Does digital flat detector technology tip the scale towards better image quality or reduced patient dose in interventional cardiology?

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ABSTRACT

As dynamic flat-panel detectors (FD) are introduced in interventional cardiology (IC), the relation between patient dose and image quality (IQ) needs to be reconsidered for this type of image receptor. On one hand this study investigates IQ of a FD system by means of a threshold contrast-detail analysis and compares it to an image intensifier (II) system on a similar X-ray setup. On the other hand patient dose for coronary angiography (CA) procedures on both systems is compared by Dose-Area Product (DAP)-registration of a patient population. The comparative IQ study was performed for a range of entrance dose rates (EDR) covering the fluoroscopy and cinegraphy working mode. In addition the IQ investigation was extended to a similar study under automatic brightness control (ABC). As well the systematic study of IQ as a function of EDR as the study performed under ABC point to a better IQ for FD in cinegraphy mode and no difference between both systems in fluoroscopy mode. The patient population study resulted in mean DAP values of 31 Gy cm² (II system) and 33 Gy cm² (FD system) (p = 0.68) for CA procedures. As well total DAP as contributions of fluoroscopy and cinegraphy on both systems are not significantly different.

To conclude, we could state that profit was taken from the intrinsic better performance of the FD for cinegraphy mode in producing higher quality images in this mode but without any effect on patient dose for CA procedures.

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1. Introduction

Ever since the use of X-rays in medical applications, equipment developers have aimed for new techniques and refinement for better image quality (IQ) for both static and dynamic examinations. Nowadays, flat detectors (FD) have gained field in both radiography and fluoroscopy, replacing screen-film combinations, digital storage phosphor systems or image intensifiers (II) [1–4]. In comparison with conventional II, FDs have shown convincing advantages of better ergonomics with better patient access, lack of geometric distortion, little or no veiling glare, no vignetting, insensitivity to magnetic fields and wider dynamic range [2,3,5,6]. However, questions regarding the capabilities of FD have not been answered completely, particularly as it pertains to IQ at low-exposure levels.

In interventional cardiology, real-time viewing of vascularisation of the heart and tiny devices such as stents and guidewires impose stringent requirements on the imaging techniques used. Up to now, IIIs achieve essentially ‘noiseless’ gain at low-exposure rates, due to their characteristics of high-electronic brightness gain and miniﬁcation gain [5]. For FDs, on the other hand, system noise becomes a limiting factor in determining system performance at low-exposure rates [7–9].

Within this scope the question for dose optimisation is complex but urgently demanding clarification. Investigations whether the introduction of FD technology into the cardiac laboratory will result in an increase in clinical IQ or improved dose efﬁciency compared to II systems, need to be performed. Literature data report on IQ assessment under automatic brightness control (ABC) circumstances by use of the Leeds TOR 18-FG phantom placed into the X-ray beam together with a certain amount of polymethyl methacrylate (PMMA) [10–12]. Other studies calculate modulation transfer function (MTF), point spread function (PSF), signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), noise power spectra (NPS) or detective quantum efﬁciency (DQE) [7,13,14] for digital detectors for fluoroscopy, cardiac implementation or radiography. However, this is the first study comparing IQ of an II-based and a FD-based cardiac system, assessed by four-alternative
forced-choice measurement to find the threshold contrast-detail detectability.

The goal of this study was to compare the performance of a FD-based cardiac X-ray system with a contemporary X-ray II system by assessment of IQ under equal exposure circumstances and under ABC in exposure ranges of clinical practice. At the same time we investigated whether the use of a FD system resulted in a higher sensitivity for fluoroscopy and cineraphy mode and in a reduction in patient dose in clinical practice.

2. Materials and methods

2.1. Imaging systems

The II based and the FD-based cardiac systems for this study were both Siemens Axiom Artis monoplane modalities, with ABC-function and three field sizes for magnification of the image. X-ray tube configuration and filtration were identical for both systems. Details are listed in Table 1. Although the size indications for the large, medium and small imaging fields are different for both systems (compare, e.g. 23 cm with 25 cm), the dimensions of the corresponding actual radiation fields are the same. Measurement of the (diagonal) diameter of the radiation fields, as presented in Table 1 was performed using 33-cm × 41-cm Kodak X-Omat V films (Eastman Kodak) at the receptor entrance plane at reference distance (100 cm) from the focus. The explanation for the different figures for indication of the imaging fields lies in the geometry of the image receptors: circular for II and rectangular for FD. Manufacturers indicate the actual visible field diameter (diagonal) and for II, this diameter is smaller than for FD due to loss of image information at the corners of the circular field. The II of the conventional system contains CCD-technology for digitalisation of the image. The FD of the more recent system is of the indirect amorphous silicon (a-Si) type, consisting of an active matrix size of 960 × 960 pixels, with a pixel size of 184 μm (Triell, Moirans, France). Conversion of the energy of the X-ray photons into light occurs in a scintillation phosphor layer consisting of a CsI:Tl needle-shape crystalline structure. The light photons are subsequently detected by pixel photodiodes on a thin film transistor (TFT) array and stored in the form of electronic charge in the capacitors associated with each pixel. Extensive description of FD systems of the indirect (and the direct) conversion type can be found elsewhere [2,3,5].

