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PAPER

Evaluation of the performance of digital x-ray systems in pelvis radiography

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Keywords: digital radiography, pelvis radiography, dose optimization, image quality, anthropomorphic phantom

Abstract

The aim of this study was to investigate the performance of eight digital radiography systems and to optimise the dose-image quality relationship for digital pelvis radiography. The study involved eight digital radiography systems used for general examinations at Vilnius University Hospital Santaros Klinikos. An anthropomorphic pelvic phantom (CIRS, US) was used to simulate a patient undergoing clinical pelvis radiography. Dose quantities entrance surface dose, dose area product (DAP) and exposure parameters (kVp, mA, mAs) were measured and the effects on the images were evaluated, considering physical contrast to noise ratio (CNR) and observer-based evaluations as image quality metrics. Increasing the tube voltage by 5 kVp from standard protocol led to a reduction in radiation dose (DAP) by 12%–20% with a slight impact on image quality (CNR decreases by 2%–10%). There was an inter-observer variability in image rating across different equipment (kappa value between 0 and 0.3); however, both observers agreed that increasing kVp up to 85–90 kV had no effect on perceived image quality. The results indicate that optimisation strategies should be tailored specifically for each x-ray system since significant performance differences and wide variations in radiation dose exist across various digital radiography systems used in clinical settings. The use of high kVp can be used for dose optimisation in digital pelvis radiography without compromising image diagnostic accuracy.

1. Introduction

Conventional radiography is one of the most widely used diagnostic tools. Even though, digital radiography imparts lower patient doses than other imaging modalities, stochastic effects including cancer may occur at any dose level. Published articles suggest that abdomen/pelvis diagnostic examinations may lead to an increased lifetime attributable risk of gonadal cancer incidence [1, 2]. Therefore, due to the large burden of medical radiation exposure on the general population, there is a need for patient dose reduction and justification to ensure 'as low as reasonably achievable' exposure while maintaining adequate diagnostic quality of the acquired images [3].

The transition to digital radiography (DR) has introduced challenges in compromising between image quality and radiation dose. The energy responses of digital detectors differ from film-screen and DR provides greater flexibility in using low levels of radiation in combination with image post-processing [4]. However, there have been concerns of higher doses through 'dose creep' due to the large dynamic range of digital imaging systems, which can lead to patient overexposure with no visible adverse effect on the image quality [4]. Past studies have revealed a tendency for patient overexpose with digital radiography [5, 6]. Gibson and Davidson in 2012 define exposure creep as a gradual increase over time of the manual exposures set by radiographers for a specific anatomical projection [7]. Overexposure became the norm for radiographers knowing that it enhances image quality, reduces quantum mottle and is less likely to be rejected by radiologists [8]. As a result, recent studies emphasized the importance of dose optimisation in DR by ensuring the selection of the appropriate technical parameters [9, 10].

Due to the factors mentioned above, individual protocol optimisation remains the key factor for decreasing patient dose. When performing optimisation in diagnostic radiology, special attention should be paid to two parameters: patient dose and image quality. The most important goal of exposure optimisation is to find parameters that result in an adequate image (i.e. image of sufficient diagnostic information) while minimizing radiation exposure to patients [11]. It is a well-known that image quality can be improved by increasing the dose but it is important to consider the tradeoff, as this may not add any additional diagnostic value. The most crucial aspect of optimisation is to strive for imaging parameters that result in a 'sufficient' image quality, rather than the best possible image [12]. Moreover, it is common for a single hospital to purchase diagnostic units from different manufacturers, through the years, depending on its need and financial resources. Thus, optimisation is necessary for each diagnostic unit as well as for each x-ray protocol.

Anthropomorphic phantoms provide the most accurate representation of the human anatomy, thereby enabling dose measurements on these phantoms to be more reflective of real patients. Image quality assessments for these phantoms can be conducted through visual analysis and by measuring the contrast among various tissue structures. However, anthropomorphic phantoms have a number of limitations such as a lower bone density than real patient, an error associated with differences in soft tissue attenuation, a lack of body shapes and contours representation. Moreover, their higher cost puts some limitations on their wider availability in the hospital environment. Previous radiography dose optimisation studies used different phantom types including anthropomorphic phantoms [13, 14], in-house developed phantoms [10–15] and quality control phantoms (e.g. CDRAD phantom and Primus-L phantom) [16, 17].

