New Developed DR Detector Performs Radiographs of Hand, Pelvic and Premature Chest Anatomies at a Lower Radiation Dose and/or a Higher Image Quality

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Abstract A newly developed Digital Radiography (DR) detector has smaller pixel size and higher fill factor than earlier detector models. These technical advantages should theoretically lead to higher sensitivity and higher spatial resolution, thus making dose reduction possible without scarifying image quality compared to previous DR detector versions. To examine whether the newly developed Canon CXDI-70C DR detector provides an improved image quality and/or allows for dose reductions in hand and pelvic bone examinations as well as premature chest examinations, compared to the previous (CXDI-55C) DR detector version. A total of 450 images of a technical Contrast-Detail phantom were imaged on a DR system employing various kVp and mAs settings, providing an objective image quality assessment. In addition, 450 images of anthropomorphic phantoms were taken and analyzed by three specialized radiologists using Visual Grading Analysis (VGA). The results from the technical phantom studies showed that the image quality expressed as IQF_{INV} values was on average approximately 45 % higher with the CXDI-70C detector compared to the CXDI-55C detector. Consistently, the VGA results from the anatomical phantom studies indicated that by using the CXDI-70C detector, diagnostic image quality could be maintained at a dose reduction of in average 30 %, depending

on anatomy and kVp level. This indicates that the CXDI-70C detector is significantly more sensitive than the previous model, and supports a better clinical image quality. By using the newly developed DR detector a significant dose reduction is possible while maintaining image quality.

Keywords Digital radiography · Image quality · Radiation dose · Equipment · Image perception · Phantoms · Imaging · Radiography

Introduction

Conventional X-ray imaging has been “digitized” and is rapidly developing. One of the latest technological advances in the field of digital radiography (DR) is a wireless DR detector (CXDI-70C, Canon, Tokyo, Japan) with high fill factor and small pixel size, presented at the European Congress of Radiology 2010 as a revolutionary product in DR [1]. Instead of having the photo sensitive areas (pixels) and the readout wirings and electronics (thin film transistor (TFT)) in the same layer, in the new detector these have been structured on multiple layers. Beneath the scintillator layer is a layer comprised primarily of the photo-sensitive elements, and underneath that is a separate layer for the readout wires and the TFT and all is built on a common base [2]. In this way the new detector gains a much higher fill factor, significantly improving its ability to exploit incoming radiation [3]. As the TFT-electronics no longer occupy space in the detector layer, the multiple layer design also allows for smaller pixel sizes without compromising the fill factor. In theory the new detector configuration should not cause any decrease in signal to noise ratio (SNR) with smaller pixel sizes as the traditional single layer TFT-detectors suffered from [3]. However, it is still not clear whether the new detector design will actually make it possible to reduce radiation dose without impairing image quality.

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Dose reduction without loss of image quality is of particular interest in pediatric imaging, as children are the most sensitive patient group [4–6]. Furthermore, reducing radiation dose while maintaining optimal image quality is a relevant topic in examinations involving radiosensitive body areas, such as pelvic examinations, and particularly relevant for patients that undergo repeated examinations, such as rheumatoid arthritis patients [7]. The higher spatial resolution is particularly interesting in examinations demanding accurate rendering of small anatomic structures or pathology changes, as for instance in premature chest or hand examinations focusing on rheumatoid arthritis [8, 9]. A more sensitive DR detector will support the ALARA principle.

In this study, two flat panel detectors from the same manufacturer (Canon, Tokyo, Japan) were investigated with respect to image quality and patient dose. The CXDI-70C is rather new and is a development of the previous detector version, the CXDI-55C, which was released a year earlier. There are similarities in the characteristics of the two detectors; however, there are some differences which are likely to affect both image quality and patient dose. The detector material is CsI for both detectors and the thickness of the scintillator is the same [10]. The pixel pitch is smaller for the CXDI-70C detector (125 μm) [2] compared to the 55C detector (160 μm) [11]. Furthermore the fill factor for the 70C detector is higher (87 %) [2] compared to the 55C detector (55 %) [10]. The smaller pixel pitch and the higher fill factor of the 70C detector suggest that this detector should be able to produce images of higher image quality and/or be operated at a lower patient dose than the 55C detector.

