduced patient dose also exists. In this study, we evaluated the difference of patient radiation and image rejection before and after OT to identify if it is necessary to carry out an OT procedure in a routine task with DR. The study consisted of a measurement of the dose area product (DAP) and entrance surface dose (ESD) received by a reference group of patients for eight common radiographic procedures using the DR system before and after OT. Meanwhile image rejection data during two 2-month periods were collected and sorted according to reason. For every radiographic procedure, *t* tests showed significant difference in average ESD and DAP before and after OT ($p < 0.005$). The ESDs from most examinations before OT were three times higher than that after OT. For DAPs, the difference is more significant. Image rejection rate after OT is significantly lower than that before OT ($\chi^2 = 36.5$, $p < 0.005$). The substantial reductions of dose after OT resulted from appropriate mAs and exposure field. For DR patient dose, less than recommended diagnostic reference level can meet quality criteria and clinic diagnosis.

Keywords Optimization · Digital radiography · Radiation dose · Diagnostic image quality · Exposure index

Introduction

Recently, radiography still remains the mainstay of medical imaging examination. Although individual patient dose in radiography is relatively low, its contribution to the collective dose is significant due to the frequent use of this examination. The collective dose only associated with chest radiography is about 18% in some western countries [1]. Optimization (OT) of image quality and patient dose still should be an important area worthy of study.

For image quality and patient safety, international and national bodies, such as International Atomic Energy Agency (IAEA), European Commission (EC), National Radiological Protection Board (NRPB), AAPM, et al. [2–5], have addressed corresponding documents and recommended diagnostic reference levels (DRLs) or guidance levels of dose for the common types of diagnostic examinations. However, these reference levels are, in general, based on experience with film–screen radiography. Recently, the replacement of conventional radiographic equipment with digital imaging systems has increased rapidly in Chinese mainland. Conventional system darkness (density), while in digital system noise, that usually identifies image quality, correlates well with dose [6]. It is necessary to reconsider the balance of image quality and patient dose and to reevaluate local DRLs when digital techniques replace film–screen techniques.

The goal of this study is OT of the image quality and radiological protection of patients undergoing digital radiography (DR). The study consisted of the measurement

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of dose area product (DAP) and calculation of entrance surface dose (ESD) before and after OT process. The DRL for digital radiography was discussed. At the same time, image reject rate analysis was carried out as an integral part of an OT program for DR.

Materials and Methods

Reference Group

In 2004, IAEA [2] gave a final report of a coordinated research project in Africa, Asia, and Eastern Europe. We applied the basic principle and methodology in the report to this study. One hundred patients referred for clinically indicated routine exams were entered into the study as reference group. In the EC document [7], a standard-sized patient (adult normal-sized patient) was assumed to be 20 cm anterior–posterior (AP) trunk thickness and 70-kg weight for the European countries. For the purpose of comparing measured doses with reference doses, and the application of EC-developed image criteria, a compromise of weight ($65 \text{ kg} \pm 10\%$) and trunk thickness ($20 \text{ cm} \pm 10\%$) was used for Chinese in this study. Recruitment into each exam category stopped once ten subjects were found. Ethics approval was obtained from the local hospital research ethics board.

Radiographic Procedures

The radiographic X-ray examinations studied in the study were limited to five selected exam categories: chest, abdomen, lumbar spine, pelvis, and skull. The projections included eight radiographic procedures: chest posterior–anterior (PA) and lateral (LAT); abdomen; lumbar spine AP and LAT; pelvis AP; skull PA and LAT.

Imaging Equipment and Measurement Instrument

The DR system was Kodak DirectView DR3000. The X-ray calibration was carried out every day and darkness calibration once a month during the trial. All images were reported by radiologists on high-contrast, high-brightness CRT displays on a standard PACS system. All examinations were of diagnostic quality.

The direct patient dose measurements proved effective and convenient [8]. The DAP meter was built into the collimator of the DR equipment. DAP reading was recorded after the exposure of each patient. The value displayed in decigray square centimeters was converted to ESD by dividing by the exposure field size at the patient, and multiplying by the backscatter factor for the field size and tube potential (kilovolt peak) of the exposure. A

standard calibration procedure for DAP meter was given with thermoluminescent dosimeter before measurement.

Evaluation of Image Reject and Patient Dose Before OT

Before OT, an image rejection analysis was performed for a period of 2 months on the DR involved in the study. Images were rejected at both the radiographer level and radiologist. The image criteria which would have led to image rejection were taken from European guidelines on quality criteria for diagnostic radiographic images [7]. The reasons for rejection of images were recorded and analyzed. Images were sorted on the respective reasons for rejection. Here, we gave a more detailed classification than before [9].

