Impact of Electronic Collimation on Reducing Unnecessary Patient Dose in Digital Radiography

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ABSTRACT

Background: In radiology, optimizing radiation protection is crucial, and field collimation plays a critical role in minimizing patient dose. As technology has evolved, electronic collimation has become the preferred method due to its effectiveness in digital imaging systems, replacing traditional film-screen systems.

Objective: The current study aimed to investigate the prevalence of cropping in digital radiography and its potential impact on patient radiation dose because of improper collimation practices.

Material and Methods: This retrospective analysis was conducted on digital X-ray machine images. Quality control tests were performed to ensure equipment accuracy, and image cropping was then measured by analyzing archived images. Finally, the cropped image fraction and associated unnecessary radiation doses were calculated.

Results: Quality control tests confirmed that all imaging equipment was functioned within acceptable alignment and angle tolerances. The analysis of 911 images revealed a high prevalence of cropping (82%), with significant variation across different projections. Lateral knee images exhibited the highest cropping rate (96.2%), while abdominal images had the lowest (36.1%).

Conclusion: Electronic image cropping can lead radiologic technologists to inaccurately define the primary radiation field, affecting image quality and potentially increasing patient radiation exposure. Based on the obtained results, proper collimation can reduce the average Dose Area Product (DAP) by 29.01%. This approach not only enhances patient safety but also minimizes unnecessary radiation exposure and potentially reduces healthcare costs.

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Keywords
Digital Radiography; Radiation Protection; Electronic Collimation; Radiation Dosage; Quality Control Radiologic; Diagnostic Reference Levels

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Introduction

In radiation protection, optimization plays a key role. The ALARA principle aimed to minimize radiation dose while maintaining necessary image quality parameters [1]. In radiography, the collimation of the radiation field is utilized to reduce exposure [2]. In the past, the limited size of the film-screen system and the high cost of radiographic film prevented unnecessary irradiation of patients with larger fields [3]. Experienced radiologic technologists would capture both projections of a limb using a single cassette [4] and also position the organ center in the middle of the light field after setting up the tube with a detector, leading to easier limitation of the radiation field. Consequently, experienced technologists can accurately identify landmarks and adjust the radiation beam to the specific Region of Interest (ROI) to properly position the radiation beam center [5].

Flat-panel detectors led to digital production of radiographic images [6]. The reduced cost and time required to create images, along with the capability of transferring and electronically archiving them, and the potential for post-processing, have significantly contributed to the complete replacement of the film-screen system by digital radiography [7]. Image post-processing resulted in adjusting image contrast and density with the capability for electronic collimation [8] to remove unnecessary parts of an image; this process is intended to eliminate the penumbra effect of the collimator. However, it is frequently misused to exclude images of body parts that have been unnecessarily exposed to radiation [9]. On the other hand, removing parts of the image by technicians might result in missing valuable information, which were not detected by the technician. Meanwhile, the patient should be informed about the information acquired during an X-ray examination [10].

However, the mentioned problems can lead to the negligence of radiologic technologists regarding the ALARA principle. Useful information might be lost by cropping the image because following up on this issue is not as straightforward as with the film-screen system. After sending the cropped image from the workstation to PACS, the original image cannot be viewed in PACS, and only the cropped image is displayed [7]. Based on imaging protocols, the radiation field should be limited to the anatomical area. In some projections, such as Anterior-Posterior (AP) and lateral skull, the field should be open one inch beyond the border of the structure [11]. However, for other projections, the protocols do not have absolute certainty, depending on the radiologic technologist's opinion to determine the radiation field [12]. The current study aimed to examine the extent of cropping in digital radiography techniques and determine the additional dose.

