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Dose and Perception of Quality in Digital Radiography

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Image-Quality Perception as a Function of Dose in Digital Radiography

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OBJECTIVE. The purpose of this article is to determine the degree to which the skin entrance dose could be lowered, by adjusting exposure parameters and filtration, and the subsequent effect on readers' confidence levels of digital radiographs.

MATERIALS AND METHODS. The study was prospectively performed on a cadaver. Digital radiographs of bones were evaluated and scored on a 9 point-scale separately by four radiologists who were blinded to the types of filtration and doses used. The study entailed three phases: phase 1, random dose and filter; phase 2, fixed filter and varying radiation doses (100%, 75%, 50%, and 25% of the standard recommended dose); and phase 3, fixed dose and varying filtration (no filtration, aluminum filter, and aluminum-copper filter). Skin entrance dose was measured using a dosimeter placed on the skin. Differences in scores were tested using a Friedman test.

RESULTS. The mean scores given to images with 100%, 75%, 50%, and 25% of the recommended standard dose were 6.18, 6.1, 5.11, and 4.07, respectively. No significant difference was noted between 100%- and 75%-dose images ($p = 0.1$). A significant difference ($p < 0.0001$) was noted when we compared the 100%- and 75%-dose images with the 50%- and 25%-dose images. The mean scores given for no filtration, aluminum filtration, and aluminum-copper filtration were 5.67, 5.43, and 5.18, respectively. No significant difference between no filtration and aluminum filtration ($p = 0.411$) was noted. A significant difference was detected between no filtration and aluminum-copper filtration ($p = 0.012$). The combination of an aluminum filter and a 75% standard dose achieved a 31.1% reduction in skin entrance dose.

CONCLUSION. It is possible to achieve a 31.1% reduction in skin entrance dose for imaging bony structures by using 75% of the standard dose and aluminum filtration without significantly affecting image quality.

Keywords: digital radiography, filtration, image quality, musculoskeletal imaging, skin entrance dose

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Advances in diagnostic imaging are contributing substantially to improved healthcare worldwide. One of these advances is digital radiography. Although digital techniques in radiology have the potential to reduce patient dose, their practical use also carries the risk of increased patient dose [1]. One of the main causes of this increase is the wide dynamic range of digital imaging systems, allowing overexposure with no adverse effect on image quality [2].

Radiation-induced effects can be divided into deterministic and stochastic effects. Deterministic effects (e.g., erythema or epilation) occur only after exceeding a certain threshold of radiation exposure, below which the effect is not observed. Conversely, stochastic effects (e.g., induction of cancer or genetic damage) are often assumed to have no clearly defined threshold. Under this assumption, the likelihood of their occurrence increases with an increase in the absorbed radiation dose, but the severity of the effect will not change regardless of the dose [3].

Previously published work [2, 4, 5] addressed radiation dose in radiography and provided recommendations for reducing patient exposure, including better training of radiographers, increased awareness of radiation exposure and hazards, and so forth.

Because the patient will be exposed to ionizing radiation, all procedures and radiation exposure should be governed by the "As Low As Reasonably Achievable" principle [6]. Hence, the delicate balance in diagnostic imaging is to obtain an image that is adequate for the clinical purpose with the minimum radiation dose

[7]. The current study was formulated to determine the degree to which the skin entrance dose could be lowered, by adjusting exposure parameters and filtration, and the effect on reader confidence levels in the diagnostic task.

Materials and Methods

This study was approved by our institutional review board. The study was performed on body parts of a cadaver. The cadaver was a fresh male cadaver aged 58 years. Imaging of the cadaver was performed within the first 6 hours after death, and the cadaver was not preserved with any form of preservation. All imaging procedures were performed using the same imaging system (Kodak DirectView DR 7500, Carestream Health) with the following specifications: pixel pitch, 143 μm; effective active area, 429 × 429 mm; image matrix size, 3000 × 3000; geometric fill factor, 100%; thalium-doped cesium iodide absorber layer, 500 μm; ADC, 14 bits; and standard filtration, 2.8 mm of aluminum. The nominal speed of the digital radiography detector as used was 400 speed. Skin entrance dose was measured using a dosimeter (Mult-O-Meter 503 L, Unfors Instruments) placed at the level of the cadaver part to be imaged.

Digital radiographs were evaluated and scored by four senior radiologists with more than 5, 8, 12, and 15 years of experience, respectively, in radiology. The imaged cadaver parts included the hand, wrist, forearm, elbow, foot, ankle, lower leg, knee, lumbar spine, and thoracic spine. Digital radiography images were created in two projections (anteroposterior and lateral) for all parts. In total, 240 digital radiography images were evaluated and reviewed on a clinical diagnostic workstation with no time limits imposed. Readers were also able to change the image presentation by adjusting the window width and level.

