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Clinical Imaging 36 (2012) 279–286

CLINICAL IMAGING

Optimization of chest radiographic imaging parameters: a comparison of image quality and entrance skin dose for digital chest radiography systems☆,☆☆

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Received 3 June 2011; received in revised form 16 September 2011; accepted 27 September 2011

Abstract

We studied the performance of three computed radiography and three direct radiography systems with regard to the image noise and entrance skin dose based on a chest phantom. Images were obtained with kVp of 100, 110, and 120 and mA settings of 1, 2, 4, 8, and 10. Significant differences of image noise were found in these digital chest radiography systems ($P<.0001$). Standard deviation was significantly different when the mAs were changed ($P<.001$), but it was independent of the kVp values ($P=.08–.85$). Up to 44% of radiation dose could be saved when kVp was reduced from 120 to 100 kVp without compromising image quality.

Keywords: Chest radiography; Digital imaging; Radiation dose; Noise; Image quality

1. Introduction

Chest radiography is the most commonly performed X-ray examination in clinical practice. Chest X-ray images are valuable for solving a variety of clinical problems and serve as the first-line diagnostic technique for determining further steps in the establishment of a diagnosis, treatment, and follow-up procedure [1]. Although individual patient dose in chest radiography is relatively low, its contribution to the collective dose is significant due to the frequent use of this examination. About 30%–40% of all diagnostic X-ray examinations are reported to be a chest X-ray [2–4]. The associated estimated contribution to the collective dose is about 18% [2]. Thus, optimization of image quality and radiation dose in chest radiography has become an important area of research over the last decade.

With the traditional film-screen systems, the range of patient dose resulting from chest radiography is inherently limited by the speed class. Due to small dynamic range, film-screen radiography images appear underexposed at low dose and overexposed at high dose parameters [5]. With digital radiography, under- or overexposure is unlikely to occur because of its wide dynamic range and window functions (window width and window level) [6]. Therefore, imaging parameters commonly used in film-screen radiography cannot be directly transferred to digital chest radiography imaging as increased dynamic range of the detector ensures sufficient visualization of both the lungs and the

☆ Conflict of interest: none.

☆☆ The study was partly supported by the National Science Council of Taiwan (NSC09-8291-2-I04-000-1) and the travel grant provided by Australian Academy of Science as International Science Linkage between Curtin University and Central Taiwan University of Science and Technology.

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doi:10.1016/j.clinimag.2011.09.006

mediastinum, even at low kilovoltage settings [7]. Hence, lowering the kilovoltage settings is technically feasible with digital radiography systems, and studies have shown that detection of lung lesions is not compromised with reducing the kilovoltage settings [8–10].

Despite the promising results about reduction of kilovoltage settings while still achieving diagnostic images as reported by researchers, very few studies have investigated the performance of different digital radiography systems [11,12]. Thus, the purpose of this study was to compare different computed radiography (CR) and direct radiography (DR) systems in terms of image noise and image quality based on a chest phantom.

2. Materials and methods

2.1. Phantom design

A chest phantom was constructed so that the response of the imaging system will be similar to that of a normal posterior–anterior chest radiographs in terms of scatter properties and attenuation and grey level, as well as for the purpose of repeated exposures and measurements of image noise [Fig. 1]. The phantom was made from sheets of plastic tubing, copper, and aluminium, which were shaped to resemble frontal radiographic projections of human thoracic structures [13]. The lungs, heart, ribs, and upper abdomen were oriented and arranged to simulate a projection of a normal thorax and sandwiched between Perspex to provide X-ray attenuation and scatter properties similar to those of a human chest anatomy. Regional test objects were incorporated into the chest phantom for image quality assessment in the lungs, heart, and retrodiaphragmatic areas. Each test object contained a matrix of low-contrast objects for contrast detail assessment. A line-pair phantom was included in the lung-equivalent, heart-equivalent, and subdiaphragm-equivalent regions for the assessment of spatial resolution.