The aim of this study was to evaluate the performance of eight digital radiology systems and assess the impact of varying exposure parameters on image noise and contrast with the object of achieving optimal patient dose for pelvic diagnostic imaging.

2. Method

2.1. Radiographic equipment

Images were obtained using eight stationary digital x-ray equipment from four different manufacturers (two General Electronics, three Siemens, two Shimadzu and one Philips) (table 1). The x-ray units included in this study were operating in different departments (radiology, emergency, infectious diseases and paediatric). All systems had undergone regular quality control and assurance testing in accordance with the radiation protection legislation of the Republic of Lithuania [18] and according to the manufacturer's recommendations.

2.2. Radiographic technique

Radiographic images of an anthropomorphic phantom (CIRS, US) simulating the lower abdomen and pelvis of an average-size adult male patient (MODEL 801-P) were acquired. This tissue equivalent phantom mimic the radiation attenuation properties of human tissues with high accuracy from 50 keV to 25 MeV, as reported by the phantom manufacturer [19].

The images were obtained with the phantom positioned on the diagnostic table in the supine position, maintaining a source-to-image detector distance (SDD) of 115–120 cm (figure 1). The pelvis area was imaged with a grid placed under the detector in accordance with standard clinical practice. Images of the phantom were obtained using the standard pelvis protocol (in automatic exposure control mode) as set by the manufacturer. Table 1 provides a summary of the automatic exposure control (AEC) parameters for each digital system. An additional set of images were acquired in AEC mode by varying voltage from 65 to 90 kVp at 5 kVp interval. In order to compare the performance of all radiology systems, the image quality and delivered dose was evaluated for images obtained using the same fixed exposure parameters (80 kVp; 10 mAs) for all equipment.

Dose following each exposure was defined as the dose area product (DAP) displayed automatically by the system and the entrance surface dose (ESD). In order to calculate the ESD, incident air kerma, measured with a calibrated solid-state sensor (Piranha RTI Dose Probe ®) placed on the surface of the phantom (figure 1), was multiplied by a backscattering factor corresponding to each beam quality [20]. DAP meters calibration was undertaken in situ by a team of medical physicists as part of an annual quality control protocol prior to the start of the study. This annual quality control procedure was done using a calibrated Piranha R&F/M 657,

Table 1. Radiology equipment information.

Department	Manufacturer	Model	AEC pelvis protocol Voltage (kVp)[a]	 Current time product (mAs)[b]	Installation year
Paediatric	GE	Definium 6000	80	17.7	2011
Infectious diseases	GE	Discovery XR656	80	17.4	2020
Radiology	Philips	CombiDiagnost R90	85	12.08	2021
Paediatric	Shimadzu	Sonialvision Safire	75	20.5	2011
Paediatric	Shimadzu	RADSpeed PRO	80	28.4	2018
Radiology	Siemens	Luminos dRF	77	16.2	2018
Emergency	Siemens	Ysio Max	77	15.1	2015
Radiology	Siemens	Axiom Aristos MX	77	18.3	2006

[a] Standard preset parameters for pelvis protocols of a medium size patient.

[b] Tube current time product (mAs) automatically acquired when imaging the anthropomorphic phantom.

Figure 1. Experimental setup to simulate pelvis x-ray examinations with CIRS phantom.

S/N: CB2-14100814, with RTI Dose Probe S/N: 1403236. The Piranha with RTI Dose Probe meters have been calibrated every two years by the RTI Group accredited calibration laboratory.