Because the study design entails the use of a single human body part and its exposure to radiation several times using different exposure parameters and filtration, the current study could not be performed on living human subjects for ethical reasons and because of the potential radiation exposure hazards. Similarly, an animal model could not be used because the exposure parameters and standard doses recommended for humans could not be transferred to animals without modification. Hence, we tried to simulate the real situation in humans by imaging body parts of a fresh human cadaver.

Study Design

The current study included three phases. Throughout the study, the readers performed their evaluations separately and were totally blinded to the study aim and design, as well as the radiation dose and filtration used for each image. The readers reviewed the images on a PACS workstation (Centricity, GE Healthcare) that was calibrated according to the DICOM gray-scale display function in accordance with our national standards and recommendation. All readers had identical workstations and monitors, and all reading sessions were performed at full resolution under the same ambient light conditions. Reading was performed using a single monitor, and images were displayed on the monitor at full resolution one after the other. All images were provided randomly to all readers in each phase of the study. Readers were provided with a scoring table (Table 1) and were asked to use this 9-point scale for their assessments. A score of 1 meant that the image was inadequate for the diagnostic purpose (defined as the ability to detect fractures, joint abnormalities, different forms of bony lesions, different forms of periosteal reactions, and bone texture abnormalities), and a score of 9 meant that the image was optimal. The wide rating scale was adopted to provide more flexibility to the reader.

Study Phases

The current study was performed in three phases with 4-week intervals between each phase and the next one to abolish the memory effect of the readers. In all phases, the readers were requested to give a score for each image separately using the 9-point score system and to rank each image among each set of given images in phases 2 and 3. Table 2 summarizes the design of the study phases. The radiation dose was varied by changing the product of tube current and exposure time (mAs) in steps of 25%—that is, we used 100% of the recommended standard dose for a specific body part (standard dose and exposure parameters are given by the European and the German Guidelines for digital radiography), as well as 75%, 50%, and 25% of the recommended dose. The x-ray tube potential (kVp) was kept constant in all phases of the study and was varied only with respect to the body part to be imaged. Tube filtration was performed for further skin entrance dose reduction, and we used three filtration models: no filtration (i.e., no added filter was used), aluminum filtration, and aluminum-copper filtration. The thickness of the aluminum filter used was 1 mm, and that of the aluminum-copper filter was 1 mm of aluminum plus 0.1 mm of copper.

Phase 1—Each reader was provided with a single digital radiography image for rating. Images were randomized with regard to radiation dose and filtration. This phase of the study was included for two purposes: first, it constituted the pilot part of the study; and second, it supported the results obtained from the other two phases through an even more randomized phase wherein both the dose and filter were randomized. In phase 1, all 240 images were evaluated in a randomized fashion.

Phase 2—In phase 2, each reader was provided with three groups, each containing four images for each body part. Each group represented a single filter choice (no filter, aluminum filter, and aluminum-copper filter), whereas the four images represented different radiation doses. Thus, in phase 2, the filter was fixed, and for each filter type, four images were obtained using different radiation doses (100%, 75%, 50%, and 25% of the recommended standard dose).

Phase 3—In phase 3, each reader was provided with four groups, each containing three images for each body part. Each group represented a single dose level (100%, 75%, 50%, and 25% of the recommended standard dose), whereas the three images represented different filter choices. Thus, in phase 3, the radiation dose was fixed but the filter was changed (no filter, aluminum filter, or aluminum-copper filter).

TABLE 1: Definition of Rating Scale Used for Image Quality Evaluation

Image Quality Score	Definition	Interpretation
9	Very satisfied	Optimal for evaluating the relevant diagnostic information
8		
7	Satisfied	Acceptable for interpretation; no loss of diagnostic information
6		
5	Neither satisfied nor dissatisfied	Suboptimal image; bordering on loss of diagnostic information
4		
3	Dissatisfied	Poor image that impairs interpretation; important diagnostic information could be lost
2		
1	Very dissatisfied	Inadequate for diagnosis; definite loss of information

TABLE 2: Designs of Study Phases

Variable	Phase 1	Phase 2	Phase 3
No. of images	One at a time	Three groups of four images each	Four groups of three images each
Radiation dose	Random	Varying	Fixed
Filtration	Random	Fixed	Varying