Material and Methods

Hospital

This retrospective analytic study was conducted by reviewing radiographic images archived in the hospital's database, Kowsar Hospital, Semnan, Iran. A total of 26 radiographers, with an average of 6.4 years of professional experience, operated the machine in mandatory shifts. The department provided services to outpatients from hospital clinics, emergency rooms, and hospital wards, excluding pediatric and women's specialties. This unit is equipped with a direct digital X-ray machine (a TOSHIBA ROTANODE model (E7275X, Japan)), and the radiography patient couch is a SYFM model (ST – 3300, Korea) with a flat panel size of 43×43 cm^2. The device's software is Konica Minolta cs-7, displaying the radiation parameters, including the tube voltage (kVp), tube current (mA), time (s), and the Dose-Area Product (DAP) in $dGy.cm^2$ after the radiography in the radiation parameters. Using the system software, the dimensions of the image field can be obtained with an accuracy of 1 mm. After the image was retrieved from the database archive, the cropped image was displayed by the radiologic technologist (Figures 1-3). The dimensions of the cropped image are first recorded and then reverted into the pre-cropping state to record the dimensions of the original radiation field and measure the extent of the image cropping.

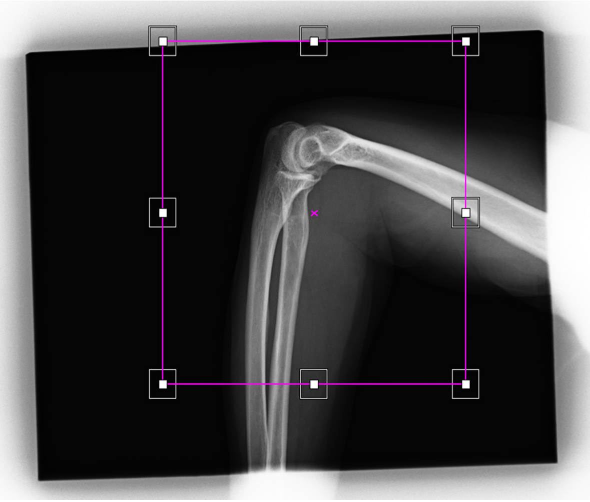

Figure 1: Represents the electronic collimation field, the radiographic collimation field, and the silver line in the lateral projection of the elbow.

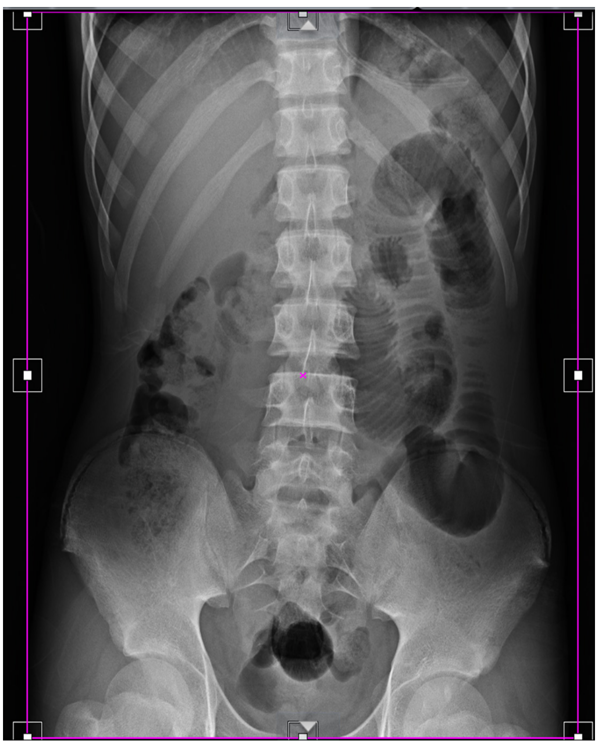

Figure 2: Anteroposterior (AP) projection of the abdomen showing minimal cropping on the sides.

Quality Control

Quality control tests were first conducted to ensure the adjusted light field aligned with the X-ray field, as any misalignment can lead to unnecessary patient radiation exposure.