The aim of this study was to examine whether the new detector design could increase image quality and/or reduce dose in hand, pelvic and premature chest examinations.

Materials and Methods

For hand, pelvic and premature chest anatomy two different image sets were produced and analyzed; one included 450 radiographs of a technical phantom and the other included 450 radiographs of three different anthropomorphic phantoms. The images were produced with various exposure settings and two different DR detectors.

DR System, Detector and Software

All radiographs were produced using a Canon DR system equipped with either the CXDI-55C or the CXDI-70C detector, both including MLT(S) Multi Frequency Processing (MFP) software version: CXDI Control Software NE V1.3.

For each exposure, the Region of Interest (ROI) was manually set to cover precisely the same object area, and the Exposure Index, Reached EXposure Index (REX) value, was recorded. According to clinical practice, experience and a former study [12], the preferred REX for optimal image quality should be between 100 and 450 depending on dose, ROI and image processing settings. The processing settings that were used were based on documented research [3, 13] and recommendations by the manufacturer for clinical practice [14] and kept constant for all images taken.

Phantoms

A conventional Contrast Detail RADiography phantom (CDRAD) was used as the technical phantom [15]. The CDRAD phantom experiment was conducted using PMMA plates of various thickness placed above the phantom, 5 cm for hand, 20 cm for pelvic and 1 cm for the premature chest anatomy corresponding to the soft tissue of the included anatomies. The results of the CDRAD images were registered quantitatively, thus yielding an objective assessment of image quality [3, 13]. By using a technical phantom only, the results would be difficult to compare directly to the anatomical structures of patients in clinical practice. This was the reason why the combination of anthropomorphic and technical phantoms was considered most optimal for this study, Fig. 1. The anthropomorphic phantoms used for hand (Sectional Hand Phantoms, XA231R, The Phantom Laboratory, New York, USA) and pelvic (Sectional Lower Torso Phantom, SK 250, The Phantom Laboratory, New York, USA) examinations consisted of genuine bone in anatomically correct positions and cast in PMMA. The anthropomorphic premature chest phantom (Neonatal Chest Phantom, Gammex 610, Middleton, USA) showed a pneumothorax on the right lung. The sizes of the anthropomorphic phantoms used were similar to real patients (adult for the hand and pelvic examinations and premature children for the chest examination), thus making it possible to assess image quality almost as if it were a real patient [16–18].

Technical Settings

The exposures of both the technical and the anthropomorphic phantoms were carried out with a total filtration of 5.2 mm Al, and with no grid. Source-to-detector distance (SID) was set to 100 cm and the field sizes were chosen to correspond to the sizes of the anthropomorphic phantoms and to the size of the technical phantom, respectively. The images were taken using various combinations of exposure values (kVp and mAs), the highest exposure value being similar to the clinically used parameters (Table 1). The image sets of 450 images (of the

Fig. 1 Examples of radiographs of the four phantoms used in the study: **a** CDRAD, **b** hand, **c** pelvic, and **d** premature chest. See main text for further details

technical and anthropomorphic phantoms) were a result of 10 repeated images for every exposure level shown in Table 1.

At every exposure level the skin dose was measured with an Unfors Xi dosimeter, the Dose Areal Product (DAP) and the REX values recorded, each as an average value of 10 exposures. All parameters except for the exposure settings (kVp and mAs) were kept constant for both the CXDI-55C and CXDI-70C experiments.

Image Analysis

The CDRAD images were assessed with the CDRAD analysis software version 2.0 from Artinis [13]. The software computed an objective evaluation of image quality, where the result was presented as a Contrast-Detail (CD) curve with a corresponding Image Quality Figure Inverse (IQF_{Inv}) value [15, 19]. Average IQF_{Inv} values of 10 images were used as the result for every exposure setting.

The anthropomorphic phantom images were assessed using relative Visual Grading Analysis (VGA) [20]. VGA is a way of quantifying subjective image quality allowing for quantitative studies, even for large amounts of images [21, 22]. The relative VGA was conducted by comparing all experimental images with a reference image produced using the previous detector model from Canon, CXDI-55C. The reference image was exposed at 70 kVp for pelvic and premature chest, and at 50 kVp for the hand examination. The highest mAs exposure settings used in each anatomy experiment corresponded to the highest SNR and therefore most optimal image quality in clinical practice and this image was therefore used as the reference image.