2.2. Imaging systems and imaging parameters

Three different CR systems and three different DR systems were used in the study to compare the image quality and digital system performance. The three CR systems were Konica CR1 (KXO-12R), Konica CR2 (DHF-155 H), and Philips CR (DMC CHBH), respectively. Two Konica CR systems belong to different generations, with Konica 1 indicating the latest model and Konica 2 the old model. The three DR systems were Siemens DR (Axion Aristos), Toshiba DR (KXO-50R), and Philips DR (Digital Diagnost), respectively.

Imaging parameters for chest X-ray were selected with mAs of 1.0, 2.0, 4.0, 8.0, and 10.0 and tube voltage of 100, 110, and 120 kVp, respectively. Due to availability of the system characteristics in the Philips CR system, the kVp was chosen to be 102, 109, and 125 kVp, respectively. Source to image distance was set at 180 cm for all of the exposures. Fifteen chest radiographic images were obtained for each digital system using the above variable imaging parameters. Thus, there were altogether 90 images obtained from these different systems with variable exposure parameters (5 mA ranges×3 kVp ranges×3 CR/3 DR systems).

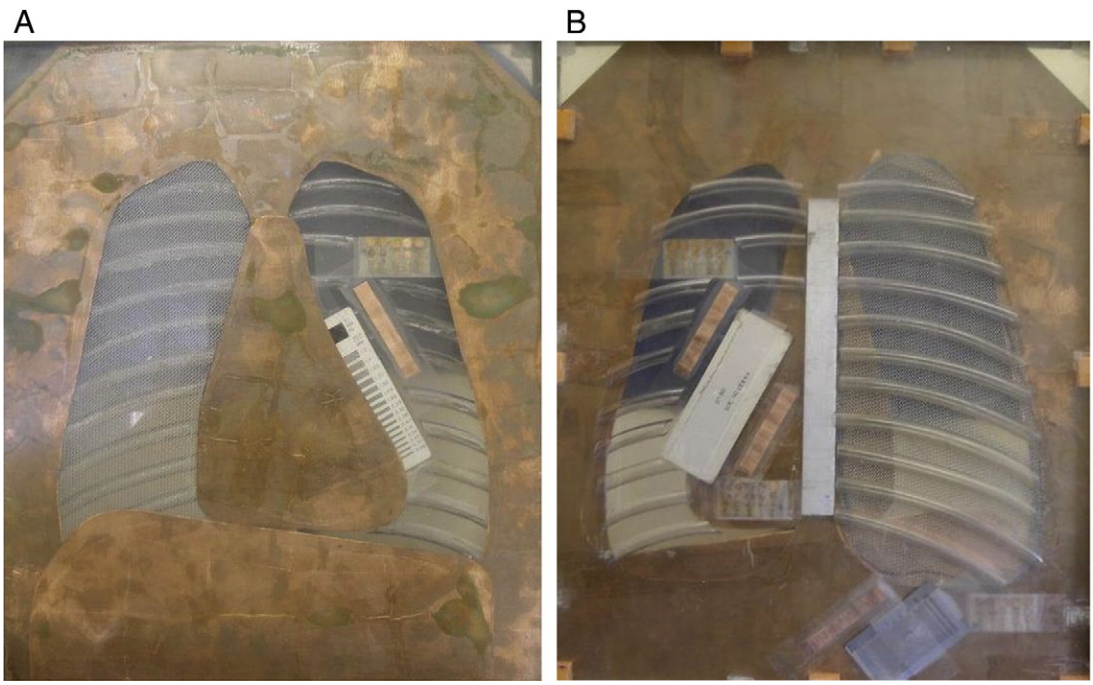

Fig. 1. Chest phantom used in the experiments (A, anterior view; B, posterior view).