For this test, a Pro-Digi radiography phantom was employed, and the light field of the device was adjusted to match the phantom's 18×24 cm^2 field lines, with the Source-to-Image Distance (SID) set at 100 cm. Exposure was performed using conditions of 50 kVp and 3 mAs, and the deviation of the radiation field from the light field lines was measured using the ruler tool with an acceptable deviation of <±2 cm on each side [13].

A cylinder with a height of 10 cm, with a ring at the beginning and a pellet at the end, was used to verify the accuracy of the radiation angle. The SID was set at 100 cm. The center of the radiation beam was then directed to the middle of the cylinder using exposure conditions of 50 kVp and 3 mAs. Following that, the deviation of the pellet from the center of the ring was measured using the ruler tool in the workstation software (deviation < less than ±1 cm) [13].

Data Collection

A total of 36 projections were evaluated (Table 1), and patient images were included in the study in both a sequential and random manner. Only the dimensions of the organ under examination were effective variables in the collimation of the radiation beam. The information was retrospectively reviewed from the image archive to avoid any potential interference from radiologic technologists and students.

Data Analysis

The cropped fraction, the ratio of the cropped area to the original image area, was calculated for the evaluation of each image, and the average amount was computed (Equation 1) [14]. The unnecessary dose was obtained by

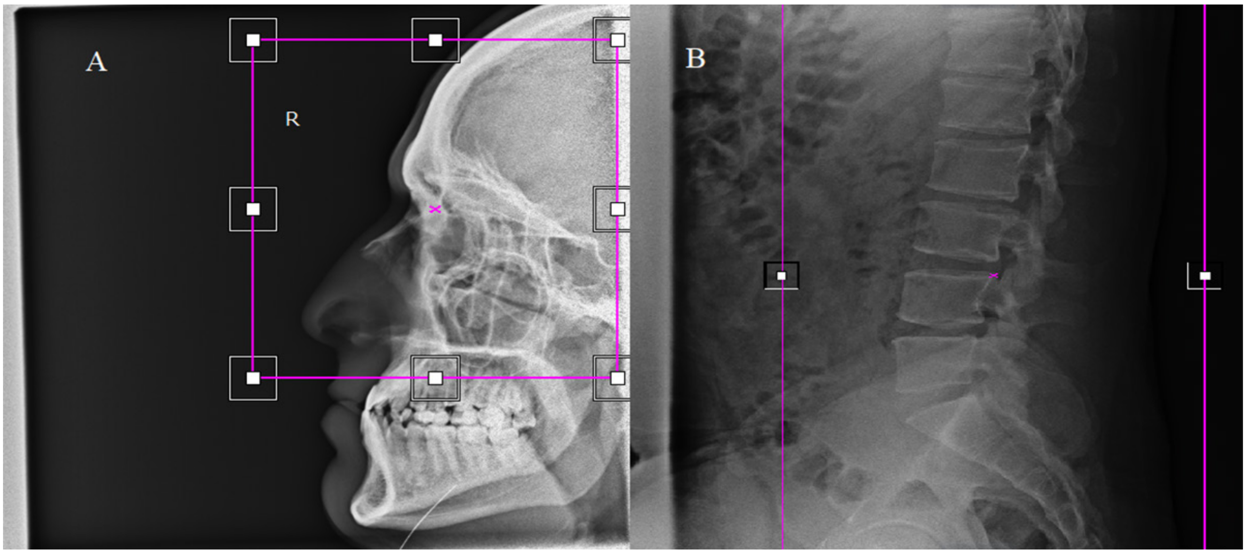

Figure 3: Lateral projections of the lumbar vertebrae and nose. Although the cropped fraction is higher in the nose, the unnecessary dose from radiation exposure to non-essential areas is higher in the lumbar spine.

Table 1: The 36 projections studied for evaluating the crop fraction and unnecessary dose.