2.3. Objective assessment of image quality

The image quality was quantified by measuring the contrast to noise ratio (CNR), an objective metric related to the contrast or signal difference between an object of interest and the image background. In this investigation, CNR was computed as follows,

$$\mathrm{CNR} = \frac{S_1 - S_2}{\sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}}$$

where S_1 and S_2, are the mean pixel values from the region of interest 1 and 2 (ROI1, ROI2) respectively, and σ_1 and σ_2 are their associated standard deviations. These different parameters were measured using the

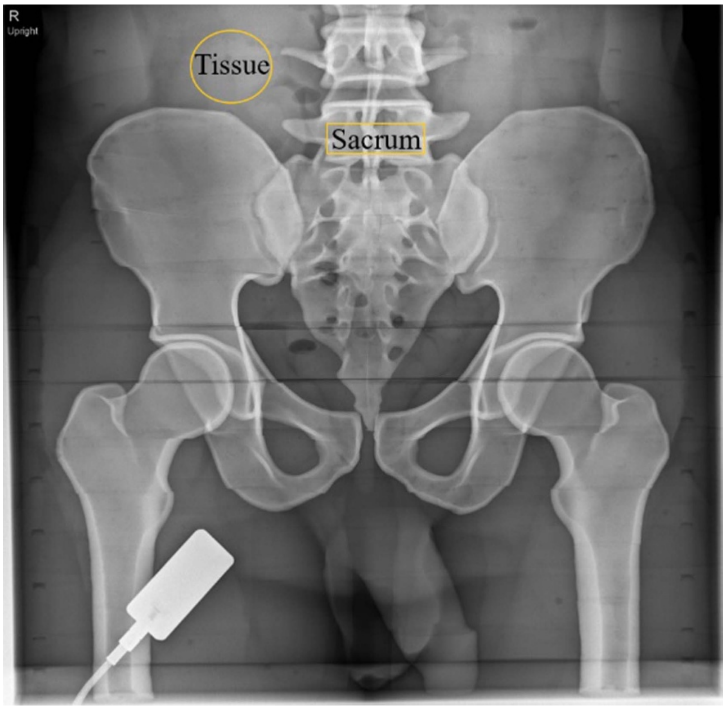

Figure 2. The regions of interest used to calculate contrast-to-noise ratio (CNR) for pelvis x-ray images.

open-source software ImageJ CNR while taking the sacrum and soft tissue as ROI1 and ROI2 respectively for each x-ray image (figure 2).

2.4. Subjective assessment of image quality

A subjective assessment of the quality of images acquired with different kVp was conducted. The image quality was assessed independently by two experienced radiologists with over five years of experience. For each protocol, the order of the images was randomized and anonymized by the removal of all visible identifying information that might influence the observer's assessment, including acquisition parameters (kVp, mAs, etc). This was done to prevent any biases that could occur due to the participants' knowledge of the preset acquisition parameters. Image quality is defined by a set of parameters that assess the effectiveness of an image in fulfilling its intended purpose. The evaluation of image quality in pelvic radiographs was based on two criteria: overall clinical acceptability and visibility of anatomical structures in the pelvic area. These criteria were adapted from the European Guidelines on Quality Criteria for Diagnostic Radiographic Images (table 2) [21]. For the subjective assessment, each question was scored based on a five-point scale, with the following scores 1, 2, 3, 4 or 5, assigned for 'very satisfied', 'satisfied', 'neither satisfied nor dissatisfied', 'dissatisfied', 'very dissatisfied' respectively. The scores for each criterion were then averaged across both observers. The final quality score for each image was calculated by summing the mean score of both previously stated questions. The observers completed the image scoring independently on diagnostic display monitors with no time constraints. In order to replicate the conditions of a typical clinical setting, the analysis was performed in a radiology reading room under the same ambient light conditions used in routine practice. In addition, participants were allowed to use available tool for zooming, adjusting window width and level, displaying image pairs simultaneously for comparison, etc. The inter-rater agreement was assessed by calculating Cohen's Kappa coefficient using SPSS Statistics (IBM Corp., Armonk, NY, SAD)

3. Results

3.1. Comparison of equipment in manual mode

The CNR and DAP of images obtained for different digital units while using the same exposure parameters (80 kVp, 10 mAs, 120 cm SDD, field size, no filtration) are presented in figure 3. The DAP ranged between 0.51 $\mathrm{Gy^*cm^2}$ (YsioMax) and 1.04 $\mathrm{Gy^*cm^2}$ (RadSpeed). While RadSpeed registered DAP value twice as higher as YsioMax, the image quality produced by this unit was 0.8 CNR. One the other hand, CNR measured with GE discovery was 3.2, followed by Axiom Aristos and Luminos (CNR = 2.4 and 1.8 respectively).