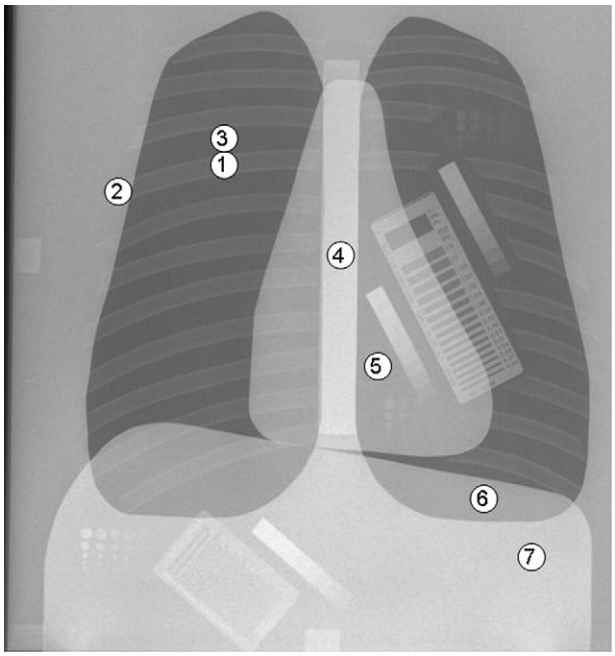

Fig. 2. Measurements of image noise at seven ROIs: ROI 1, middle right fourth rib; ROI 2, area to the left of the right fourth rib (soft tissue reading); ROI 3, interspace between third rib and fourth rib; ROI 4, middle of the spine; ROI 5, heart beside the step wedge; ROI 6, area below the diaphragm; ROI 7, left side of abdomen.

2.3. Measurement of image noise standard deviation

Quantitative measurements of image quality were conducted at seven regions of interest to determine the relationship between image noise, imaging parameters, and different digital systems. Fig. 2 shows the selected regions of interest (ROIs) that were chosen in the chest radiograph for measurements of image noise. Image noise was defined as the standard deviation (S.D.) of the pixel value within the region of interest. The S.D. is well recognized as the standard method used to reflect the degree of noise when imaging parameters are changed [14].

All of the original chest radiographic images were saved in DICOM (digital imaging and communication in medicine) format, burned into CDs, and then transferred to a separate workstation for measurements of image noise using a commercially available software Analyze V 7.0 (Analyze V, AnalyzeDirect, Inc., Lenexa, KS, USA).

2.4. Measurement of entrance skin dose

Entrance skin dose (ESD) was measured using a solid-state detector (PTW Diados, Germany) on the chest phantom during each image acquisition with all digital chest systems under variable imaging parameters. The detector was fixed on the posterior part of the phantom.

2.5. Statistical analysis

A three-factor split plot design (also known as a repeated-measures design) was employed to examine the effects of (a) two technologies: CR and DR; (b) three tube voltages: 100, 110, and 120 kVp; and (c) five tube currents: 1.0, 2.0, 4.0, 8.0, and 10.0 mAs. Six digital systems were chosen for the study: three involving CR and another three involving DR. These six units comprised the main plots (or, in repeated-measures terms, the "subjects") of the design. The 15 cross combinations of three voltages and five currents constituted the subplots (or within-subject factors) of the design, executed within each of the six main plot units. Factor main effects, two-factor interaction effects, and the three-factor interaction effect were all tested in the analysis of variance (ANOVA). Each of the seven ROIs provided 90 image noise (S.D.) observations for statistical analysis.

Table 1
Imaging parameters of CR and DR systems with corresponding measured ESD

kVp/mA	ESD measured with CR systems (mGy)			ESD measured with DR Systems (mGy)		
	Konica CR1	Konica CR2	Philips CR	Siemens DR	Toshiba DR	Philips DR
100/1.0	0.017	0.030	0.035	0.035	0.031	0.020
100/2.0	0.034	0.055	0.075	0.070	0.072	0.040
100/4.0	0.084	0.105	0.150	0.155	0.157	0.085
100/8.0	0.167	0.215	0.300	0.310	0.329	0.175
100/10.0	0.199	0.275	0.370	0.385	0.414	0.220
110/1.0	0.020	0.035	0.040	0.040	0.037	0.025
110/2.0	0.040	0.070	0.085	0.090	0.088	0.050
110/4.0	0.105	0.150	0.170	0.185	0.189	0.105
110/8.0	0.205	0.285	0.340	0.370	0.399	0.210
110/10.0	0.240	0.355	0.425	0.460	0.505	0.265
120/1.0	0.025	0.045	0.055	0.055	0.055	0.035
120/2.0	0.045	0.085	0.110	0.110	0.100	0.070
120/4.0	0.110	0.175	0.225	0.225	0.220	0.150
120/8.0	0.225	0.340	0.445	0.450	0.470	0.290
120/10.0	0.270	0.430	0.560	0.565	0.600	0.360
Mean dose (mGy)	0.12	0.17	0.22	0.23	0.24	0.14

