Radiography 30 (2024) 574–581

Contents lists available at ScienceDirect

Radiography

journal homepage: www.elsevier.com/locate/radi

Comparing the standard knee X-ray exposure factor, 10 kV rule, and modified 10 kV rule techniques in digital radiography to reduce patient radiation dose without loss of image quality

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ARTICLE INFO

Article history:
Received 16 November 2023
Received in revised form
18 December 2023
Accepted 18 January 2024

Keywords:
Kilovoltage rule
Digital radiography
X-ray
Radiation dose
Image quality

ABSTRACT

Introduction: The 10 Kilovoltage (kV) rule was a historic exposure adaption technique designed for film screen X-ray imaging to reduce ionising radiation dose without loss of image quality. This study evaluates knee X-ray radiation dose and image quality between standard patient exposure factors, the historic 10 kV rule (−50 % Milliampere-second (mAs), and a modified 10 kV rule (−75 % mAs) using a digital radiography (DR) system.

Method: Applying the exposure factors of 63 kV and 8 mAs (standard pre-set exposure), 73 kV and 4 mAs (historic 10 kV rule) and 73 kV and 2 mAs (modified 10 kV) to a phantom knee and recording entrance skin dose (ESD) using thermoluminescence dosemeters (TLDs). The ESD was analysed with a *t*-test. The image quality was assessed using a Likert 5-point Visual Grading Analysis (VGA) by ($n = 3$) independent observers. The ESD data was analysed with Analysis of Variance (ANOVA) for differences between the techniques.

Results: The ESD reduction for the historic 10 kV rule was 32.1–33.7 % (20.9 μGy; $p = 0.00$), and the modified 10 kV rule 81.5–81.8 % (42.1–43.7 μGy; $p = 0.00$) compared to the standard pre-set exposure technique. The historic and modified 10 kV exposure parameters image quality for the AP views knee X-rays scored higher ($p = 0.00$) than the standard preset exposure images. The VGA for the lateral knee view using the historic (−0.1 VGA; $p = 0.02$) and the modified 10 kV (−0.3 VGA; $p = 0.00$) were slightly lower than the standard preset image quality, related to the trabeculae pattern and cortical outlines.

Conclusion: The findings suggest dose reductions could be made by modifying the exposure factors without reducing the quality of diagnostic images in the AP Knee position. The findings for the lateral knee X-rays indicate the image quality scored lower but was still within diagnostic range. Further research is required in laboratory conditions of exposure adaptations over a larger sample of anatomy thickness and applying a wider exposure (kV) range.

Implications for practice: One of a radiographer's many roles are to optimise techniques to improve image quality of anatomy and reduce the radiation dose to the patient. The findings have shown there is potential for further research using the modified 10 kV rule.

Introduction

Diagnostic X-rays are causative of approximately 14 % of the total annual exposure worldwide of radiation sources. It is estimated that in the United Kingdom (UK), about “0.6 % of the cumulative risk of cancer to age 75 years”[1] can be linked to diagnostic X-rays, which equates to “700 cases of cancer per year”.[1] From November 2021 to November 2022, the National Health Service (NHS) England Diagnostic Imaging Dataset[2] recorded $n = 21, 245, 685$ plain film X-ray examinations, the highest of all radiology modalities. The linear no-threshold (LNT) model[3] assumption is a dose–response model that exposure to ionising radiation is related to the likelihood of developing cancer[4] (carcinogenesis mutational events[3]). Under the UK Ionising Radiation Medical Exposures Regulations (IR (ME)R),[5] it is the responsibility of the radiographer to ensure all radiation doses from an imaging examination are kept

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https://doi.org/10.1016/j.radi.2024.01.013

As Low As Reasonably Practicable (ALARP). Although the radiation dose to the patient is low for knee X-rays, exposure factors should be selected to optimise image quality while lowering the patient dose.[6] The main intention of optimisation is to decrease stochastic effects.[7] Knee X-rays are frequently requested to assess the bony and soft tissue anatomy for traumatic injuries, malignancies, or degenerative changes.[8,9]

Studies have explored the term ‘dose creep’[10–14] surrounding the clinical practice of radiographers[11,12] and student radiographers[15] using higher exposure factors in digital imaging to improve image quality. Over time, adjustments in this way could lead to a cumulative effect on patients who have repeated X-ray studies during their treatment.[16] Hayre and Cox[10,11] concluded the reasons for these actions were digital radiography systems have a large dynamic range and the decoupling of exposure factors with contrast and image brightness.[10]