For every selected exam category, DAPs of ten standard-sized patients were sampled. Projection was carried out with kilovolt peaks and tube currents (milliamperage) by default, time by automatic exposure control (AEC), exposure field and focus flat panel detector (FFD) distance by hand according to technician's routine. All of parameters were not adjusted deliberately. The following items were collected for each of the ten patients in the sample for each projection:

- Patient name and identifier
- Age, sex, height, weight, trunk thickness of the patient
- Kilovolt peak, milliamperage, exposure time
- FFD, exposure field, DAP, exposure index (EI)
- Use of grid
- Use of AEC
- X-ray machine model, wave form, filtration

Three chest radiologists with a range of clinical experience [5 years (PD), 15 years (JRM)] then reviewed the obtained images together on CRT displays. Under no circumstances should an image, which does not fulfill diagnostic requirement, be rejected and repeated.

OT Process

The purpose of OT is to reduce patient dose in radiography by a number of improvements without losing the necessary information for diagnosis. The following quality controls were performed:

- Complete calibration of DR equipment and printer according to user's manuals
- Resetting the kilovolt peak; considering the EC criteria were used higher kilovolt peak than the recommendations of vendor
- Resetting FFD in accordance with the recommendations of “European guidelines on quality criteria for diagnostic radiographic images” [7]

Table 1 Comparison of patient doses and EI for DR before and after OT

Radiographic procedure	ESD (mGy)			DAP (dGycm ²)			EI	
	Before OT	After OT	<i>p</i> value	Before OT	After OT	<i>p</i> value	Before OT	After OT
Chest PA	0.29	0.09	<0.001	4.58	1.12	<0.001	1,803	1,311
Chest LAT	0.269	0.18	<0.005	4.13	2.05	<0.005	1,562	1,303
Skull PA	1.41	0.47	<0.001	10.17	2.76	<0.001	1,719	1,318
Skull LAT	0.95	0.30	<0.001	6.58	1.74	<0.001	1,762	1,311
Lumbar spine AP	2.12	0.61	<0.001	19.68	3.15	<0.001	1,871	1,302
Lumbar spine LAT	4.60	1.52	<0.001	42.7	7.80	<0.001	1,654	1,312
Abdomen AP	1.42	0.30	<0.001	23.5	4.62	<0.001	1,982	1,302
Pelvis AP	1.36	0.42	<0.001	22.5	5.98	<0.001	1,788	1,304

- Obtaining appropriate milliamperes with EI and AEC. For Kodak DR system, the relationship of EI and incident dose on detector surface (*D*) is [10]:

$$EI = 300\log_2 D + 2996.58 \quad (1.25\mu\text{Gy} < D < 10\mu\text{Gy}, \\ 1,100 < EI < 2,000)$$

With long-term experience, EI>1,300 can satisfy radiographer and radiologist. So we adjusted the AEC feedback circuit to keep EI equal to 1,300 or so.

- Reducing exposure field
- One week of training for radiographers
- Relevant training for patients before projection for good cooperation

Evaluation and Measurement After OT

Image rejection analysis was repeated after the OT procedure had been completed and mastered by radiographers. The analysis was performed for the other period of 2 months and images were sorted by the same way as before.

A second series of dose measurements took place after having implemented OT actions resulting from quality control and radiographer training. Similar to previous evaluations, DAPs of ten standard-sized patients were sampled for every selected exam category. The same three chest radiologists read the images together. Images that cannot fulfill the diagnostic requirement or do not meet the quality criteria of the EC [7] would be investigated to find the cause of rejection, and the patient was reexamined by adjusting the radiographic parameters. The items referred to before OT also were recorded here.

Statistics

Single-tailed, two-sample *t* tests were used to determine if the differences in patient dose (ESD and DAP) before and

after OT were statistically significant. Image rejection rates before and after OT were compared using two-sample chi-square test.

Results

Comparison of Patient Doses Before and After OT

Patient doses were measured before the implementation of the OT program to assess the status. Following the introduction of the OT procedure and including corrective actions, patient doses were again assessed to gauge the impact on doses. Table 1 presents a summary of the average ESD, DAP, and EI for the chest, skull, lumbar spine, and pelvis X-ray examinations with ten standard-sized patients, both before and after OT. For every radiographic procedure, the *t* tests showed a significant difference in the average ESD and DAP before and after OT (*p*<0.005). The ESDs from most examinations before OT were three times higher than that after OT. For DAPs, the difference is more significant. Note that the DAP from the lumbar spine AP examination before OT was six times higher than that after OT.