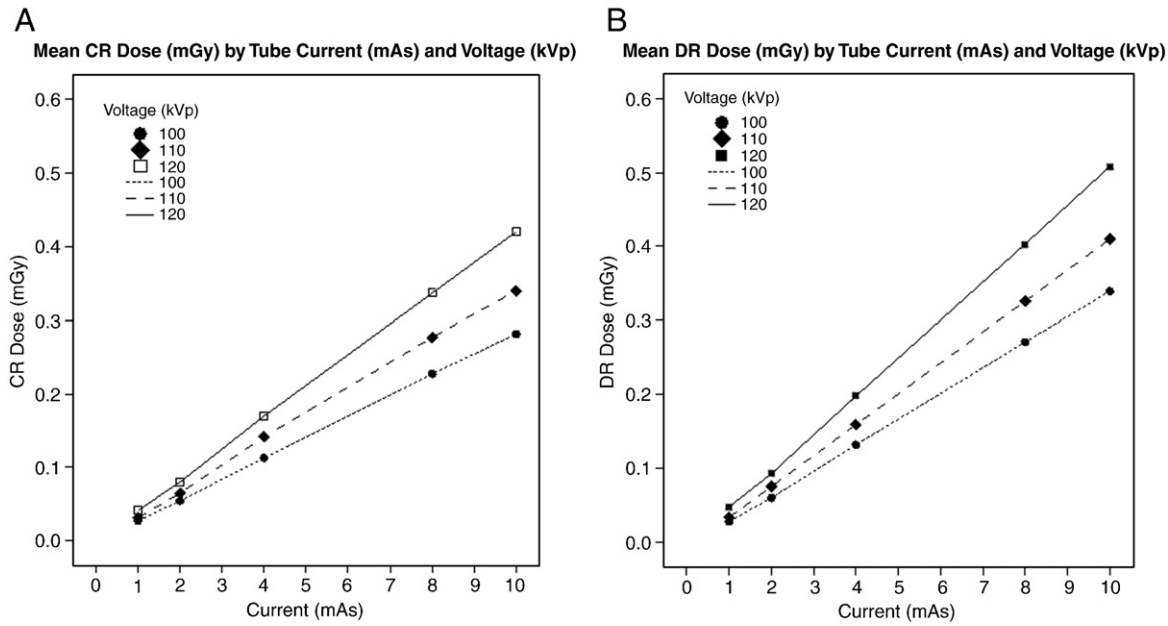

Fig. 3. Relationship between mean CR dose and kVp and mA (A); mean DR dose in relation to kVp and mA (B).

CR and DR dose was measured at the six digital chest radiography systems. The ANOVA model was simplified to a randomized block design, where the digital system constituted three blocks and each block contained the 15 voltage/current combinations described above. Factor main effects and the two-factor interaction effect were all tested in the ANOVA.

Statistical analyses were computed with NCSS 2007, and the response profile charts were prepared with SPSS version 15 (SPSS, Chicago, IL, USA).

3. Results

Table 1 shows the image acquisition parameters and radiation exposure for the six digital chest radiography systems. As shown in the table, the interesting finding of our results is that the CR and DR systems performed variably in terms of ESD, with the lowest mean ESD produced by the Konica CR1 system (mean dose: 0.12 mGy) and the Philips DR system (mean dose: 0.14 mGy). ESD increased significantly with the increase of the kVp and mAs ($P<.001$) in both CR and DR systems, and this is especially apparent when the mAs were increased, demonstrating the linear relationship with the mAs. Fig. 3 shows the relationship between ESD and kVp and mAs in CR and DR systems.