Historically, many systems have adapted patient exposure parameters to compensate for patient anatomy thickness based on film screen combination X-ray or Computed Radiography (CR) systems to reduce patient dose.[17] Common systems used in clinical practice include the Half Value Layer (HVL) technique (double the exposure for every 3 cm (cm) of anatomy thickness),[18] 25 % Rule technique (25 % increase in Milliampere-second (mAs) for every 1 cm of tissue thickness),[18,19] Automatic Exposure Control (AEC) technique (pre-set level of exposure),[20–23] 15 % rule (15 % increase in Kilovoltage (kV) relates to 50 % decrease in mAs),[21,22,24] the 10 KV rule (increase by 10 kV equal to double the mAs).[25]

The 15 % rule works on the inverse power relationship between tube potential (between 50 and 100 kV) and mAs (decrease by a factor of 2) creating an increase in the number of x-ray photon incidents on the patient (approximately proportional with kVpˆ2) and the increased penetrability that increases the likelihood of the x-rays to pass through the patient to reach the image receptor. In general the 15 % rule works best for musculoskeletal (MSK) thickness up to 15cm[24] (where AEC techniques are not usually used due to the thinness of anatomy).

The alternative substitute method in clinical practice is the 10 kV rule[26,27] (a factor of 2 mAs for a change of 10 kV between 50 and 100 kV). However, the majority of these studies are based on CR technology[28]; modern NHS radiology departments are phasing out CR X-ray technology in favour of modern Digital Radiography (DR) systems.[29]

There is a paucity of published literature regarding the 10 kV rule (50 % decreased mAs) within DR systems. A study by Coffey et al.,[27] in which the 10 kV rule was tested on DR for hand, knee, and shoulder extremities, demonstrated lower entrance skin dose (ESD) for hand and shoulder but produced mixed results for the knee, possibly due to experiment errors. However, the image quality was not assessed for any differences. DR systems have the performance potential to produce images with the same quality as CR but using lower radiation dose than CR systems due to having a higher detective quantum efficiency (DQE),[30] a wide latitude, improved spatial resolution (through the modulation transfer function), and post-processing algorithms.[31] Although, potentially, there are still the effects of scattered radiation, focal blurring, geometric magnification effect, and anatomical noise (from a phantom) that can deteriorate an image.

This study aims to explore the ESD reduction from the pre-set patient parameter setting using the historic 10 kV rule (50 % decrease in mAs) and a modified 10 kV rule (75 % decrease in mAs) using a digital radiography (DR) system for Anterior-Posterior (AP) and lateral Knee X-rays.

The null hypothesis (H_0) will be using a modified 10 kV (75 % decrease in mAs) technique, which will result in no change to radiation dose or diagnostic image quality. The alternative hypotheses will be a change in radiation dose (higher H_1) or lower (H_2) or a change to higher (H_3) or lower (H_4) image quality.

Methods

Institutional ethical approval was granted for this study (ETH 202223-AW) for radiation exposure within a controlled X-ray room and recruitment and participant image evaluation. Quality assurance of the X-ray tube (Siemens Opti X-ray unit 150/30/50HC-100) was performed at the start of the exposures to ensure consistency of radiation tube[32] output dose[33] by placing an ion chamber[34] upon a tissue equivalent block connected to a test meter, with a dose meter diagnostic focus.[34] A source-to-image distance (SID) of 100 cm, a small focal spot, and exposure factors of 63 kV and 8 mAs were applied (pre-set patient X-ray knee parameter). The collimation field was set to the ion chamber,[34] and three exposures took place, with each dose recorded between exposures.

Twenty thermoluminescent dosimeters (TLDs)[35] were used to measure ESD for the knee examinations. The TLDs are made of lithium fluoride (LiF) crystals, which are tissue equivalent and have electron traps to capture the X-ray energy when irradiated. Thus, they required annealing in an electric Carbolite[36] TLD oven to remove any previously amassed radiation. This was performed by heating them to 242° to release the electron traps and cooled rapidly.[37] The TLDs were then calibrated after annealing to assess their sensitivity.[38] The TLDs were placed on top of the tissue equivalent block (to reduce backscatter) and exposed using the same parameters of the quality assurance of the X-ray tube. All the TLDs were then placed into a TLD platen using vacuum tweezers to avoid grease or oil from human handling,[37] which would affect the readings when heated.[38] The TLD platen was then placed in the TLD reader[39,40] to read the light counts[39] of the stored energy.

The light counts were recorded and inputted into a Microsoft Excel[41] spreadsheet. The three TLDs with similar sensitivity were grouped together, put in a re-sealable small plastic zip storage bag, and used to measure the ESD. The three most sensitive TLDs were used to measure background radiation.