Region	Projection	Region	Projection	Region	Projection
Abdomen	AP	T spine	AP, LAT	Elbow	AP, LAT
Pelvic	AP	L spine	AP, LAT	Humerus	AP, LAT
Chest	AP, PA, LAT	Hand	PA, OBL	Shoulder	AP, LAT
Skull	AP, LAT	Wrist	AP, LAT	Foot	AP, OBL
C spine	AP, LAT	Forearm	AP, LAT	Ankle	AP, LAT
Leg	AP, LAT	Knee	AP, LAT	Femur	AP, LAT

AP: Anteroposterior, PA: Posteroanterior, LAT: Lateral, OBL: Oblique

multiplying the DAP by the cropped fraction for each image. Furthermore, the percentage of unnecessary doses was calculated from the ratio of the unnecessary dose to the DAP of each image.

$$\text{cropped fraction} = \frac{\text{area of radiation field} - \text{area of electronic collimation}}{\text{area of radiation field}} \quad (1)$$

Data with normal distribution were assessed using the t-test statistical method to evaluate any significant difference between the area of the initial image and electronic collimation. For non-normally distributed data, the Mann-Whitney test was utilized. All statistical tests were performed using a significance threshold of P-value<0.05. The statistical analysis was carried out using Microsoft Office Excel 2024 and IBM SPSS Statistics version 26 software.

Results

Quality Control

The quality control of radiographic devices importantly affects the reduction of unnecessary patient doses. In the present study, the quality control tests of the radiographic equipment are reported at Kowsar Hospital, Semnan, Iran, and the alignment of the light field with the radiation field was first assessed with the acceptable range of ±2 cm of deviation at 100 cm SID from each side of the radiation field (Table 2).

Subsequently, the accuracy of the radiation angle was tested with a 0.2-centimeter deviation of the pellet image from the center of the circle, which is well within the defined standard range of 1 cm. The outcomes of these tests indicate the device's satisfactory performance in producing quality images.

Cropped Fraction

In total, 911 radiographic images were evaluated from the database archive. The extent of image cropping and unnecessary radiation dose to patients was analyzed. According to the results, 82% of all examined images were cropped, and the remaining images were then sent to the PACS without any cropping. Among the cropped images, projections related to joints and the vertebral column had the highest share, leading to cropping in 96.2% of knee lateral projection images. Images of larger body regions, like the abdomen and femur, showed the least cropping. In fact, only 36.1% of abdominal X-ray images required cropping.

The results obtained from the current study for 36 projections are shown in Table 3. Statistical analyses related to the area of electronic collimation in comparison to the area of the radiation field showed significant differences for all projections (P-value<0.05).

Figure 4 displays the difference between the area of the radiation field and electronic collimation for each projection. These differences clearly highlighted the necessity of optimization in the process of primary beam collimation.

Table 2: Results of the alignment test between the light field and the radiation field.

Direction	Deviation (cm)
Right	0.9
Left	0.9
UP	0.5
Down	0.5

As shown in Figure 5, the lateral projections of the cervical spine, the AP projection of the skull, and both the anterior and lateral projections of the elbow exhibited higher cropped fractions compared to other projections. Among these, the lateral projection of the elbow has the highest cropped fraction, at 0.466. Conversely, the anterior projection of the abdomen has the lowest cropped fraction, at 0.068.

Additional Dose

Based on the results of the present study, which assessed the DAP across various projections, the highest and lowest DAP values were observed in the lateral projection of the lumbar vertebrae and the nasal bone, with an average of 5.40 and 0.04 dGy.cm^2, respectively. Additionally, this research revealed that, among the 36 analyzed projections, the dose ranged from 0.017 to 1.444 dGy.cm^2 for areas subjected to supplementary radiation. As illustrated in Figure 6, projections involving large body areas and high exposure parameters, such as those of the spine, are subject to greater amounts of unnecessary radiation. Therefore, precision in the application of radiological collimation for these projections is of paramount importance.