Result showed that the S.D. in different parts of CR and DR images was found to be significantly different among the different digital systems ($P<.0001$) (Fig. 4). S.D. measured with CR systems was generally higher than that measured with DR systems in all of these seven ROIs, indicating the

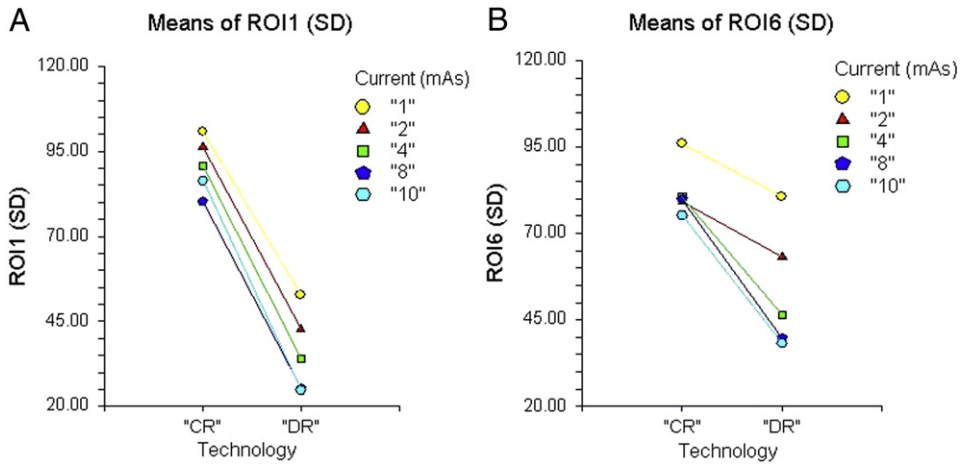

Fig. 4. Mean S.D. measured at selected ROIs with CR and DR systems and their relationship to the mA settings (A, B). In most of the situations, the S.D. measured with CR systems was lower than that measured with DR systems.

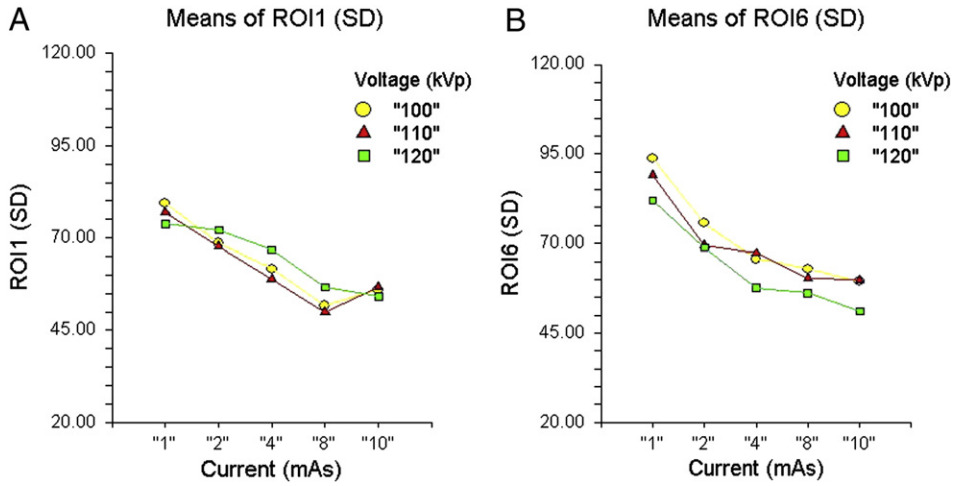

Fig. 5. Mean S.D. measured at selected ROIs in relation to the kVp and mA settings (A, B). As shown in these graphs, a significant relationship was found between S.D. and mA, but there was no significant difference between S.D. and kVp changes.

superiority of DR images over CR image with respect to noise. This is especially apparent for Konica CR2 as the S.D. measured with this digital system is significantly higher than that measured with other digital systems.

S.D. decreased significantly when the mA was increased ($P<.001$) in both CR and DR exposures; however, there was no significant difference of S.D. when the kVp settings were increased from 100 to 120 (or 125) ($P=.08–.85$). Fig. 5 is the ANOVA of the data demonstrating the relationship between the mean S.D. measured at the selected ROIs of CR systems and corresponding kVp and mA values. Again, these plots show the significant interaction between S.D. and mAs, but S.D. is less dependent on the kVp values.