A tissue equivalent Alderson Rando[42] right knee phantom was positioned in the AP position against a DR detector.[43] The re-sealable plastic zip storage bag of TLDs was positioned in the central crosshairs of the X-ray tube[32] collimation, which was set at 24 cm by 13 cm to include a distal third of the femur and proximal third of tibia and fibula and laterally to include soft tissue borders. The X-ray tube[32] was at a distance of 100 cm perpendicular and centred 1.5 cm distal to the apex of the patella.[44] The exposure factors of 63 kV and 8 mAs were applied, with three exposures to compensate for any electricity fluctuation. After each exposure, the TLDs were read, and the light counts were recorded on a Microsoft Excel[41] spreadsheet. The Alderson Rando[42] right knee phantom was then positioned in the lateral position (Fig. 1) against the DR detector[43] for the further three exposures. The ESD (absorbed dose) was calculated by deducting the mean of the three TLDs light count of the background radiation from the TLDs light count, then using the Reader Calibration Factor,[40] Element Correction Coefficient,[40] and Conversion Factors[40] to convert the light counts of Nanocoulombs (nC) to dose units of Micrograys (μGy).[37] The exposure index (EI) and dose area product (DAP) were recorded after each exposure for quality assurance.[45]

The second phase of exposures applied 73 kV and 4 mAs (the historic 10 kV rule of increasing the kV by 10 and decreasing the mAs by 50 % from the pre-set exposure factor). At the same time, all other parameters stayed constant for the three individual exposures (AP and Lateral), with the TLDs read after each exposure. For the final phase of exposures 73 kV and 2 mAs (modified 10 kV rule of increasing the kV by 10 and decreasing the mAs by 75 % from the

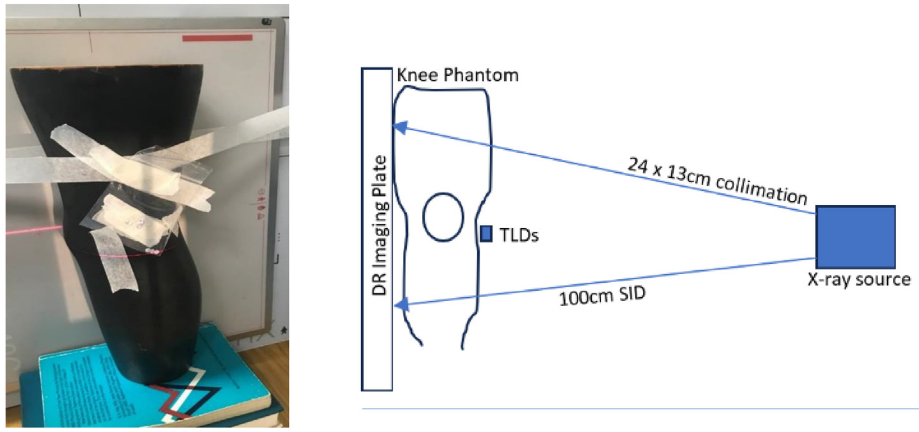

Figure 1. Set up for lateral Knee X-ray.

pre-set exposure factor s setting) and all other parameters were kept constant for the three AP and three Lateral exposures, with the TLDs read after each exposure.

All $n = 18$ examination images were transferred from the DR X-ray equipment[43] and uploaded to the university picture archiving and communication system imaging system (PACS).[46] Each image was allocated a number by random order[47] to avoid image interpretation bias, with date and time stamps and all DICOM headers information removed to anonymise them.

For the review of image quality, a recruitment email was sent to $n = 8$ diagnostic radiographer university lecturers independent from the project team (although a convience sample recuriment the criteria included having a reporting radiographer qualification and holding a clinical post for reporting X-ray images) with a link to the study participant information and consent forms to participate in the image quality assessment survey anonymously using Microsoft Forms.[48] The recruited university lecturers were asked to review the quality of each image using a Visual Grading Analysis (VGA) 5-point Likert ordinal response (−2 clearly the image is inferior in quality, −1 the image is slightly inferior in quality, 0 the image is equal to what a good quality knee x-ray, +1 the image is slightly superior in quality, +2 the image is superior in quality)[49] to a good quality DR xray reference image of the same Phantom knee. The VGA tool applies the European Guidelines on Quality Criteria[50] to assess each of the $n = 18$ images in a random order for image quality based on the reproduction and visualisation of anatomical structures (soft tissues, trabecular bone pattern, cortical bone outline, and femoral condyles).

The data analysis of the dose used descriptive statistics to calculate a mean and standard deviation (SD) and displayed visually in box and whisker plots from each set of three knee X-ray examinations (AP and lateral) at each exposure parameter to compare any increase or decrease in dose. Further statistical analysis of a paired two sample for means *t*-test[51] (*p*-value significance level $p \le 0.05$) and scatter diagram (dose (µGy) values against mAs values) were applied. The Likert (ordinal) data analysis applied the Analysis of Variance[52] (ANOVA) for both AP and Lateral to determine any significant difference in the image quality of the three exposures.