The VGA assessments of an image can be summarized in a single score using the following equation [23].

$$VGAS = \frac{\sum_{O,I} S_c}{N_i N_o}$$

Where:

S_c is the individual score for observer O (radiologist) and image criteria I

N_i is the total number of image criteria

N_o is the total number of observers

The VGA scale steps belong to an ordered qualitative variable (ordinal scale) and not to a discrete quantitative variable (interval scale). Although the VGAS lacks statistical validity [24], we still think the VGAS is an indication of whether one technique is better than another, and therefore it was used in this paper.

For this study, the image criteria were based on Bontrager's international procedural book [25] and the European Guidelines [4, 26], where criteria such as "exposure without movement" were eliminated since this was not relevant in a phantom study (Table 2).

A total of 450 test images were scored in accordance with the VGA scale from −2 to +2 as shown in Table 3 [27–29].

The images were read 'blind' by three specialized radiologists, all having 10 to 20 years of experience in digital image based diagnostics and PACS [30, 31]. In order to reduce bias in the VGA scores the radiologists were given 'unlimited' time and allowed to work undisturbed. The VGA experiment was undertaken at the same physical location with the same PACS system, diagnostic monitor and physical surroundings

Table 1 Exposure parameters used in the experiments (setting used in clinical practice are marked with bold and asterisk)

Hand	kVp	45	50*	55			
	mAs	0.2	0.5	1	1.6	2.5*	
Pelvic	kVp	60	70*	80			
	mAs	2.5	5	10	16*		
Premature chest	kVp	50	60*	70			
	mAs	0.1	0.2	0.4	0.8	1.2	1.6*

Table 2 Image criteria for the experimental images of the anthropomorphic phantoms [4, 25, 26]

Hand	
1	Visualization of periarticular soft tissue level
2	Sharpness of the demarcation between cancellous bone and compact bone
3	Sharpness of trabecular structure
Pelvic	
1	Visualization of the head, neck and trochanter of the femora, the sacrum, sacroiliac joints, pubic and ischial rami of the pelvic
2	Visualization of periarticular soft tissue level
3	Sharpness of the demarcation between cancellous bone and compact bone
4	Sharpness of trabecular structure
Premature chest	
1	Sharpness of Carina of the trachea
2	Sharpness of the bronchus lobe
3	Sharpness of the heart limitation
4	Sharpness of trabecular structure
5	Sharpness of pneumothorax
6	Visualization of vascular pattern according to costae

[23, 27]. To examine intra-observer agreements 10 % of the 450 anthropomorphic images were repeatedly presented to the radiologists in the VGA experiments.

Statistics

Data were analyzed and displayed descriptively according to their type.

The IQF_{Inv} values were analyzed using 95 % confidence level 2 sided t tests to test for differences in image quality (and thus dose efficiency) between the two detectors CXDI-70C and CXDI-55C.

VGA scores were used to compare differences in dose efficiency and diagnostic image quality between the two detectors and analyzed using a Wilcoxon–Mann–Whitney test for non-parametric unpaired data.

Inter-observer agreement was assessed by Randolph's fixed-marginal multirater Kappa value [32], when raters are forced to assign a certain number of cases to each category. Values of $Kappa$ can range from -1.0 to 1.0 , with -1.0 indicating perfect disagreement below chance, 0.0 indicating agreement equal to chance, and 1.0 indicating perfect agreement above chance. A rule of thumb is that a $Kappa$ of 0.70 or above indicates

adequate inter-observer agreement. The intra-observer agreement was evaluated by a Bland–Altman analysis for each radiologist.

All statistical analyses were performed using STATA 12 [33].

Results

The REX values for each exposure showed a higher sensitivity (higher REX value) of the CXDI-70C detector as a function of increasing kVp and mAs, compared to the CXDI-55C. See Table 4 for the REX values at each detector for each anatomy.