In order to compare IQ in a correct way, the same magnification factor for image capture and storage is necessary. To this end a grid positioned at the isocentre of the system was used. An arbitrary distance on the grid was compared with the distance measured at the monitor in the catheterisation room. A magnification factor of 2.78 and 2.73 for medium field size was obtained for the II system and the FD system, respectively, which is a satisfactory result.

2.2. Test object details and images

IQ was evaluated using the commercially available CDRAD 2.0 contrast-detail phantom (Instrumentale Dienst, Nijmegen, The Netherlands [15]). This phantom is designed to perform four-alternative forced-choice measurements (4-AFC). The advantage of this method is that there is no need for the observer to set any subjective thresholds as is the case with, e.g., the Leeds TOR 18-FG phantom [16]. Moreover, with 4-AFC the detection errors by the observer are controlled by the correction scheme described in the manual of the test object [15]. Nevertheless, as in all psychophysical measurements, variations among observers cannot be neglected [17]. For averaging purposes, each image was scored by five independent readers. Based on these measurements, contrast-detail curves are obtained, reflecting the visibility limitations by the noise properties of the imaging system. A numerical value, the inverse image quality figure (IQFinv) can be calculated as the sum of the products of hole depth and hole diameter for the objects in the phantom at the limit of visualisation.

Scoring of the images was performed for both II and FD systems on the same monitor, a 19 in. TFT-LCD Avidav monitor (Jetway Computer Corporation, USA). For this scoring the freely available medical viewer software ezDICOM [18] was used, allowing dynamical presentation of all runs. Use was made of the ‘Contrast Autobalance’ function, meaning that readers were not allowed to change window and level of the images. Scoring was performed in a darkened room and no restrictions were implied on viewing distance or viewing time.

2.3. Image quality measurements

The first set of measurements concerned IQ evaluation by IQF_{inv} determination of both II and FD systems for a range of EDR used in clinical practice. For this study a tube potential setting of 70 kV and a fixed filtration of 0.2 mm Cu at small focus were chosen on both imaging systems (Table 2). Image receptor EDR was gradually increased from 23 up to 240 nGy/p (manufacturer settings). A phantom of 20 cm PMMA (with the CDRAD 2.0 phantom in the middle) was used to simulate the patient. Measurements were performed at a reference distance of 100 cm from source to image receptor entrance plane. The distance between exit of the phantom and the image receptor housing was kept 5 cm, in order to simulate clinical practice. All measurements were performed for the medium field size. All images were recorded and phantom EDR was measured with a standard 60 cm² ionisation chamber (Radcal Corporation, Monrovia, USA) for each radiation setting chosen.

A second set of measurements was performed to provide a numerical value for the IQ under ABC settings, for the three different field sizes by IQF_{inv} determination. This means that different X-ray spectra were generated according to the ABC settings of the systems. The X-ray systems were set to their default clinical values.
Table 2
Exposure parameters for imaging of CDRAD 2.0 test object for increasing phantom entrance dose rate (mGy/min) for medium field, 15 f/s and additional filtration of 0.2 mm Cu

<table>
<thead>
<tr>
<th>Tube potential (kV)</th>
<th>Tube current (mA)</th>
<th>Pulse duration (ms)</th>
<th>Phantom entrance dose rate (mGy/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>67</td>
<td>9.1</td>
<td>13.5</td>
</tr>
<tr>
<td>70</td>
<td>106</td>
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<td>26.1</td>
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<td>70</td>
<td>138</td>
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<td>70</td>
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<td>7.8</td>
<td>14.2</td>
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<tr>
<td>70</td>
<td>109</td>
<td>9.0</td>
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</tr>
<tr>
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<td>9.7</td>
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<tr>
<td>72</td>
<td>373</td>
<td>10.0</td>
<td>92.4</td>
</tr>
<tr>
<td>79</td>
<td>324</td>
<td>9.7</td>
<td>106.8</td>
</tr>
</tbody>
</table>