Table 2 Technique factors used for DR after OT

Radiographic procedure	kVp	mAs	FFD
Chest PA	110	3.2	150
Chest LAT	120	5	150
Skull PA	70	12.8	115
Skull LAT	70	8	115
Lumbar spine AP	75	25	115
Lumbar spine LAT	85	40	115
Abdomen AP	80	12.5	115
Pelvis AP	75	15.7	115

Table 3 Percentage comparison of rejected images according to reason for rejection before and after OT

Reason for rejection		Before OT		After OT	
		Percentage of rejects (%)	Rank	Percentage of rejects (%)	Rank
Positioning error		35.0	1	19.2	3
Movement	Body deviation ^a	23.3	2	6.4	4
	Motion blur	2.5		2.6	
Artifacts	In body	5	3	3.8	5
	Out of body	11.7		0	
Exposure error	Overexposure	1.7	4	0	1
	Underexposure	8.3		35.9	
Clipped anatomy		9.2	5	28.2	2
Nontechnical error ^b		2.5	6	2.6	6
Equipment trouble		0.8	7	1.3	7

^a Body deviation means the center of body part to be examined deviates from that of exposure field because of patient's movement.

^b Nontechnical error means rejection does not result from technician's specialty, such as patient registry error, image interface operation error, wrong sort of patients, orientation mark confusion, et al.

Technique Factors Used After OT

Table 2 summarizes the techniques used for 100 standardized patients with eight radiographic procedures after OT. The kilovolt peak settings were derived from the manufacturer's reference value by an appropriate increase. The milliamperage was controlled by AEC, which was reset to be fit for EI equal to 1,300 or so. The relatively lower milliamperage used after OT was associated with the decrease in ESD observed.

Image Rejection Analysis

Before OT, 480 images were rejected out of a total of 5,505; image rejection rate is 8.72%. After OT, 5,119 images were obtained which consisted of 4,820 qualified images and 299 rejected images, image rejection rate is 5.84%, which is significantly lower than before OT ($\chi^2=36.5$, $p<0.005$).

Table 4 Reference levels (in milligray) recommended by various advisory groups

Radiographic procedures	IAEA	EC	NRPB	AAPM
Chest PA	0.4	0.3	0.2	0.25
Chest LAT	1.5	1.5	1.0	
Skull PA	5.0	5.0	3.0	
Skull LAT	3.0	3.0	1.5	
Lumbar spine AP	10	10	6	5.0
Lumbar spine LAT	30	30	14	
Abdomen AP		10	6	4.5
Pelvis AP	10	10	4	

AAPM American Association of Physicists in Medicine

Table 3 stratifies the rejected image percentage for the cause of rejection.

Discussion

The experiment results showed that patient doses were significantly different before and after OT. The factors of higher doses for the former include: (1) the wide dynamic range of digital detectors and postprocessing makes it more difficult to determine if a radiograph was over- or underexposed as the images may be of diagnostic quality in either case. Instead, underexposure manifests itself as an increased image noise while overexposure is rewarded by high image quality. As result, radiographers favor overex-

Table 5 Clinical imaging tasks requiring high, medium, or low image quality (Busch 2003)

Clinical problem	Image quality	Comment
Primary bone tumor	High	Image may characterize the lesion
Chronic back pain with no pointers to infection or neoplasm	Medium	Degenerative changes are common and nonspecific. Mainly used for younger patients (e.g., less than 20 years of age, spondylolisthesis, etc.) or older patients (e.g., more than 55 years of age)
Pneumonia adults: follow-up	Low	To confirm clearing, etc. Not useful to reexamine patient at less than 10-day intervals as clearing can be slow (especially in the elderly)

posure over underexposure to avoid complaints, and vendors tend to set AEC higher levels than necessary to show their equipment excellence [6, 11]. (2) With clip function provided in DR postprocessing, radiographers prefer larger exposure fields and display only regions of interest to radiologists, which significantly increases the exposed surface area of patients, thereby the DAP followed. After OT, patient ESD was decreased by applying FFD recommended by EC and milliamperes reduced manually, patient DAP decreased by narrowed exposure field and less milliamperes.