On average the CXDI-70C had 66 % higher REX average values for the hand phantom, 58 % higher REX for the pelvic phantom and 52 % higher REX value for the premature chest phantom.

The IQF_{Inv} values and VGA scores for all exposures are shown in Figs. 2, 3, and 4, where the error bars show the 95 % confidence intervals for the average values based on $n=10$ measurements at every mAs value.

The other kVp levels, not shown here, show the same tendency as the ones shown in these graphs, i.e. IQF_{Inv} and

Table 3 VGA scale for image quality score [21]

Score	Definition of score
−2	Clearly worse than the reference image
−1	A little worse than the reference image
0	Comparable with the reference image
+1	A little better than the reference image
+2	Clearly better than the reference image

Table 4 Variation in REX values for the two detectors and different anatomy areas

Detector	Phantom		
	Hand	Pelvic	Premature chest
CXDI-55C	38–923	25–648	38–2,878
CXDI-70C	58–1,473	18–1,014	52–4,367

Fig. 2 IQFinv values and VGA Score for the hand phantom at 50 kVp

VGAS increase with mAs. The dose differences between the 10 repeated exposures and the REX values at every dose level were negligible and therefore interpreted as the same between the two detectors.

The CXDI-70C and CXDI-55C performances were compared using 2-sided *t* tests on the IQFinv values from all kVp and mAs combinations. The differences between the IQFinv values for the CXDI-70C and CXDI-55C detectors, as a percentage in favour of the CXDI-70C detector, are shown in Table 5 for all kVp and mAs value settings. *p* value were all found to be <0.05.

The VGAS scores for the two detectors were compared using a Wilcoxon–Mann–Whitney test for unpaired data, and showed a statistical significance difference in favour of the CXDI-70C detector, with *p* < 0.05 for all anatomies and for every mAs values examined. Boxplot diagrams are shown

here to visualize the difference in the effect found by the Wilcoxon–Mann–Whitney test for the VGA result, Figs. 5, 6, and 7.

The intra-observer agreement was evaluated by a Bland–Altman analysis for each radiologist. A relatively good intra-observer agreement between all the three radiologists was found. The limits of agreement, bias ± 2SD was for radiologist 1 [−0.27, 0.27], radiologist 2 [−0.33, 0.33] and for radiologist 3 [−0.27, 0.27].

To compare the inter-observer agreement between the three radiologists, the following Kappa values are calculated for hand, pelvic and premature chest images by the image criteria shown in Table 2. The Kappa values showed a spread from 0.25 to 0.42 for the hand, 0.33–0.36 for the pelvic and 0.23–0.57 for the premature chest phantom.

Fig. 3 IQFinv values and VGA Scores for the Pelvic phantom at 70 kVp

Fig. 4 IQF_{inv} values and VGA Scores for the premature chest phantom at 60 kVp

Discussion

Based on the recorded REX values, the sensitivity of the CXDI-70C detector was on average 59 % better than the CXDI-55C detector for all anatomic regions and exposure settings included in this study. The sensitivity of the CXDI-70C detector outperforms the CXDI-55C detector by 66 % for the hand, 58 % for the pelvic and 53 % for the premature chest examinations for all kVp settings, respectively. The largest

difference in REX values between the two detectors was seen at the low kVp and mAs settings, where the CXDI-70C is clearly above REX value 100, which is considered as the lower limit for achieving optimal image quality in clinical practice. As the same processing settings were used for all images, and all images were recalculated on the background of an identical positioning of ROI, the recorded REX value can be regarded as an indicator of the image signal displayed from the detector in the X-ray. Hereby the images could be

Table 5 The percentage difference in IQF_{inv} between the CXDI-70C compared to CXDI-55C detector for the hand, pelvic and premature chest anatomies at the different kVp and mAs values

Hand				
mAs	45 kVp [%]	50 kVp [%]	55 kVp [%]	
0.2	67	96	59	
0.5	30	45	28	
1.0	23	22	17	
1.6	20	20	19	
2.5	18	26	13	
Average	32	42	27	34 %
Pelvic				
mAs	50 kVp [%]	60 kVp [%]	70 kVp [%]	
2.5	50	50	44	
5	60	44	91	
10	43	64	79	
16	60	40	76	
Average	53	50	73	59 %
Premature chest				
mAs	50 kVp [%]	60 kVp [%]	70 kVp [%]	
0.1	76	64	55	
0.2	56	60	55	
0.4	67	62	37	
0.8	46	30	24	
1.2	23	20	16	
1.6	20	20	16	
Average	48	43	34	42 %