Results

Three sets of exposures (pre-set, 10 kV (−50 % mAs), and 10 kV (−75 % mAs) were performed for both Lateral and AP positions, each having three separate TLD readings (Table 1).

Two minor outliner anomalies were noted on one of each of the three TLDs on the AP exposures. ESD values were higher (67.2 µGy) for the historic 10 kV rule lateral view 1, and 44.5 µGy for the modified 10 kV rule lateral view 2. These TLD ESD readings could be due to a setup error in the experiment. Alternatively and more likely, the TLD manufacturing process causes microscopic crystal lattice impurities and imperfections, creating unique sensitivities[38] which may account for the outlier readings.[53]

The mean ESD doses for the 10 kV with 50 % decreased mAs in the AP knee position was 20.9 µGy (33.7 %; $p = 0.00$) less than the pre-set exposure, with the lateral knee view 20.9 µGy (32.1 %; $p = 0.00$) less than the pre-set exposure (H_2). The mean ESD doses for the modified 10 kV with 75 % decreased mAs in the AP knee position was 42.1 µGy (81.8 %; $p = 0.00$) less than the pre-set exposure (H_2). With the lateral knee view, 43.7 µGy (81.5 %; $p = 0.00$) less than the pre-set exposure (Table 2, H_2). The findings display a significant ($p = 0.00$) reduction in ESD levels when using

Table 1
ESD results with mean and standard deviations (SD) for the three exposure factors.

Exposure	TLD Dose	Standard		10 kV −50 %		10 kV −75 %	
		AP	Lateral	AP	Lateral	AP	Lateral
1	1	72.1 µGy	79.7 µGy	49.5 µGy	51.2 µGy	27.7 µGy	26.9 µGy
	2	73.6 µGy	74.3 µGy	49.6 µGy	67.2 µGy	27.7 µGy	33.9 µGy
	3	79.6 µGy	73.0 µGy	56.7 µGy	51.7 µGy	34.5 µGy	27.9 µGy
2	1	75.1 µGy	74.0 µGy	58.0 µGy	59.9 µGy	30.4 µGy	29.3 µGy
	2	70.2 µGy	74.2 µGy	49.3 µGy	51.9 µGy	34.8 µGy	28.6 µGy
	3	69.6 µGy	79.8 µGy	49.5 µGy	50.9 µGy	27.7 µGy	44.5 µGy
3	1	69.9 µGy	73.9 µGy	47.1 µGy	56.0 µGy	28.5 µGy	30.4 µGy
	2	66.9 µGy	78.2 µGy	50.1 µGy	51.8 µGy	34.8 µGy	30.2 µGy
	3	75.4 µGy	72.7 µGy	54.9 µGy	50.8 µGy	27.7 µGy	34.9 µGy
mean (SD)		72.5 µGy (SD 3.85)	75.5 µGy (SD 2.86)	51.6 µGy (SD 3.84)	54.6 µGy (SD 5.61)	30.4 µGy (SD 3.32)	31.8 µGy (SD 5.42)

Table 2
Comparison data applying the *t*-test for the three exposure factors.

	Standard	10 kV −50 %	Comparison					
	mean (SD)	mean (SD)	Diff. in mean	Reduction %	95 % CI	*t*-test	DF	*p*-value
AP	72.5 μGy (SD 3.85)	51.6 μGy (SD 3.84)	−20.90 μGy	−33.7 %	−29.6 to — 12.2	−6.66	4	*p=0.0026*
Lateral	75.5 μGy (SD 2.86)	54.6 μGy (SD 5.61)	−20.90 μGy	−32.1 %	−30.9 to — 10.8	−5.75	4	*p=0.0045*
	Standard mean (SD)	10 kV -75 % mean (SD)	Comparison Diff. in mean	Reduction %	95 % CI	*t*-test	DF	*p*-value
AP	72.5 μGy (SD 3.85)	30.4 μGy (SD 3.32)	−42.10 μGy	−81.8 %	−50.2 to — 33.9	−14.34	4	*p=0.0001*
Lateral	75.5 μGy (SD 2.86)	31.8 μGy (SD 5.42)	−43.70 μGy	−81.5 %	−53.5 to — 33.9	−12.35	4	*p=0.0002*
	10 kV -50 % mean (SD)	10 kV -75 % mean (SD)	Comparison Diff. in mean	Reduction %	95 % CI	*t*-test	DF	*p*-value
AP	51.6 μGy (SD 3.84)	30.4 μGy (SD 3.32)	−21.20 μGy	−51.7 %	−29.3 to — 13.1	−7.23	4	*p=0.0019*
Lateral	54.6 μGy (SD 5.61)	31.8 μGy (SD 5.42)	−22.80 μGy	−52.7 %	−35.3 to — 10.3	−5.06	4	*p=0.0072*