DRL is a useful tool to manage patient doses in medical imaging tasks. Different organizations have recommended some form of DRLs for the common types of diagnostic examinations included in this study (Table 4) [2–5]. However, these reference levels are based on experience with film–screen radiography. Reevaluation of local DRLs should be undertaken when digital techniques replace film–screen techniques, as DRLs for nondigital imaging tasks are not necessarily applicable to similar digital imaging procedures. ESD resulting from this study is close to but still lower than that recommended by NRPB. In general, for equivalent image quality, the DR system requires less exposure than the film–screen system because of the detector system and postprocessing of DR.

Not all medical imaging tasks require the same level of image quality or diagnostic information even for the same patient or the same radiographic procedures, so different dose levels are required for different clinical purposes. Busch [12] gave an example of clinical imaging task classifications according to their required image quality (Table 5). Quality criteria should be established for all medical imaging tasks to avoid excessive doses where there is no clear net benefit in the diagnosis or the image quality.

Image reject analysis is an important aspect for OT. It has been mandated for mammography by the US government [13] and recommended for projection radiography by multiple advisory groups [14–16]. Overall, in this study there was an obvious decrease in the image reject rates after the introduction of the OT program, which suggests OT process is necessary for DR system. The quantity of rejected images because of positioning error was mostly reduced, which advises improvement for the technician. The quantity of rejected images because of patient movement reduced greatly, which requires training and cooperation for patients. In the pursuit of the smallest possible exposure field, the operator often cannot completely project the required anatomical region to the exposure field. This is the main factor of image rejection after OT. With an operator with more experience, this situation can be improved.

Basic training in the management of image quality and patient dose in DR is necessary for radiologists, medical

physicists, and radiographers involved in the use of new techniques. This training should include basic aspects of radiation protection for patients and staff, details of the operation of the installed X-ray systems, use of visualization units, postprocessing capabilities, and the operation of the PACS, etc.

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References

1. Wouter JHV, Lucia JMK, Jacob G: Dose and perceived image quality in chest radiography. *Eur Radiol* 72:209–217, 2009
2. International Atomic Energy Agency (IAEA): Optimization of the radiological protection of patients undergoing radiography, fluoroscopy and computed tomography. Vienna: IAEA, 2004
3. European Commission: Guidance on diagnostic reference levels for medical exposures. Radiation protection 109. Luxembourg: Office for Official Publications of the European Communities, 1999
4. Hart D, Hillier MC, Wall BF: Doses to patients from medical X-ray examinations in the UK 2000 review. Oxford: National Radiological Protection Board Publication, 2002
5. Gray JE, Archer BR, Butler PF, et al: Reference values for diagnostic radiology: application and impact. *Radiology* 235:354–358, 2005
6. International Commission on Radiological Protection (ICRP): Managing patient dose in digital radiology. ICRP Publication 93. Annals of the ICRP 34, No. 1. Oxford: Pergamon Press, 2004
7. European Commission: European guidelines on quality criteria for diagnostic radiographic images. Report EUR 16260 EN. Luxembourg: Office for Official Publications of the European Communities, 1996
8. John EA, Emerenciana D, Pat D, et al: Optimization of dose and image quality for computed radiography and digital radiography. *J Digit Imaging* 19:126–131, 2006
9. Jones AK, Polman R, Willis CE, et al.: One year's results from a server-based system for performing reject analysis and exposure analysis in computed radiography. *J Digit Imaging* 2009. doi:10.1007/s10278-009-9236-2
10. Cornelia SP, Ulrich N, Henk WV, et al: Digital chest radiography: an update on modern technology, dose containment and control of image quality. *Eur Radiol* 18:1818–1830, 2008
11. International Commission on Radiological Protection (ICRP): Radiological protection in medicine. ICRP Publication 105. Annals of the ICRP 37, No. 6. Oxford: Pergamon Press, 2007
12. Busch HP: Management of dose and quality in digital radiography. *Fortschr Röntgenstr* 175:17–19, 2003
13. United States Food and Drug Administration: Code of federal regulations, 21CFR900.12(e)(3)(ii), 2008
14. National Council on Radiation Protection and Measurements. Report 99. Quality assurance for diagnostic imaging. Bethesda: NCRP, 1988
15. American Association of Physicists in Medicine. Report 74. Quality control in diagnostic radiology. Madison: Medical Physics, 2002
16. American College of Radiology: ACR technical standard for diagnostic medical physics performance monitoring of radiographic and fluoroscopic equipment. Reston: ACR, 2006, pp. 1139–1142