Table 3
Exposure parameters during phantom (20 cm PMMA) measurements in cinegraphy and fluoroscopy mode at 15 f/s and large focus, under automatic brightness control for the II and FD system

<table>
<thead>
<tr>
<th>Field size (cm)</th>
<th>Tube potential (kV)</th>
<th>Tube current (mA)</th>
<th>Additional filtration (mm Cu)</th>
<th>Pulse duration (ms)</th>
<th>Phantom entrance dose rate (mGy/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cinegraphy mode</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II system</td>
<td>23</td>
<td>65</td>
<td>800</td>
<td>0.3</td>
<td>6.4</td>
</tr>
<tr>
<td>17</td>
<td>68</td>
<td>703</td>
<td>0.1</td>
<td>6.2</td>
<td>130.4</td>
</tr>
<tr>
<td>13</td>
<td>74</td>
<td>800</td>
<td>0.1</td>
<td>6.4</td>
<td>176.3</td>
</tr>
<tr>
<td>25</td>
<td>65</td>
<td>715</td>
<td>0.2</td>
<td>7.8</td>
<td>81.1</td>
</tr>
<tr>
<td>20</td>
<td>68</td>
<td>692</td>
<td>0.2</td>
<td>7.6</td>
<td>102.3</td>
</tr>
<tr>
<td>16</td>
<td>68</td>
<td>800</td>
<td>0.2</td>
<td>8.0</td>
<td>132.5</td>
</tr>
<tr>
<td>FD system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>67</td>
<td>158</td>
<td>0.2</td>
<td>12.4</td>
<td>28.2</td>
</tr>
<tr>
<td>13</td>
<td>73</td>
<td>100</td>
<td>0.6</td>
<td>13.5</td>
<td>12.2</td>
</tr>
<tr>
<td>20</td>
<td>67</td>
<td>156</td>
<td>0.6</td>
<td>13.2</td>
<td>18.4</td>
</tr>
<tr>
<td>16</td>
<td>69</td>
<td>170</td>
<td>0.6</td>
<td>13.8</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Fig. 1. Image quality figure inverse (IQFinv) vs. phantom entrance dose rate (mGy/min) for medium field size at the II and the FD system, for a radiation quality of 70 kV with 0.2 mm Cu filtration.

3. Results

Assessment of IQ was performed by calculation of IQFinv based on the scoring of images of the CDRAD 2.0 test object. Fig. 1 shows the relation between IQFinv and the EDR at the 20 cm PMMA phantom, with the CDRAD 2.0 test object in the middle, resulting from potential, tube current and filtration) and tube angulations were also registered.

2.5. Statistical analysis

Statistical significance of differences between the two digital systems was assessed with the two-factor analysis of variance (ANOVA) using system-type (II or FD) and hole depth as independent variables and the observed threshold diameter as dependent variable.

For DAP patient data analysis a non-parametric two-tailed Mann–Whitney test was performed. Correlations between groups were calculated by means of the non-parametric Spearman’s rank correlation coefficient (r). To calculate the regression coefficients in the relation between two quantities, linear regression analysis was performed using the Levenberg–Marquardt algorithm.

In all statistical analyses a confidence interval of 95% was applied. Hence, a p-value <0.05 was considered as significant. All statistical tests were performed with a statistical application package (S-PLUS software—Insightful Corporation, Seattle, WA, USA).

and EDR was measured. Exposure parameters are summarized in Table 3. Images of the CDRAD 2.0 phantom, positioned in between two layers of 9.5 cm PMMA (resulting in a total thickness of 20 cm PMMA) were registered and scored afterwards by the same five readers of the first set of measurements.

2.4. Patient dose measurements

Patient dose measurements consisted of real-time DAP registration during diagnostic cardiac interventions (CA) performed on both systems. In order to avoid large variations in procedure protocol, therapeutic procedures as percutaneous transluminal coronary angioplasty (PTCA) were not included in the study. The same team of cardiologists and nursing staff operated at both imaging systems, to minimize variation in clinical protocol.

Eighteen procedures were followed on the II system, while this number was 26 for the FD system. The average age of the patients was 66 years (range: 35–86 years) for the II system and 67 years (range: 44–83 years) for the FD system. Both populations had an average weight of 73 kg (II: range 55–100 kg; FD: range 55–88 kg). This indicates that there was no bias with respect to patient population characteristics. DAP was registered for fluoroscopy and cinegraphy mode separately, allowing us to investigate the contributions of both modes. For each run, exposure parameters (tube potential, tube current and filtration) and tube angulations were also registered.
the first set up of measurements. The error bars represent the standard deviations between the scores of the five independent readers. A linear regression curve was plotted for both systems. The dose rate at the entrance of the phantom ranged from 14 to 107 mGy/min (Table 2). When we compare these values with the settings selected by the ABC system for a phantom of total thickness of 20 cm PMMA presented in Table 3, we notice that the EDR range of the data is clinically relevant both for fluoroscopy and cinegraphy mode.