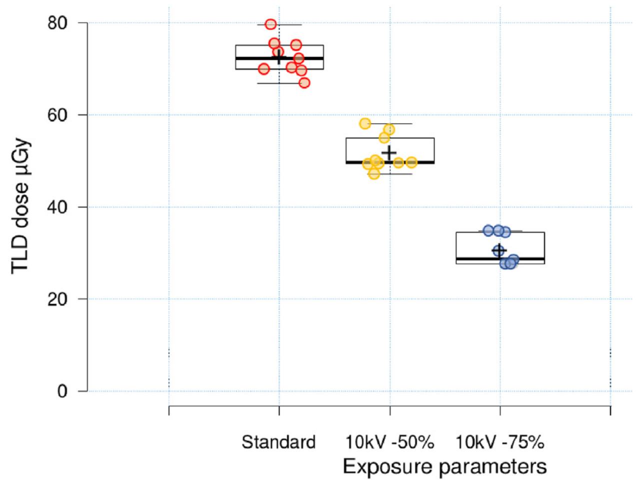

Figure 2. Box and whisker plot (with median line) and data points overlayed of all three exposure parameters for AP view examinations.

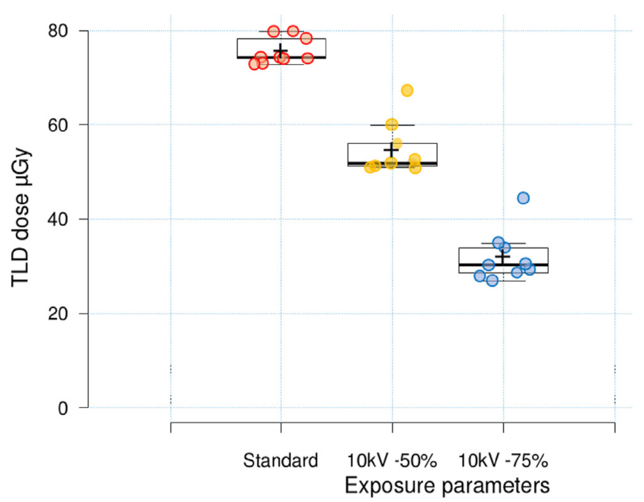

Figure 3. Box and whisker plot (with median line) and data points overlayed of all three exposure parameters for lateral view examinations.

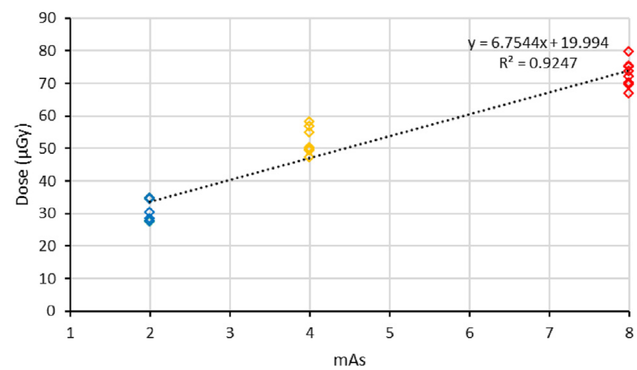

Figure 4. Scatter diagram of the AP dose (μGy) values against mAs values with a line of best fit.

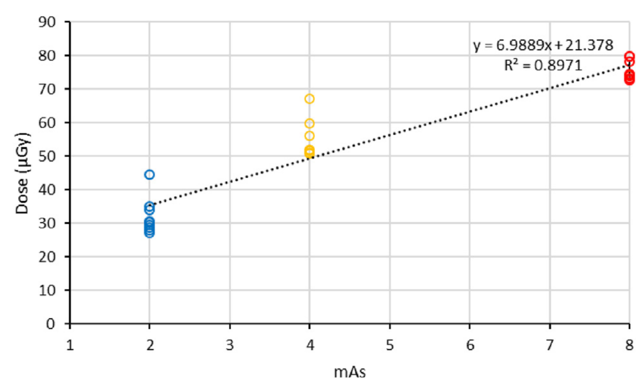

Figure 5. Scatter diagram of the lateral dose (μGy) values against mAs values with a line of best fit.

the modified 10 kV with 75 % decreased mAs technique compared to the historic 10 kV with 50 % decreased mAs exposure ($p = 0.00$) and the pre-set knee exposure ($p = 0.00$; Table 2).

The box and whisker plots visually demonstrate the knee X-ray ESD values throughout all three sets of AP and Lateral exposures, with minor TLD sensitivity grouped around the mean value (Fig. 2) and demonstrating the anomaly outlier data in the lateral plot

(Fig. 3) from the variance of the sensitivity and make-up of an individual TLDs.