Despite increasing mAs to a higher range, most of the CR and DR images are diagnostic with demonstration of these anatomical structures and the incorporated objects and line-pair phantoms, except in the Konica CR1 and Siemens DR systems. Images acquired with two these digital systems were uninterpretable when the mA was increased to more than 4.0. The S.D. measured with these two digital systems was decreased by more than 80% when the mA increased from 4.0 to 8.0. Fig. 6 is an example showing a number of chest radiographic images acquired with Philips CR with 100 kVp but different mA settings, while Fig. 7 is another example of chest radiographic images acquired with Toshiba DR system with 100 kVp and different mA ranges. In spite

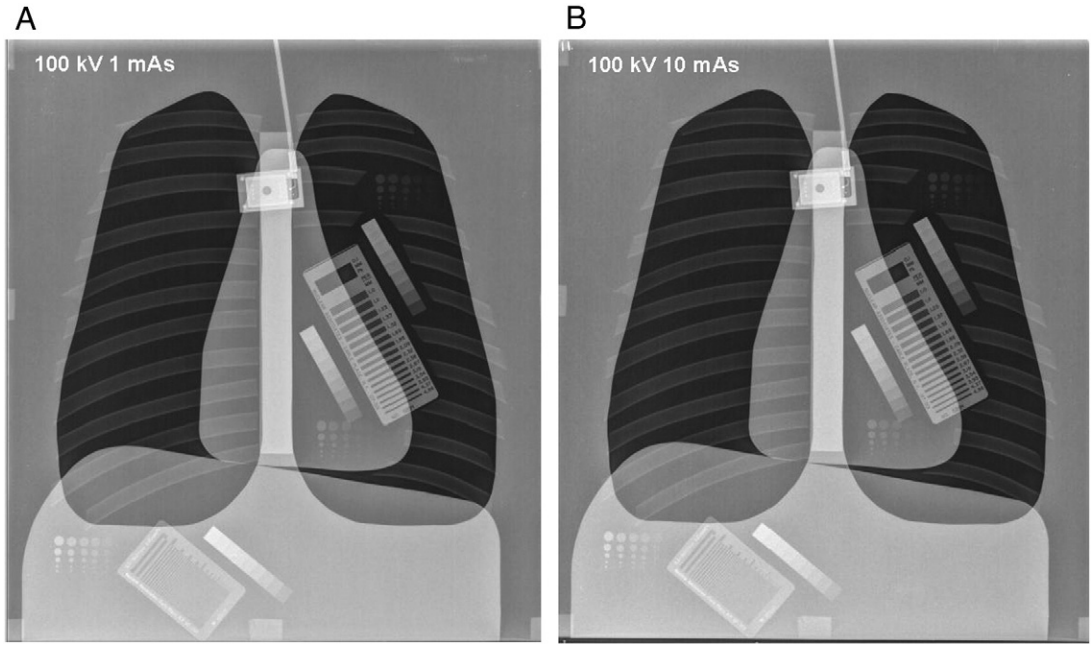

Fig. 6. Chest radiographic images were acquired using Philips CR system with 100 kVp and 1.0 and 10.0 mA (A, B). Dose reduction was significant when the lower mAs were used compared to higher mAs, but with no significant effect on the image visualization.