Fig. 5 Boxplot of the VGA scores for the two detectors for the hand anatomy images at 50 kVp

compared and the difference in REX values can be considered an indicator of the difference in sensitivity between the two detectors. Hence, CXDI-70C utilized approximately 59 % more of the incoming radiation compared to CXDI-55C, and can be explained by the difference in fill-factor. Thus theoretically, 59 % higher sensitivity has the potential to allow for an average dose reduction of 37 % ($59/(100+59)$) without impairing image quality.

The published DQE values for the two detector types do not support these findings. The DQE for the CXDI-55C detector at 0 lp/mm and 4.3 μGy (which is a typical dose level used for imaging patients) is 0.7 [11] and for the 70C

Fig. 7 Boxplot of the VGA scores for the two detectors for the premature chest anatomy images at 60 kVp

detector at 0 lp/mm and 4 μGy it is 0.6 [2] according to published data. The small dose difference at the determination of the DQE is unlikely to have a big impact on the results. An increased dose level will increase the DQE but only to a smaller degree, and cannot explain the large difference in DQE of the two detectors. However, in the same publications, the dose levels used for patient imaging are compared to the speed of screen/film systems, i.e. at what speed will this dose level results in an acceptable optical density? Typical patient doses for the two detectors are equivalent to 400–800 screen/film system (for the 55C detector), and 500–1,000 screen/film system (for the 70C detector), indicating that the published DQE values are not in accordance with these typical patient doses neither to our measured REX values.

Fig. 6 Boxplot of the VGA scores for the two detectors for the pelvic anatomy images at 70 kVp

The results from the CDRAD study also showed a clear difference between the two detectors according to an objective score in image quality. Based on the IQF_{Inv} values, the image quality was clearly higher for the CXDI-70C detector compared to the CXDI-55C for the same exposure settings. The T-test of the recorded IQF_{Inv} values from the two detectors yielded a p value far below 0.05, proving a statistically significant better image quality when using the CXDI-70C rather than the CXDI-55C. This difference between the detectors could likely be explained by the smaller pixel pitch (higher spatial resolution) and the higher fill-factor (lower noise) of CXDI-70C detector. In the case of the hand and premature chest examination setting, the largest difference in IQF_{Inv} values were found at the lower kVp and mAs settings, where on the average the IQF_{Inv} values for the 70C detector were 67 % and 76 %, respectively, higher than for the CXDI-55C detector. In the case of the pelvic exposure settings, the largest difference in IQF_{Inv} values was found to be at the high kVp settings (on average 80 % higher for

the CXDI-70C detector), while correspondingly 64 % at the low kVp settings. This can either be explained by a low SNR at low kVp, which means that there was not enough radiation penetrating the thick anatomic object, or by uncertainty in the IQF_{Inv} results. The difference between the two detectors at the highest kVp and mAs settings was only 13 % for hand and 16 % for premature chest, which can be explained by the lower noise level, or again maybe an uncertainty in the IQF_{Inv} results. As IQF_{Inv} is dependent on radiation dose, it will therefore be possible to reduce dose and/or improve image quality by the above mentioned percentages by using the CXDI-70C detector. In summary, the CDRAD experiment indicated that radiation dose in average can be reduced by 31 % ($45/(100+45)$) for all the examined anatomic regions and exposure settings when using CXDI-70C compared with CXDI-55C.

Again our results do not agree with the published DQE values, although they correspond well with the higher fill factor, the smaller pixel pitch and the lower typical patient doses of the 70C detector compared to the 55C detector.

The IQF_{Inv} value is an overall indicator for a combination of spatial resolution and low-contrast resolution, which is why two images with the same IQF_{Inv} can differ in terms of clinical image quality. VGA was used to assess spatial resolution and low contrast resolution separately, together with a subjective assessment of the images' usability as well as the visibility of different anatomic structures, which all pose various requirements to spatial and low-contrast resolution, respectively.