Table 2.. Image scoring criteria for pelvis. Only structures that can be visible in the CIRS phantom were included in the evaluation.

Pelvis
Visually sharp reproduction of the sacrum and its intervertebral foramina
Visually sharp reproduction of the pubic and ischial rami
Visually sharp reproduction of the sacroiliac joints
Visually sharp reproduction of the necks of the femora
Visually sharp reproduction of the spongiosa and corticalis, and of the trochanters
Overall diagnostic quality of Image

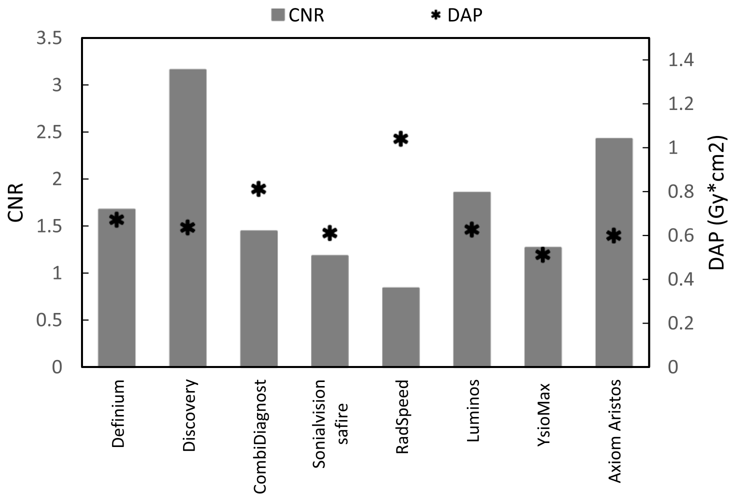

Figure 3. Comparison of image quality (CNR) and dose (DAP, Gy* cm^2) registered for different digital x-ray units under a fixed pelvis protocol using 80 kVp and 10 mAs.

3.2. Effect of kVp on image quality and patient dose

The effect of increasing tube voltage in AEC on image quality and patient dose is shown in figure 4. Both radiation dose (ESD and DAP) as well as image quality (CNR) decreased with increasing tube voltage across all x-ray units. The correlation between CNR and voltage was almost linear for all equipment. The percentage decrease in CNR when increasing voltage from 65 kVp to 90 kVp was extremely similar for all equipment (between 40% and 44%), with the exception of the Axiom Aristos (34%) and YsioMax (50%). Both ESD and DAP exhibited an exponential correlation with tube voltage. Moreover, ESD and DAP values agreed well in all cases. For instance, in case of Discovery, ESD and DAP decreased by 22.9% and 22.3% respectively when increasing voltage from 65 to 70 kV, by 18.3 and 20.2% from 70 to 75 kVp, by 17.8% and 17.7% from 75 to 80 kVp, by 11.7% and 13.3% from 80 to 85 kVp, and decreased by 10.8% and 10.6% when increasing tube voltage from 85 to 90 kVp. Similar results were observed for other equipment. Moreover, the percentage decrease in DAP when increasing voltage from 65 kVp to 90 kVp was 46% for Definium, 60.5% for Discovery, 64% for Axiom Aristos and approximately 70% for the other equipment.

3.3. Observers evaluation

The scores assigned by both radiologists for images acquired in AEC at different tube voltage are provided in figure 5. For the currently used exposure parameters, both observers rated images acquired with all x-ray equipment of satisfactory quality except for images taken with Definium, ComDidiagnost and RadSpeed which were rated as neither satisfied nor dissatisfied by observer 2 while being rated satisfactory by observer 1. At higher tube voltage, image rating varied between both observers as well as between different equipment (figure 5). In general, there was a tendency for observer 2 to evaluate images more strictly. Additionally, the agreement on image quality level between both observers was weak. For CombiDianost and RadSpeed, there was no agreement between observers (kappa value = 0). A slight agreement was found between the rating of observers for images of Discovery, Definium and Safire (kappa value = 0.08, 0.05, 0.11 respectively). While for Luminos, YsioMax and Aristos, a fair agreement was seen (kappa value = 0.22, 0.3 and 0.27 respectively).