Figs. 2 and 3 compare contrast-detail curves representing phantom threshold hole diameter versus hole depth for equivalent phantom EDR used in fluoroscopy and cinegraphy mode. This type of curves is used to deduce the IQF inv values represented in Fig. 1. The curves were obtained at the following phantom EDR values: 37.2 mGy/min (II) and 39.7 mGy/min (FD) for fluoroscopy mode (Fig. 2) and 91.6 mGy/min (II) and 92.4 mGy/min (FD) for cinegraphy mode (Fig. 3). Error bars correspond again to the standard deviations between the results of the readers.

Application of the clinically used ABC of both systems for imaging of the test object, resulted in IQF inv values shown in Fig. 4. Exposure conditions for these images in both fluoroscopy and cinegraphy mode can be found in Table 3. A difference in additional filtration and tube current can be attributed to differences in ABC settings of both systems. However, with respect to dose settings, the image receptor EDR was programmed to be 170 nGy/p in cinegraphy mode for both systems. For fluoroscopy mode, the ABC settings for dose were 36 nGy/p for the FD system and 32 nGy/p for the II system. This implies other filtration, tube potential, tube current and pulse duration restrictions to produce the same (or equivalent) image receptor EDR. Figs. 1–4 support a better image quality for the FD system at EDR values used in cinegraphy mode while not statistically significant differences were observed at low EDR values typical for fluoroscopy.

The DAP data obtained from the patient dose measurements are summarized in Fig. 5. A comparison of DAP histograms for diagnostic coronary angiography procedures performed with the II system (dashed line) and FD system (full line). Mean values are indicated by vertical lines.

4. Discussion

A first set of measurements focussed on image receptor performance as a function of increasing phantom EDR (Fig. 1). The same...
X-ray radiation quality, tube current, field size and frame rate were used to visualize the CDRAD 2.0 test object either on II or FD. A linear relationship \( r = 0.99 \) for FD and \( r = 0.98 \) for II) between EDR and IQ\text{\textsubscript{FD}} was obtained for both systems, in accordance with the characteristic linear response curve for FD [4]. The left-lower part of the graph with EDR ranging from 10 to 35 mGy/min, is representative for fluoroscopy mode which is supported by the EDR values obtained under ABC conditions in this study (Table 3). Similar EDR values were used in comparative studies between II and FD for fluoroscopy also on a Siemens Axiom Artis system: 22 mGy/min by Vaño et al. [11] and 9 mGy/min by Nickoloff et al. [19]. The right-upper part of Fig. 1, with rates ranging up to 107 mGy/min is representative for cinegraphy mode. Under ABC-conditions EDR values of 102 and 130 mGy/min were measured for medium size field for this mode (Table 3). The higher EDR values in the ABC study can be explained by the fact that a large focus is programmed in ABC settings according to clinical protocol while a small focus is applied in service mode of the equipment used for the IQ\text{\textsubscript{FD}} versus EDR study. Vaño et al. [11] used EDR values of 151 and 86 mGy/min in cinegraphy mode studies with Siemens Axiom Artis II and FD systems, respectively, while Nickoloff et al. [19] applied 53 mGy/min in a similar study. Fig. 1 shows very clearly that within the EDR fluoroscopy range IQ\text{\textsubscript{FD}} of FD does not differ significantly from that of II. On the other hand, for the higher EDR range corresponding to cinegraphy mode the FD system shows a significantly better IQ\text{\textsubscript{FD}} than the II system. As within the frame of measurements all exposure parameters were the same, the higher IQ\text{\textsubscript{FD}} values reflect the intrinsic better imaging performance of FD with respect to II when higher EDR are considered (cinegraphy mode). Figs. 2 and 3, representing a comparison of the contrast-detail curves of the II and FD systems for typical fluoroscopy and cinegraphy EDR values, also support these observations. Fig. 2 shows overlapping curves for fluoroscopy mode resulting in a p-value of 0.56 for system dependency for an EDR of 37.2 mGy/min (II) and 39.7 mGy/min (FD). Thus, no difference in imaging performance between II and FD technology in the fluoroscopy mode is observed. On the contrary, the situation is notably different in the cinegraphy mode. The comparison of contrast-detail curves results in a p-value of 0.001 for EDR of 91.6 mGy/min (II) and 92.4 mGy/min (FD) supporting significance in technology dependency for IQ, with advantage for the FD system. From Fig. 3 we can conclude that the gain in IQ for the FD system compared to the II system is due to both better contrast and better resolution, reflected by the entire shift of the FD contrast-detail curve towards the lower left corner of the graph.