TABLE 3: Scores Given for Each Radiation Dose and Filter Type Used

Dose and Filter	No. of Images	Score	
		Mean ± SD	Median (Range)
Percentage radiation dose			
100	60	6.18 ± 1.74	6 (2–9)
75	60	6.1 ± 1.68	7 (2–9)
50	60	5.11 ± 2.32	5 (1–9)
25	60	4.07 ± 2.67	4 (1–9)
Filter			
None	80	5.67 ± 2.14	6 (1–9)
Aluminum	80	5.43 ± 2.23	6 (1–9)
Aluminum-copper	80	5.18 ± 2.40	5 (1–9)

Data Collection and Statistical Analysis

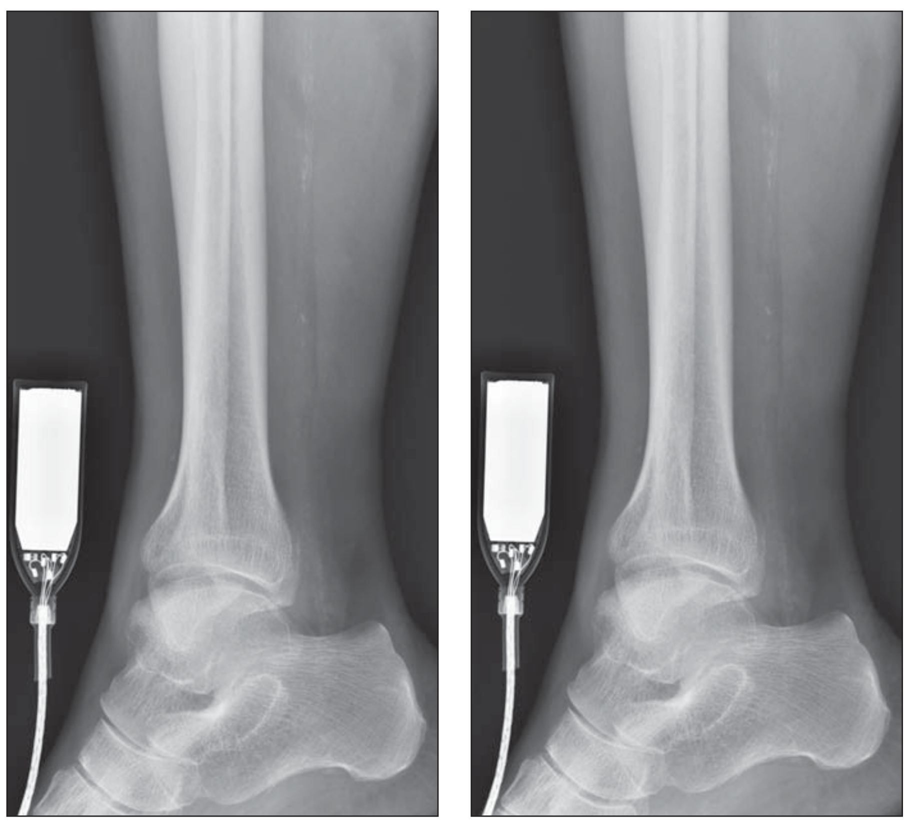
All reader scores were collected and tabulated. Interobserver differences for all scores from all radiation doses and filters were evaluated using an intraclass correlation test to determine whether there was statistically significant agreement between the four observers. For each image evaluated, the average of score from all reviewers was calculated, and the differences in scores related to each radiation dose and to each filter were tested for statistical significance using a Friedman test with multiple comparisons. All statistical analyses were performed using BiAS for Windows software (epsilon-Verlag).

Results

Statistical analysis using intraclass correlation test showed the presence of statistically significant agreement among all four reviewers ($p = 0.002768$).

Radiation Dose

Table 3 summarizes the mean (± SD) score as well as the range and median of the scores given to the images from all reviewers with respect to each radiation dose. The mean score given to images with 100% of the recommended standard radiation dose was 6.18 (median, 6), whereas that given to 75% of the recommended standard radiation dose was 6.1 (median, 7) (Figs. 1A and 1B). Statistical analysis using a Friedman test with multiple comparisons showed no statistically significant difference between the scores given to images obtained with 100% of the recommended standard radiation dose and those obtained with 75% of the recommended standard radiation dose ($p = 0.1$). A statistically significant difference was detected between scores given to images obtained with a 100% dose and those obtained with 50% and 25% of the standard radiation dose ($p < 0.0001$ and $p < 0.0001$, respectively). In addition, a statistically significant difference was detected between scores given to images obtained with a 75% dose and those obtained with 50% and 25% of the standard radiation dose ($p < 0.0001$ and $p < 0.0001$, respectively). No statistically significant difference was noted between the scores given to images obtained with 50% of the standard radiation dose and 25% of the standard radiation dose ($p = 0.08$). Table 4 shows the percentage reduction in skin entrance dose in relation to each change in the given radiation dose. It is worth mentioning that a reduction of standard radiation dose from 100% to 75% was associated with a 23.8% reduction in the skin entrance dose.