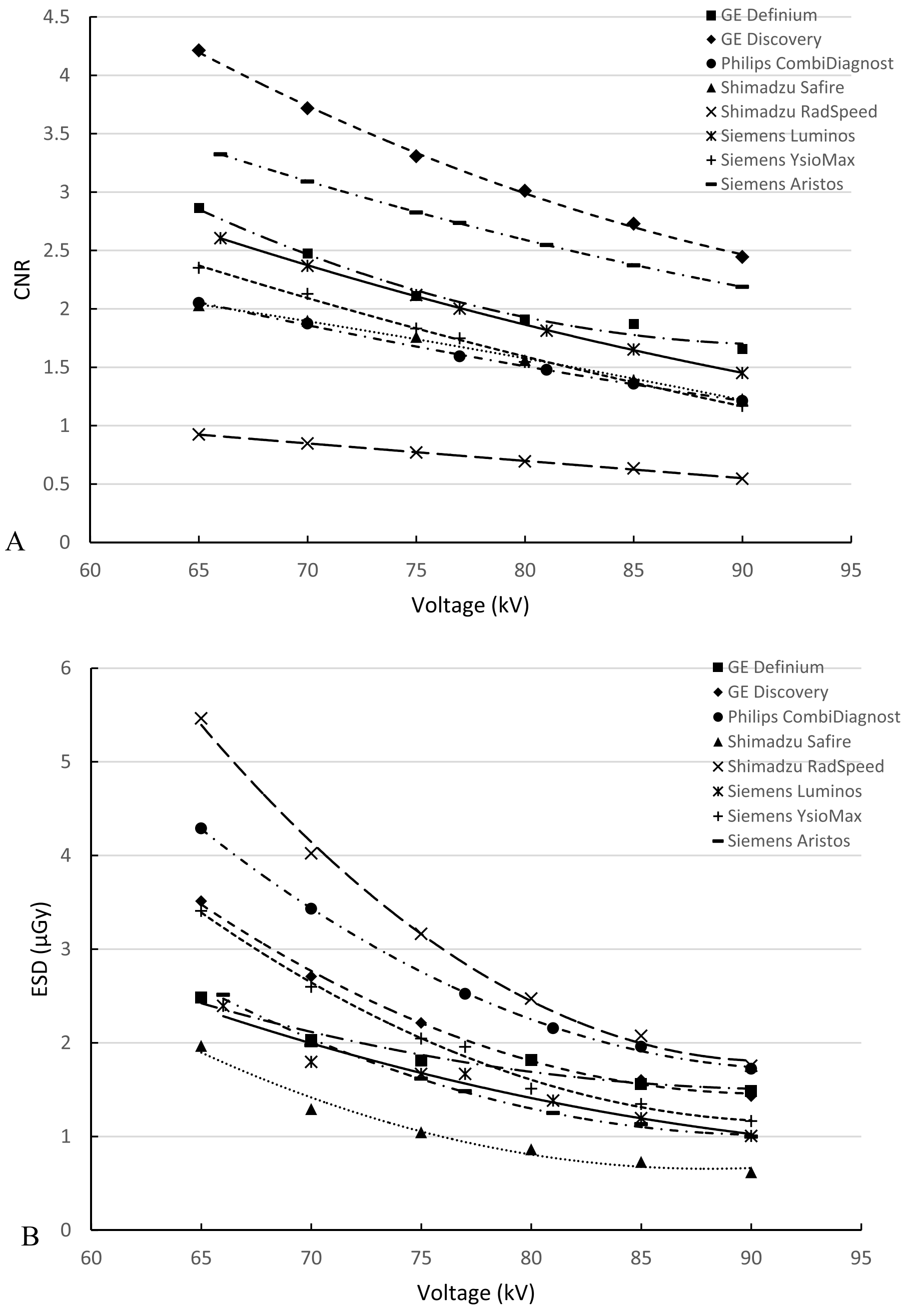

Figure 4. Effect of increasing kVp on the CNR (A), ESD (μGy) (B) and DAP (Gy*cm^2) (C) of different digital equipment.