Additional correlation analysis of the ESD data for the AP and Lateral positions at all three exposure parameters displayed a linear relationship[54] between the exposure factors (kV and mAs) and the reduction of ESD (Figs. 4 and 5). The dose and mAs were directly proportional which predicted dose when repeated at 1 mAs intervals.

The image quality assessment of the $n = 3$ images for each AP and lateral position for each exposure parameter ($n = 36$ X-rays; Figs. 6–8) against the Likert scales ($n = 5$) for the VGA criteria ($n = 4$) was carried out by $n = 3$ participants (diagnostic radiography lecturers). The VGA observer data findings for the AP view reported higher than the standard expected image quality of a knee x-ray for all exposures (pre-set exposures were 0.4 VGA above, historic 10 kV exposures were 0.1 VGA above, and the modified 10 kV exposures were 0.3 VGA above). All the 10 kV exposure parameters image quality (Figs. 7 and 8) scored statistically significant at $p = 0.00$ compared to the pre-set exposure (Fig. 6, Table 3, H_3).

The VGA observer data findings for the lateral view reported both the historic 10 kV exposure parameter (−0.1 VGA) and the modified 10 kV (−0.3 VGA) slightly lower than the pre-set image quality (Figs. 6–8), with the change not statistically significant $p = 0.02$ and $p = 0.00$ (Table 4). The minor differences noted between both the 10 kV exposure parameters ($p = 0.38$; Table 4) of bony quality of the trabeculae pattern and cortical outlines; however, all the images' overall mean VGA scores (Tables 3 and 4) deemed them diagnostic.

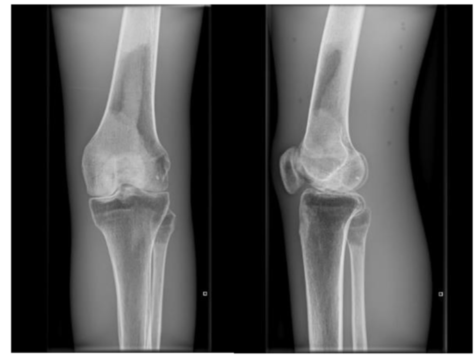

Figure 6. Images produced using the pre-set exposure for AP and Lateral knee X-rays.

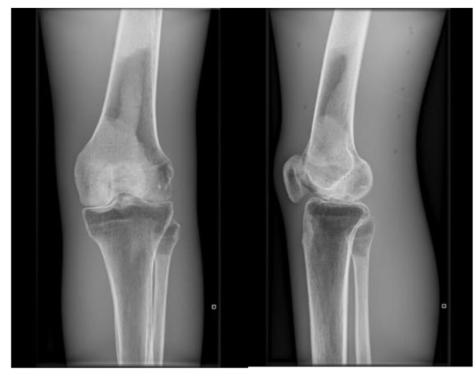

Figure 7. Images produced using the historic 10 kV rule (50 % decreased mAs) AP and Lateral knee X-rays.

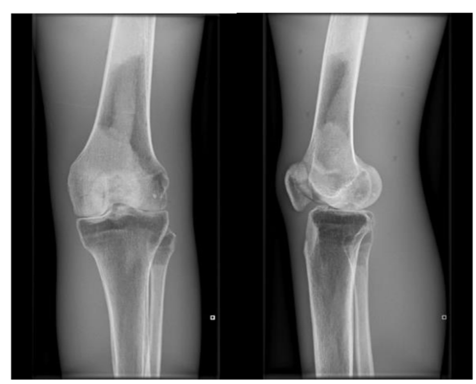

Figure 8. Images produced using the modified 10 kV (75 % decreased mAs) AP and Lateral knee X-rays.

Discussion

The study explored if exposure factors for two-view knee X-rays could be altered so that the patient ESD was reduced and image quality remained diagnostic. The findings demonstrated the AP view to be 81.8 % less dose ($p = 0.00$; Table 2) between the modified 10 kV (75 % decrease in mAs) exposure parameters and the pre-set Knee X-ray, with no change in image quality ($p = 0.00$; Table 3). Analysis of the findings demonstrated a linear correlation between the ESD and exposure factors (Figs. 4 and 5). The difference for the lateral view between the modified 10 kV (75 % decrease in mAs) exposure parameters and the pre-set Knee X-ray was 81.5 % less dose ($p = 0.00$; Table 2); however, the VGA image quality evaluation recorded the VGA score to be slightly less than (−0.3 VGA score, $p = 0.00$) below being equal (a score of 0) to the quality expected of a knee X-ray.