The Wilcoxon–Mann–Whitney test performed for the VGA results did show a significant difference between the detectors for all of the anatomies included in this study. Based on the results of the descriptive statistical data analysis showed in Table 4, as well as on the VGA graphs (Figs. 1, 2, and 3) for all kVp settings, the image quality achieved with the CXDI-70C detector was significantly higher compared to that of the CXDI-55C detector. This was most obvious at the lower exposure levels, where for example hand images taken at 0.5 mAs (using CXDI-70C) and 1.6 mAs (using CXDI-55C) resulted in the same VGA score for the two detectors. In the few exposure levels where CXDI-55C had a higher VGAS score than the CXDI-70C, the REX value for CXDI-70C exceeded 2,500 (i.e. an overexposed image). Since the software was optimized according to the CXDI-55C detector, the lower VGAS of the CXDI-70C images in these cases can therefore be explained by the fact that relevant anatomic structures are burned out because of overexposure, and that this reduces the performance of the CXDI-70C detector. In general this might indicate that images taken on CXDI-70C can become overexposed at lower exposure settings (mAs) than on CXDI-55C, because of CXDI-70C's higher sensitivity. Judging by the extent to which the individual images can be used for diagnostic purposes, CXDI-70C is capable of delivering proper diagnostic images at mAs settings that are 10–69 % lower than for the CXDI-55C estimated from

Figs. 1, 2, and 3, depending on anatomic region and kVp settings. The results therefore suggest that CXDI-55C for every mAs level included at all anatomies included in average requires approximately 30 % (obtained as a simple average between hand, 43 %; pelvic, 24 % and premature chest, 23 %) higher dose to achieve comparable image quality to the reference image compared to CXDI-70C, and thus confirms the big difference in sensitivity between the detectors.

The analysis of the VGA experiment showed small intra-rater variation. As is always the case with a subjective assessment of image quality, some variation was seen, but this is not expected to affect the clarity of the VGA results. The Kappa values, however, which indicate the degree of inter-observer agreement, were much lower than 0.7, suggesting, not uncommonly in these type of experiment, only a fair agreement better than chance. In order to achieve higher generalizability of the results, more than three radiologists should have been involved in the study.

The limitation of this study was the use of anthropomorphic phantoms. The phantoms had a construction similar to human anatomy regarding absorption, and moreover, the hand and pelvic phantoms were made of human bones. These phantoms are thus produced for scientific projects and have been used in several similar studies [34]. The premature chest phantom showed a pneumothorax which was too easily visualized on the radiographs compared to the one seen in clinical practice, which is why the demand on image quality according to this image criteria would be higher when diagnosing real patients. Due to this, the result should be implemented with caution. Software optimization was not done on the anthropomorphic radiographs and the preprocessing was optimized according to the CXDI-55C detector at the clinically used kVp for each type of anatomy and afterwards kept similar for all exposures. This would probably have influenced the image quality, especially the contrast. Therefore the VGA result could be affected by software optimization according to specific detector and kVp levels, in the cases where former projects have shown positive outcomes [12].

Conclusions

The study showed that optimal image quality can be maintained at a lower dose and/or image quality, and could be improved using the CXDI-70C detector for both hand, pelvic and premature chest examinations, based on the technical and anthropomorphic phantom results. The performance of the CXDI-70C detector in terms of IQF_{Inv} values was on average 45 % better than the CXDI-55C detector, depending on anatomy, kVp and mAs levels. According to the VGA results, depending on anatomy and kVp levels, optimal image quality was maintained for the CXDI-70C detector at an estimated dose reduction of 30 % on average. The difference in sensitivity is biggest at the

lower exposure levels for hand and premature chest experiments. However, CXDI-70C still gives the highest difference in VGA scores for pelvic examination at the higher kVp levels, thereby confirming that the increased scattered radiation does not negatively affect image quality too much, even when no grid was used in the experiment. Based on the REX results, for all anatomic regions and exposure settings, an average dose reduction of 37 % can be gained by shifting to the CXDI-70C detector, a significant argument in terms of complying with the ALARA principle.

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