4. Discussion

Due to the variety of x-ray equipment used in the clinical practice, standardisation and harmonisation of x-ray examinations becomes challenging. In this study, none of the investigated digital equipment behaved similarly in terms of image noise and entrance skin dose. Even though, Discovery, Sonialvision Safire, Luminos and Axiom Aristos displayed similar DAP values (∼0.6 Gy*cm^2), each of these units produced images of different qualities (CNR = 3.2, 1.2, 1.8 and 2.4 for Discovery, Sonialvision Safire, Luminos and Axiom Aristos respectively). As previously mentioned, all equipment investigated in this study were digital x-ray systems. According to the equipment specifications, these systems utilize cesium iodide flat panel detectors, except for the Shimadzu Sonialvision Safire, which uses an amorphous selenium direct conversion detector. Therefore, the differences in equipment performance related to image quality are unlikely to be solely related to the types of installed image receptors. Several other factors are known to influence image quality, including detector quantum efficiency, pixel size, and image post-processing techniques. These factors combined contributed to the significant differences in image quality observed between the

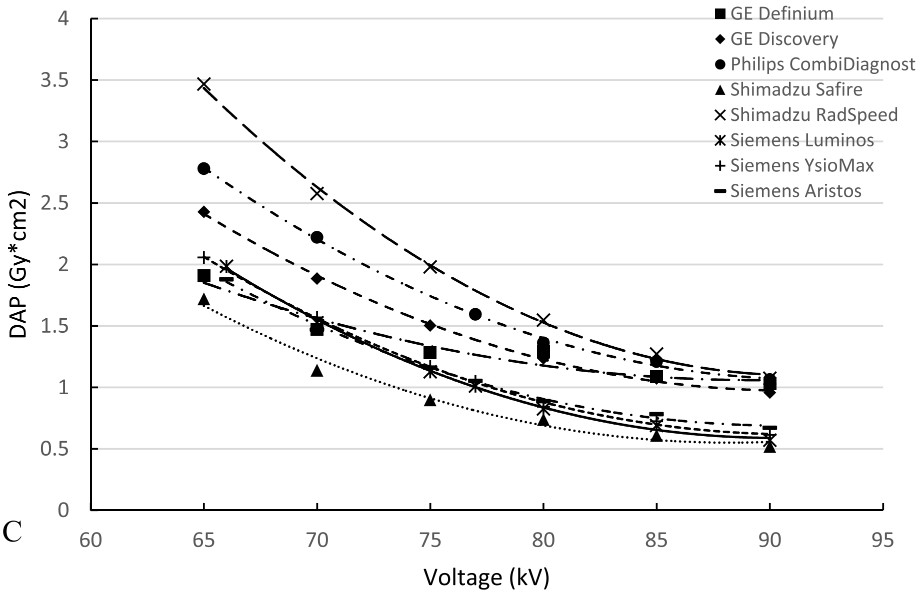

Figure 4. (Continued.)

equipment. However, the extent to which these factors influenced the results remains unclear, particularly since information about the image post-processing algorithms employed by each system is not disclosed by the manufacturers. Based on these results, optimisation should be performed for each specific x-ray unit and for each examination [21]. Similar results were reported by Sun *et al* in their chest radiographic imaging optimisation study of six digital systems, including three computed radiography and three digital radiography systems [10]. The results showed a significant disparity among the digital systems with regard to the diagnostic performance of detecting simulated chest disease. Radiation dose (ESD) was found to be similar in four out of six digital systems in this study while stating a variable performance of different systems [10].

Although some studies indicate that the use of high kVp (i.e. X-ray beam hardening) may lead to reduced contrast [22, 23], our findings suggest that the removal of lower-energy photons through higher kVp results in a higher mean energy x-ray beam passing through the patient, ultimately leading to a substantial reduction in radiation dose (DAP decreased by 12%–43.5% when using 90 kVp instead of standard protocol). Increasing the beam energy allows for dose reduction while maintaining image quality, despite some loss of original image information (CNR decreased by 2%–10% when increasing tube voltage by 5 kVp from the standard protocol, while further 7%–14% reduction in CNR with 10 kVp increase from standard protocol). Other authors have reported similar results regarding the effects of the use of high kVp on the radiation dose and image quality. Jang *et al*, demonstrated that a dose reduction in abdominal digital radiography can be achieved by employing 92 kVp with 0.1 mm copper filtration compared to using 80 kVp without filtration, all while preserving image quality [24]. The study compared the abdomen radiographs taken from two GE Definium 8000 and demonstrated a 48.3% and 46.7% reduction in mean DAP for supine and standing positions, respectively, when using 92 kVp with copper filtration [24]. Previous studies focusing on chest digital radiography also concluded that the use of high kVp reduces the radiation dose and provides an equivalent image quality [25–27].