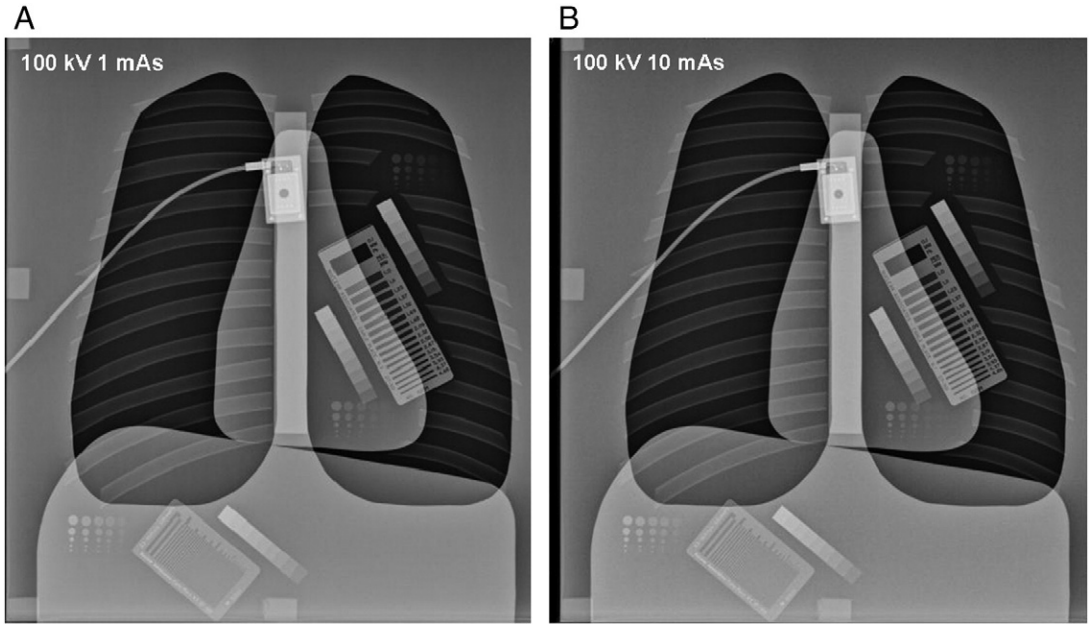

Fig. 7. Chest radiographic images were acquired using Toshiba DR system with 100 kVp and 1.0 and 10.0 mA (A, B). There is no significant difference among these images in terms of image quality, but dose reduction was significantly different when the lower mAs were used compared to higher mAs.

of the mA changes, low-contrast objects and line-pair phantom were clearly visualized in these CR and DR images as shown in these figures. It is noted that DR images offer better resolution than CR images in demonstrating these objects and line-pair phantom.

4. Discussion

This study has two important findings which are considered useful for clinical application: first, different digital radiography systems perform differently in terms of image noise and entrance skin dose; thus, imaging parameters used in one system cannot be directly transferred to another system. Second, image noise is mainly determined by the mAs and is less dependent on the kVp changes, indicating that kVp can be reduced from 120 to 100 with reduction of radiation dose without compromising image quality.

Owing to the variety of X-ray units used in clinical practice, X-ray examinations cannot be standardized. Therefore, optimization is necessary for each particular X-ray unit and for each X-ray examination [15]. This is confirmed in this study due to the variable performance of different digital systems. Similar results have been reported by Kroft et al. [11] in their study based on an anthropomorphic chest phantom. In their report, eight different digital chest systems were assessed with regard to the diagnostic performance of detection of simulated chest disease, and significant differences were found among these digital chest systems. Radiation dose also varied among the digital systems. Our results are consistent with the findings of Kroft et al. to a greater extent, especially in terms of the variable performance of different systems. However, radiation exposure (ESD) was found to be quite similar in four out of six digital systems in our study which included two CR and two DR systems. According to the study by Kroft et al., the DR systems significantly outperformed the CR system with respect to image quality, whereas the dose levels acquired with DR systems were lower. Although we did not notice the dose difference between CR and DR systems in our study, DR outperformed CR for image visualization, as shown in Figs. 4, 6, and 7.

In the past decades, a shift has occurred from the principle of "image quality as good as possible" to "image quality as good as needed." Radiation dose to patients should be as low as reasonably achievable, while still providing diagnostic image quality [16,17]. The relationship between dose and image quality can be assessed quantitatively and qualitatively. Quantitative assessment involves objective physical measurements, such as modulation-transfer function, detective quantum efficiency or contrast-to-noise ratio, and contrast-detail studies. Qualitative assessment mainly refers to the observer performance studies (lesion detection or quality rating). However, studies differ in how much a radiologist's perception and abilities (or experience in reading images) are involved and how well they represent the clinical situation. Schaefer-Prokop et al. [18] in their recent extensive review of 27 studies that investigated dose requirements and image quality of various digital chest radiography systems indicated that the majority of studies applied only one methodology. They pointed out that there is increasing interest in how well objective measures reflect the subjective grading of image quality and how much small differences in visual grading affect diagnostic performance under clinical conditions. In most of the studies, the ranking of system performance was identical for both methodologies

[19–21]. Thus, we believe that the analysis involving only the objective assessment of image quality and dose in this study is valid, so results can be recommended for clinical practice.