Although the minor drop of −0.3 VGA score below that expected for a reference standard knee X-ray for the lateral knee view might have been a subjective finding on the reproduction and visualisation of anatomical structures (soft tissues, trabecular bone pattern, cortical bone outline, and femoral condyles), and a larger observer sample size might have reflected a different finding. The reproduction and visualisation of the trabeculae pattern and cortical outlines is important for diagnosis of traumatic findings such as suspicion of fractures or degenerative and metabolic conditions of thinning bone structures, and thus it is recommended that in future studies, a large observer sample and range of other appendicular MSK bodies parts are imaging using this modified 10 kV technique to see if the VGA scores are reproduced and what affect on a range of diagnosing pathological condition there might be.

At present, there is a paucity of 10 kV MSK studies using DR systems to compare data against. A study by Coffey et al.[27] applying the traditional 10 kV rule (50 % decrease in mAs) produced similar results for shoulder and hand X-rays using DR systems, which lowered ESD and still maintained or improved image quality compared to the DR system pre-set techniques. Coffey et al.[27] found an increase in the ESD of the knee X-rays using the historic 10 kV rule (50 % decrease in mAs) compared to the pre-set exposure techniques, which was not replicated in this study.

Table 3
Comparison for the AP knee X-ray position examination image quality across all exposure parameters.

Exposure parameter	Knee Position	VGA Criteria	Clearly Inferior (−2)	Slightly Inferior (−1)	Equal (0)	Slightly Superior (+1)	Clearly Superior (+2)	Mean score	Overall mean score
Standard preset	AP	Soft tissue	0	0	7	0	2	0.4	0.4
		Trabeculae pattern	0	0	7	0	2	0.4	
		Cortical outline	0	0	7	0	2	0.4	
		Femoral condyles	0	0	7	0	2	0.4	
10 kV (−50 % mAs)	AP	Soft tissue	0	0	7	1	1	0.3	0.1
		Trabeculae pattern	0	3	4	1	1	0	
		Cortical outline	0	2	5	1	1	0.1	
		Femoral condyles	0	2	5	1	1	0.1	
10 kV (−75 % mAs)	AP	Soft tissue	0	0	6	3	0	0.3	0.3
		Trabeculae pattern	0	1	4	4	0	0.3	
		Cortical outline	0	1	5	3	0	0.2	
		Femoral condyles	0	0	6	3	0	0.3	

ANOVA (AP Knee Standard preset vs. 10 kV (-50 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
Standard preset AP	4	1.6	0.4	0		
10 kV (50 % decrease in mAs) AP	4	0.5	0.13	0.02		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.15	1	0.15	19.11	0.00	5.99
Within Groups	0.05	6	0.01			
Total	0.20	7				

ANOVA (AP Knee Standard preset vs. 10 kV (-75 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
Standard preset AP	4	1.6	0.4	0		
10 kV (75 % decrease in mAs) AP	4	1.1	0.28	0.00		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.03	1	0.03	25	0.00	5.99
Within Groups	0.01	6	0.00			
Total	0.04	7				

ANOVA (AP Knee 10 kV (-50 % mAs) vs. 10 kV (-75 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
10 kV (50 % decrease in mAs) AP	4	0.5	0.13	0.02		
10 kV (75 % decrease in mAs) AP	4	1.1	0.28	0.00		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.05	1	0.05	4.91	0.07	5.99
Within Groups	0.06	6	0.01			
Total	0.1	7				

The addition of copper (Cu) filtration may further the practice of the 10 kV rule by reducing the dose further whilst improving image quality. Mifsud et al.[55] demonstrated the use of Cu filtration to absorb low-energy photons (reduce noise) and assist the beam hardening (higher energy spectrum from higher kV) of increasing by 10 kV in knee (AP view) X-rays using DR image acquisition and VGA image assessment. However, the effects of the modified kV exposures with Cu filtration on the ESD of the AP knees were not measured[55] (only tube output via the DAP meter reading adjacent to the CU filter). Mifsud et al.[55] noted a decrease in DAP output, a small contrast-to-noise (CNR) ratio decrease, but a minor reduction in image quality (−4.05 %).

It could be argued that DR imaging systems are much more capable today due to the broader exposure latitudes and post-processing algorithms to compensate for underexposure (low mAs) to reduce grain and quantum mottle appearances.[17] The clinical application of 10 kV rules is more implementable in MSK X-ray DR imaging today than when 10 kV adaptions were initially introduced in film screen radiography. Assisted also in part by DR systems not utilising characteristic curve response in dynamic range/latitude for image contrast.[14] Thus, they have the potential to counterbalance DR dose creep behaviours[11,56] and maintain ALARP principles to reduce the radiation dose to patients through optimisation techniques.[57]

A limitation of this pilot study was the small sample size (anatomical body part), which recorded two outliner TLD doses. A more extensive data set may explore these erroneous values further as well as other appendicular MSK examinations. Furthermore, the historic 10 kV rule generally only applies for exposures between 60 and 100 kV,[24,25] whilst it could be assumed the modified 10 kV rule would be the same; further testing over the full diagnostic tube potential range of exposures would be required to confirm.