The relationship between dose and image quality can be evaluated through both quantitative and qualitative methods. In a review by Schaefer-Prokop *et al*, of 27 studies investigating image quality and dose requirements of various digital radiography units, it was noted that the majority of studies used only one methodology for image quality analysis [28]. The authors highlighted the growing interest in understanding the correlation between objective measures and subjective grading of image quality and to what extent slight differences in visual grading impact diagnostic performance in clinical conditions [28]. According to Jones *et al*, the ranking of Siemens Axiom Aristos MX performance at different kVp and filtrations was consistent for both quantitative and subjective methodologies [14]. The study found that for paediatric lateral angle radiographs, image quality is highest at 40 kVp while the use of the image processing algorithm ‘Diamond View’ improved image scores at tube potentials >55 kVp [14].

In this study, less consistent correlation was present between both objective and subjective image evaluation. While the CNR values decreased steadily with increasing tube voltage for all equipment, there

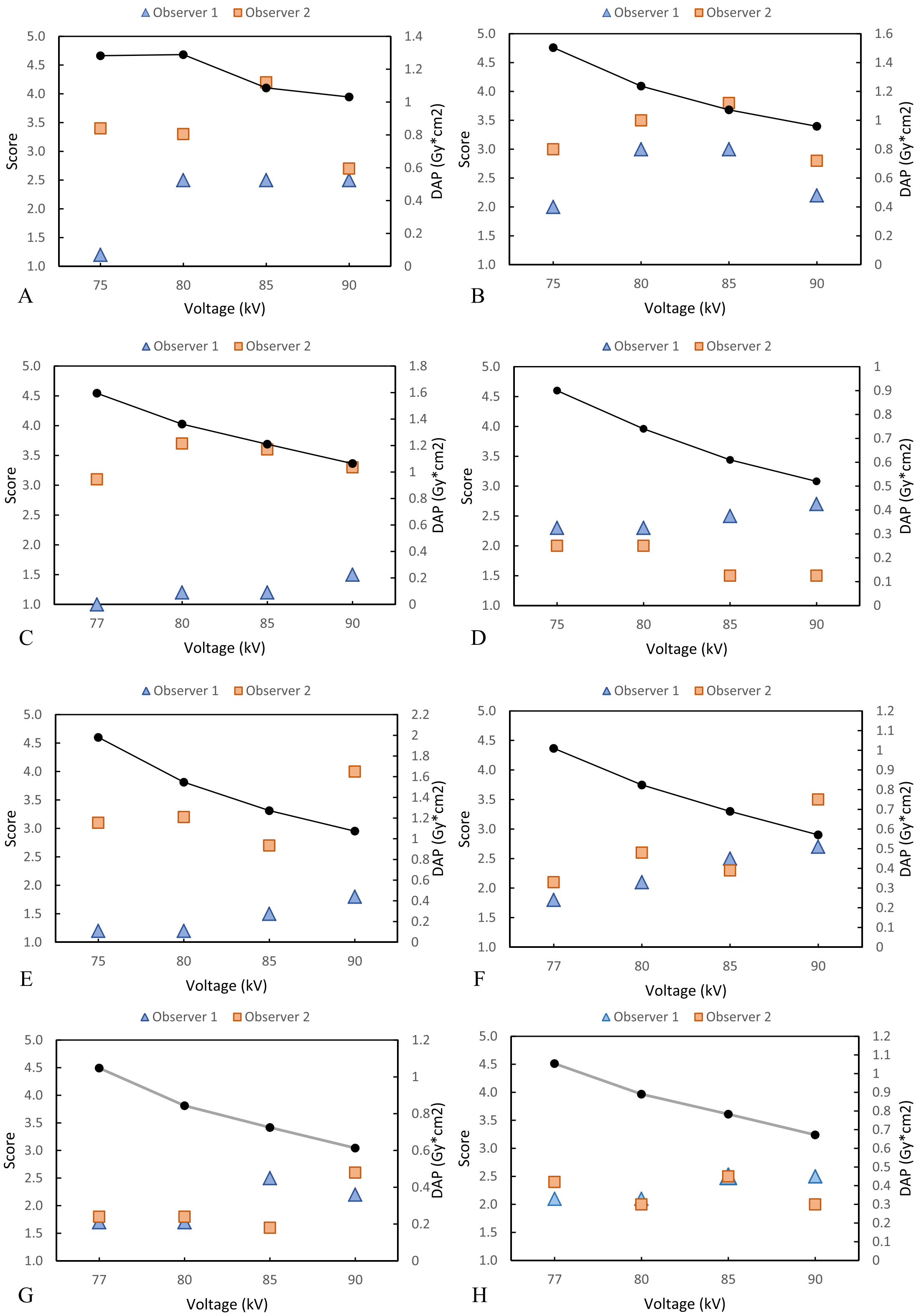

Figure 5. Image scoring of two observers based on varying tube voltage (kVp) for Definium (A), Discovery (B), CombiDiagnost (C), Sonialvision Safire (D), RadSpeed (E), Luminos (F), YsioMax (G), Axiom Aristos (H). A five-point scoring scale was used with a score of 1 assigned for very satisfactory quality and score of 5 for very dissatisfactory quality.

was different trends for observer evaluation depending on each equipment. The image rating decreased with increasing kVp only for Luminos. At standard parameters (77 kVp), both observers rated the acquired image acquired with Luminos of satisfactory quality while when the kVp was raised to 90 kVp, observer 1 was neither satisfied nor dissatisfied with image quality and observer 2 was dissatisfied. On the other hand, no significant change in image score across all chosen tube voltage was seen for all other equipment. It should be noted that the results indicated a week agreement between observers on image rating (kappa value between 0 and 0.3). The lowest agreement was observed for the CombiDiagnost and RadSpeed, likely due to Observer 2's lack of experience working with these devices, which may have influenced his evaluations. Other factors that could have led to discrepancies in image scoring between the two observers include their different approaches to image evaluation and levels of experience. Even though, the low levels of agreement between observers could be considered a limitation; this finding reflects the difference between radiologist's perception and experience in reading images and highlight the necessity for individual optimisation based on radiologist preferences.