The inverse correlation between radiation dose and image contrast is eliminated with digital systems. Image contrast and brightness can be optimized independently. Therefore, "film blackening" due to higher doses does not exist with digital systems [22]. This is observed in most of the digital systems included in our study. Surprisingly, the "blackening effect" because of overexposure (higher mAs) was observed in two digital systems (one CR and one DR). This may be due to the system characteristics or relatively sensitive response to the overexposure, although further investigation in this aspect needs to be performed.

A number of studies have been reported in the literature to investigate the possible clinical effects of dose reduction in digital chest radiography and how low dose reduction can be achieved [23–25]. A 50% dose reduction was found to be feasible in a variety of simulated chest pathologies without significant loss in diagnostic performance [23,24]. Another study using subjective assessment of image quality reported that lowering the radiation dose from 100% to 50%, 25%, or 12% had no effect on lesion detection in the lungs, but had a prominent effect on lesion detection in the mediastinum [24]. Our results are consistent with these reports regarding the dose reduction in relation to the image quality. A 44% dose reduction was achieved in our experiments without significant effect on image quality in these digital chest radiographs. This again emphasizes the fact that radiation dose of digital chest radiography can be minimized to a greater extent while still acquiring diagnostic images.

Most of the previous studies that evaluated the potential of dose reduction of chest radiography systems compared CR with film-screen or CR with DR systems [7,8,20,23–27]. To the authors' knowledge, very few studies have compared the performance of different digital systems [11,12,28]. Although the transition from conventional film-screen imaging to digital imaging has been almost completed over the last decade, imaging parameters used in conventional radiography must be adjusted before adopting them directly to the digital systems. Therefore, optimization of the imaging parameter is still necessary since there is considerable heterogeneity across the digital systems and each system performs differently according to our and other reports. Different from previous reports, our analysis was based on comprehensive measurements of the ROIs in representative anatomic locations of the lung field and upper abdomen. The results from this study based on these different digital systems could be used to guide judicious use of the digital systems in chest radiography.

Diagnostic reference levels (DRLs) are defined as dose levels for typical examinations for groups of standard-sized patients or standard phantoms for broadly defined types of equipment. DRL is a tool used in the optimization process. The mean dose measured with the digital systems included in this study is within the recommended ranges for chest radiography (0.25–0.3 mGy) [22]. Since digital systems have greater freedom in setting the dose level without overexposure, adherence to DRL is of paramount importance to avoid dose levels to the patient that do not contribute to the clinical diagnostic purpose of a medical imaging task.

This study suffers from several limitations. Firstly, no subjective assessment was performed in this study. Since there were no simulated lesions such as nodules in our phantom, subjective evaluation of the phantom images does not seem to provide valuable information; especially, observer's perception on lesion detection is an essential component for optimization of imaging parameters. Secondly, the parameter settings for individual systems were not identical to daily clinical conditions. Consequently, the authors cannot rule out that the performance per system may have been substantially affected by dose. Thirdly, although six digital systems were tested, some common models such as Agfa and Fuji systems were not included in the study. Further studies with inclusion of various systems are needed to verify these results. Fourthly, the authors cannot ensure that the differences observed in this study are not influenced by possible inappropriate setup parameters as the study was carried out at different clinical centers. Finally, the current study was based on a chest phantom without simulating pathological lesions. Insertion of simulated lung nodules with comparison of the performance of different digital systems for detection of lesions is under investigation in our research group.

The authors conclude from the results that there is significant performance difference among different CR and DR systems in chest radiography imaging. Radiation dose can be reduced by up to 44% through lowering the kVp from 120 to 100 without affecting the image quality. The overall performance of DR system was superior to that of CR system. When comparing digital systems and evaluating the potential for dose reduction, attention should be paid to which type of CR or DR system is used in a clinical environment.

Acknowledgments

The authors would like to thank Mr. Gil Stevenson for his assistance in the statistical analysis. We are grateful to the assistance of the radiographers from the following hospitals at TaiChung, Taiwan, for our study: LinShin Hospital, Buddhist Tzu Chi Tai Chung Hospital, San Da Radiology Clinic, Chung Shan Medical University Hospital, and Xiu Chuan Hospital.

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