The expectation of the modified 10 kV (75 % decrease in mAs) exposure parameter may produce slightly inferior quality knee X-ray images (due to photon starvation causing quantum mottle) than the pre-set knee exposure parameter, which may have been a contributor in the lateral knee VGA scores. However, the modified 10 kV AP views scored higher than the historic 10 kV parameter, similar to the pre-set knee exposure parameter. A follow-up with a larger population of observers (to include clinicans who report X-ray images) will reduce subjective bias in the VGA assessment and a larger sample size of different human knee thickness[24] (grid and non-grid exposures) on a range of different X-ray vendor equipment

Table 4
Comparison for the lateral knee X-ray position examination image quality across all exposure parameters.

Exposure parameter	Knee Position	Structures	Clearly Inferior (−2)	Slightly Inferior (−1)	Equal (0)	Slightly Superior (+1)	Clearly Superior (+2)	Mean score	Overall mean score
Standard preset	Lateral	Soft tissue	0	0	7	0	2	0.4	0.3
		Trabeculae pattern	0	2	4	1	2	0.3	
		Cortical outline	0	3	4	0	2	0.2	
		Femoral condyles	0	0	7	0	2	0.4	
10 kV (−50 % mAs)	Lateral	Soft tissue	0	0	7	2	0	0.2	−0.1
		Trabeculae pattern	3	0	4	2	0	−0.4	
		Cortical outline	1	2	4	2	0	−0.2	
		Femoral condyles	0	3	4	2	0	−0.1	
10 kV (−75 % mAs)	Lateral	Soft tissue	0	2	5	2	0	0	−0.3
		Trabeculae pattern	0	6	1	2	0	−0.4	
		Cortical outline	0	6	1	2	0	−0.4	
		Femoral condyles	1	3	3	2	0	−0.3	

ANOVA (lateral Knee Standard preset vs. 10 kV (-50 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
Standard preset lateral	4	1.3	0.33	0.01		
10 kV (50 % decrease in mAs) lateral	4	−0.5	−0.13	0.06		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.41	1	0.41	11.30	0.02	5.99
Within Groups	0.22	6	0.04			
Total	0.62	7				

ANOVA (lateral Knee Standard preset vs. 10 kV (-75 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
Standard preset lateral	4	1.3	0.33	0.01		
10 kV (75 % decrease in mAs) lateral	4	−1.1	−0.28	0.04		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.72	1	0.72	32	0.00	5.99
Within Groups	0.14	6	0.02			
Total	0.86	7				

ANOVA (lateral Knee 10 kV (-50 % mAs) vs. 10 kV (-75 % mAs)

Exposure parameter	VGA Criteria	Sum	VGA Mean	Variance		
10 kV (50 % decrease in mAs) lateral	4	−0.5	−0.13	0.06		
10 kV (75 % decrease in mAs) lateral	4	−1.1	−0.28	0.04		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.05	1	0.05	0.92	0.38	5.99
Within Groups	0.30	6	0.05			
Total	0.34	7				

may display the trabeculae pattern and bone cortex differently than the non-grid phantom images were able to in this study.

Conclusion

This study findings in laboratory conditions with a knee phantom have highlighted the X-ray ESD reduction that can be made by adapting exposure factors whilst attaining diagnostic quality images.

The ESD reduction was significant for the historic 10 kV rule (50 % decrease in mAs) 32.1–33.7 % (20.9 μGy; $p = 0.00$), and the modified 10 kV rule (75 % decrease in mAs) 81.5–81.8 % (42.1–43.7 μGy; $p = 0.00$) exposure parameters.

The image quality assessment using VGA observer data for the AP view reported higher than the average expected image quality of a knee x-ray for all exposures. The historic and modified 10 kV exposure parameters image quality for the AP views knee X-rays scored higher ($p = 0.00$) than the pre-set exposure. The VGA findings for the lateral view of the historic (−0.1 VGA) and the modified 10 kV (−0.3 VGA) were slightly lower than the pre-set image quality, although not statistically significant $p = 0.02$ and $p = 0.00$. The minor differences related to the bony quality of the trabeculae pattern and cortical outlines; however, all the image's overall mean VGA scores deemed them diagnostic.

Further research is recommended on the modified 10 kV (75 % decrease in mAs) exposure parameter is recommended using a wider range of kV, multiple vendor equipment, different anatomical thicknesses (to include greater than 15 cm thickness utilsing AEC equipment), and a large sample of image quality observers to assess the efficacy and validity of the technique before application in the clinical environment.

Conflict of interest statement

None.

Acknowledgements

None.

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