A **B**

Fig. 1—Examples of images obtained at different doses with no added filtration.
A, Image was obtained at 100% of standard dose.
B, Image was obtained at 75% of standard dose.

TABLE 4: Percentage of Skin Entrance Dose Relative to the Value Under Standard Dose Conditions, for Various Combinations of Radiation Dose and Filtration

Filtration	Skin Entrance Dose Relative to Standard Condition (%)			
	100% mAs	75% mAs	50% mAs	25% mAs
None	100	76.2	52.3	27.1
Aluminum	90.6	68.9	45.9	24.8
Aluminum-copper	70.9	56.6	37.3	18.3

Filtration

Table 3 summarizes the mean score as well as the range of scores given to the images from all reviewers with respect to each filtration type. The mean score given to images with no filtration was 5.67 (median, 6), whereas that given to images obtained with aluminum and aluminum-copper filters were 5.43 (median, 6) and 5.18 (median, 5), respectively (Figs. 2A and 2B). Statistical analysis using Friedman test with multiple comparisons showed no statistically significant difference between the scores given to images obtained with no filtration and those obtained with aluminum filtration ($p = 0.411$). A statistically significant difference was detected between scores given to images obtained with no filtration and those obtained with aluminum-copper filtration ($p = 0.012$). In addition, no statistically significant difference was detected between scores given to images obtained with aluminum filtration and those obtained with aluminum-copper filtration ($p = 0.061$). Table 4 shows the percentage of skin entrance dose relative to the value under standard dose conditions, for various combinations of radiation dose and filtration. It is worth mentioning that the skin entrance dose is reduced by an extra 7.3% when 75% of the standard radiation dose is used with an aluminum filter and by 9.4% when 100% of the standard radiation dose was used.

Image Ranking

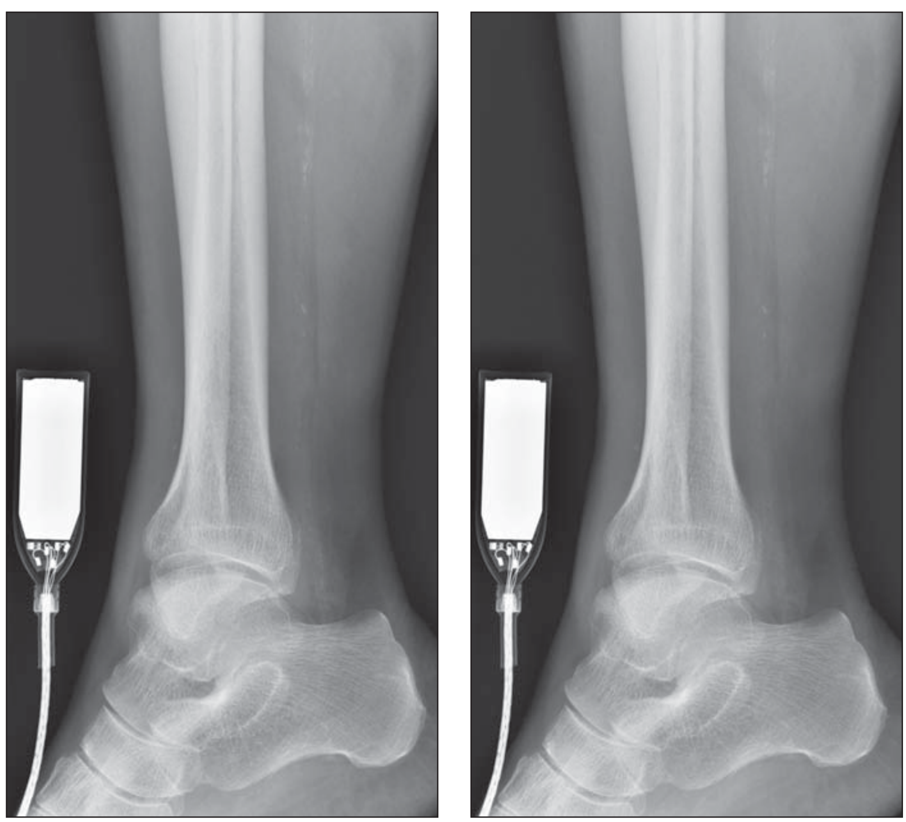
For images obtained without filtration, the four reviewers could not differentiate between images obtained with 100% and 75% of the recommended radiation dose in 54.17% of cases, and they could not recognize the difference between the images obtained with 75% and 50% of the standard dose and those obtained with 50% and 25% in 37.5% and 31.25% of cases. In the case of aluminum filtration, the percentages of inability to recognize the difference between 100% and 75%, 75% and 50%, and between 50% and 25% of the standard radiation dose were 62.5%, 29.17%, and 30% respectively. In the case of aluminum-copper filtration, the percentages of inability to recognize the difference between 100% and 75%, 75% and 50%, and between 50% and 25% of the standard radiation dose were 66.67%, 33.33%, and 20.83%, respectively.