The IQ conclusions of present study based on phantom measurements are in agreement with reports regarding DQE(f) (f: spatial frequency lp/mm) [7,14,20]. For high exposures in the cinegraphy range (80–400 nGy—entrance dose per pulse at image receptor), the DQE(0) is superior for the FD systems while in the fluoroscopy range (5–80 nGy) DQE(0) values of FD and II are overlapping. For II the DQE(0) remains almost constant over the whole exposure range covered in fluoroscopy and cinegraphy while for FD the DQE(0) increases steadily for receptor entrance doses from 1 to 100 nGy. The low DQE(0) of FD for low dose is a consequence of the low SNR of low-dose images.

Based on the results obtained in the first set of measurements we could expect a better dose-IQ relationship for the FD system, in cinegraphy mode. This means that in cinegraphy mode the same IQ as for the II system could be obtained for lower dose settings, resulting in a net patient dose reduction. To investigate whether exposure parameters of the system were optimised towards dose reduction or towards better IQ we performed a contrast-detail study under ABC—settings for both modes and for different field sizes (Fig. 4). From this figure, a better IQ for smaller fields and for cinegraphy compared to fluoroscopy is apparent. For the fluoroscopy mode, data do not reveal a significant difference in IQ between FD and II (\( p = 0.26 \)). On the contrary a statistically significant better IQ for the FD system is observed in the cinegraphy mode (\( p = 0.02 \)). Together with the same EDR (at image receptor) of 170 nGy/p programmed for both the II and FD system, this shows that the dose versus IQ relationship was not optimised towards dose reduction. Rather profit was taken from the intrinsic better performance of the FD for cinegraphy mode to produce images of higher quality for similar entrance doses.

Finally, DAP measurements were performed in order to investigate the influence of FD technology on patient dose in clinical practice. Mean values of 31 Gy cm\(^2\) (II system) and 33 Gy cm\(^2\) (FD system), are in agreement with previously published values for both conventional and digital technology: mean values of 31.2 Gy cm\(^2\) (II) and 33.4 Gy cm\(^2\) (FD) were reported by Trianni et al. [10] and median values of 30 Gy cm\(^2\) (II) and 31 Gy cm\(^2\) (FD) reported by Tsapaki et al. [12]. The measurements (Fig. 5) could not reveal a significant dose reduction by introduction of the FD system (\( p = 0.68 \)). Analysis of the DAP data according to the fluoroscopy and cinegraphy contribution did also not highlight a difference in patient dose (\( p = 0.15 \) and 0.82). Similar findings were reported by Tasapaki et al. [12] and Trianni et al. [10]. None of them could show a significant patient dose reduction for neither FD nor II technology. Combining the patient dose results with the phantom IQ measurements we can state that for procedures performed on patients in daily practice, a better IQ is obtained with the FD system in cinegraphy mode. This better IQ is appreciated by the cardiologists but apparently does not lead towards dose reduction by, e.g., a decrease in procedure exposure time. This would have become clear in reduced DAP values, which was not the case.

Whereas in cinegraphy an optimisation towards dose reduction is possible with the use of FD technology, this is not directly the case for fluoroscopy. To this end further evolution of FD technology is necessary by reducing system noise for low exposures.

5. Conclusions

Image quality related to the introduction of FD in interventional cardiology, has been evaluated and compared to the IQ of an II imaging system in a similar X-ray setup. At low-exposure rates used in fluoroscopy, no significant difference in IQ was found. Contrarily, at high-exposure rates used in cinegraphy a remarkably (statistically significant) better IQ could be attributed to the presence of FD imaging technology. Mean DAP values, as estimates for patient dose, resulted to be the same for diagnostic (CA) procedures performed on either the FD system or the II system. No differences were noted not even when the fluoroscopy or the cinegraphy contribution was considered separately. The implementation of FD imaging technology was appreciated by the cardiologists for better IQ in cinegraphy mode, but did not involve a lowering of patient dose. Optimisation of ABC towards lower patient dose is possible in cinegraphy mode. In fluoroscopy mode further evolution of FD technology with respect to system noise at low-exposure rates is necessary to improve IQ and/or reduce patient dose.

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