This study is limited by the fact that only two radiologists participated in the evaluation of image quality. However, due to the significant variability of radiologist's opinion seen in our results, the input of all other radiologists working in the hospital should be considered in future works. Secondly, both radiologists noted that the anthropomorphic phantom used did not accurately replicate the anatomy of a real patient and that the images interpretation was confounded by the use of a phantom instead of a radiograph of an actual patient; thus, it is likely that the use of the anthropomorphic phantom may have influenced the results. Finally, the phantom is representative, in terms of size, of an average male patient and may be less suitable for optimisation of small patient and large patient pelvis protocols. Therefore, care is required when extending the results of the study into routine clinical practice, given the limitations presented above.

5. Conclusion

Digital radiography encompasses a variety of imaging systems each with its unique technical specifications and performance characteristics. Our findings indicate that there is a significant performance difference and wide variations in radiation dose exist among different digital radiography systems currently in use in clinical settings. Optimisation strategies should be tailored specifically for each x-ray system as optimal dose setting may not be interchangeable between two systems. By increasing the tube voltage by 5 kVp from standard protocol, radiation dose (DAP) can be reduced between 12%–20% while slightly affecting the image quality (CNR decreased by 2%–10%). There was no perceived change in image quality by both observers, when increasing kVp above standard parameters for all equipment. Therefore, dose reduction for pelvic digital radiography can be achieved without compromising diagnostic accuracy by using up to 85–90 kVp depending on the equipment. Following this study, routine pelvic protocols were adjusted for each equipment according to the study's findings with close follow up in order to monitor the effect of the new protocol on quality of clinical images as well as patient doses.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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