Discussion

Ever since the first introduction of x-ray in medical usage, it has always been the aim of radiologists over time to reach an accurate diagnosis with minimal radiation exposure. Digital radiography is a technology that is advancing rapidly and will soon affect hundreds of millions of patients. If careful attention is not paid to radiation protection issues in digital radiology, medical exposure of patients could increase significantly without concurrent benefit [8]. Patient dosimetry and evaluation of image quality are basic aspects of any quality control program in diagnostic radiology. Image quality must be adequate for diagnosis and obtained with reasonable patient doses [5]. No dose limit applies to medical exposure to patients, but diagnostic reference levels or reference values have been proposed by the International Commission on Radiologic Protection [9, 10], and specific legislation and guidelines requiring member states to adopt such diagnostic reference levels have been published in the European Union [11, 12].

In the current study, we gradually reduced the radiation dose by reducing the exposure at the machine level and by using additional tube filtration, while at the same time evaluating the diagnostic usability of the resulting images and the readers' diagnostic confidence.

In the current study, it was noted that the use of 75% of the standard radiation expo-



A B

Fig. 2—Examples of images obtained at 75% of standard dose with filtration.
A, Image was obtained with aluminum filtration.
B, Image was obtained with aluminum-copper filtration.

sure was associated with a 23.8% reduction in the skin entrance dose, but was not associated with a statistically significant reduction of the reader scores compared with those obtained using the standard radiation dose. Similarly, it was also noted that the use of aluminum tube filtration was associated with an additional 7.3% reduction of the skin entrance dose, without a statistically significant difference in the scores compared with images obtained with no filtration. Thus, it is possible to achieve an overall reduction of the skin entrance radiation dose by 31.1% by using 75% of the standard exposure parameters and added aluminum filtration without significantly affecting the image quality or the diagnostic confidence level of the readers.

Hamer et al. [13] conducted a study on chest radiographs with a design similar to phase 3 of the current study, where they evaluated the image quality of chest radiographs after the addition of copper filtration. They concluded that the use of copper filtration resulted in a 30% radiation dose reduction, with similar image quality observed in images obtained with and those obtained without copper filtration. We achieved similar image quality through the addition of an aluminum filter, which resulted in a skin entrance dose reduction of only 9.4% (at 100% of the standard dose). The difference between both studies can probably be attributed to the difference in filter thickness (0.3 mm in the study by Hamer et al.) and the difference in the filter material used. In addition, the standards for image quality regarding chest radiographs are different from those used in extremity imaging.

Limitations of the current study include the imaging of body parts of cadavers. However, for ethical reasons and because of the special design of the current study, it was not possible to perform the current study on living humans. A second limitation is the restriction to joints and bony structures and the exclusion of chest or abdominal radiographs. However, because of the study design and the use of a cadaver, we included only structures that are most likely to remain unaffected by the postmortem status. In this way, the study stays as close as possible to the real clinical situation and allows recommendations to be made that can be directly transferred to living humans. A third limitation is the fact that the imaged bony structures were healthy; however, we tried to overcome this limitation by blinding the reviewers to circumstances of death and the fact that the cadaver does not contain any known bony abnormality to us.

We regard the current study as a basis for the conduct of similar studies on living humans using a randomized study design with different body parts and disease entities and with different filter materials and thicknesses, with the goal of minimizing skin entrance dose without affecting image quality and the diagnostic confidence level of the reading radiologist.

Thus, we conclude that it is possible to achieve up to 31.1% reduction of the skin entrance dose while imaging bony structures by using 75% of the recommended standard radiation dose and added aluminum filtration at the same time without affecting the image quality or the degree of confidence of the reading radiologist in making a diagnosis from the provided image.

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