The additional dose percentage was calculated for each projection's images. The results indicate that the lateral projection of the

Table 3: Findings for the 36 radiographic projections studied.

Region	Projection	Sample	Cropped image%	Mean Area radiation field (cm²)	Mean Area electronic collimation (cm²)	*P*-Value	Mean Cropped fraction	Mean Area Dose (dGy. cm²)	Additional Dose (dGy. cm²)	Additional Dose%
Abdomen	AP	36	36.1	1742	1603	0.043	0.068	3.72	0.254	5.55
Pelvis	AP	24	75.0	1740	1415	0.000	0.188	3.43	0.648	17.14
Nasal	Lateral	10	90.0	402	234	0.001	0.385	0.04	0.017	43.49
Chest	Erect PA	40	72.5	1706	1390	0.000	0.188	0.56	0.107	18.83
	Erect Lat	20	80.0	1733	1345	0.000	0.221	1.03	0.229	19.36
	Supine	51	76.4	1750	1441	0.000	0.180	1.11	0.202	16.77
Skull	AP	8	87.5	1203	644	0.000	0.442	0.96	0.477	46.79
	Lateral	8	87.5	1116	754	0.031	0.289	0.78	0.227	31.56
C spine	AP	22	81.8	894	559	0.001	0.331	0.34	0.117	38.75
	Lateral	23	91.3	1054	594	0.000	0.401	0.49	0.208	40.21
T spine	Ap	10	60.0	1093	852	0.018	0.187	1.71	0.320	23.64
	Lateral	10	90.0	1337	934	0.000	0.289	3.53	1.021	30.85
L spine	AP	34	82.3	1189	884	0.000	0.230	2.52	0.582	24.95
	Lateral	33	93.9	1449	1047	0.000	0.267	5.40	1.444	27.61
Hand	PA	52	71.1	664	495	0.000	0.207	0.14	0.029	24.02
	Oblique	51	74.5	647	453	0.000	0.252	0.13	0.034	29.43
Wrist	PA	35	68.5	540	401	0.005	0.229	0.12	0.028	24.99
	Lateral	34	91.1	519	333	0.000	0.311	0.13	0.042	36.81
Forearm	AP	23	91.3	916	613	0.000	0.299	0.16	0.048	35.11
	Lateral	24	87.5	870	598	0.000	0.278	0.20	0.058	31.46
Elbow	AP	25	92.0	852	428	0.000	0.443	0.11	0.049	50.63
	Lateral	25	92.5	901	460	0.000	0.464	0.14	0.066	50.78
Humerus	AP	12	91.6	1232	710	0.008	0.377	0.54	0.178	35.48
	Lateral	16	87.5	1377	971	0.002	0.276	0.50	0.139	28.69
Shoulder	AP	20	95.0	1302	801	0.000	0.370	0.39	0.147	36.57
	Lateral	7	85.7	1260	762	0.024	0.359	0.35	0.126	37.13
Foot	AP	37	94.5	642	442	0.000	0.283	0.12	0.034	31.14
	Oblique	37	86.4	631	456	0.000	0.237	0.12	0.029	26.72
Ankle	AP	28	92.8	604	366	0.000	0.358	0.13	0.049	39.70
	Lateral	29	86.2	668	407	0.000	0.342	0.14	0.048	37.36
Leg	AP	19	89.4	1001	762	0.001	0.217	0.19	0.043	22.48
	Lateral	15	86.6	1028	824	0.007	0.178	0.22	0.039	18.53
Knee	AP	26	92.3	919	617	0.000	0.289	0.53	0.155	31.30
	Lateral	27	96.2	1121	687	0.000	0.365	0.41	0.152	39.57
Femur	AP	23	52.7	1256	1018	0.009	0.161	1.05	0.170	14.18
	Lateral	17	88.2	1406	1012	0.020	0.262	1.31	0.343	27.04

AP: Anteroposterior, PA: Posteroanterior, LAT: Lateral

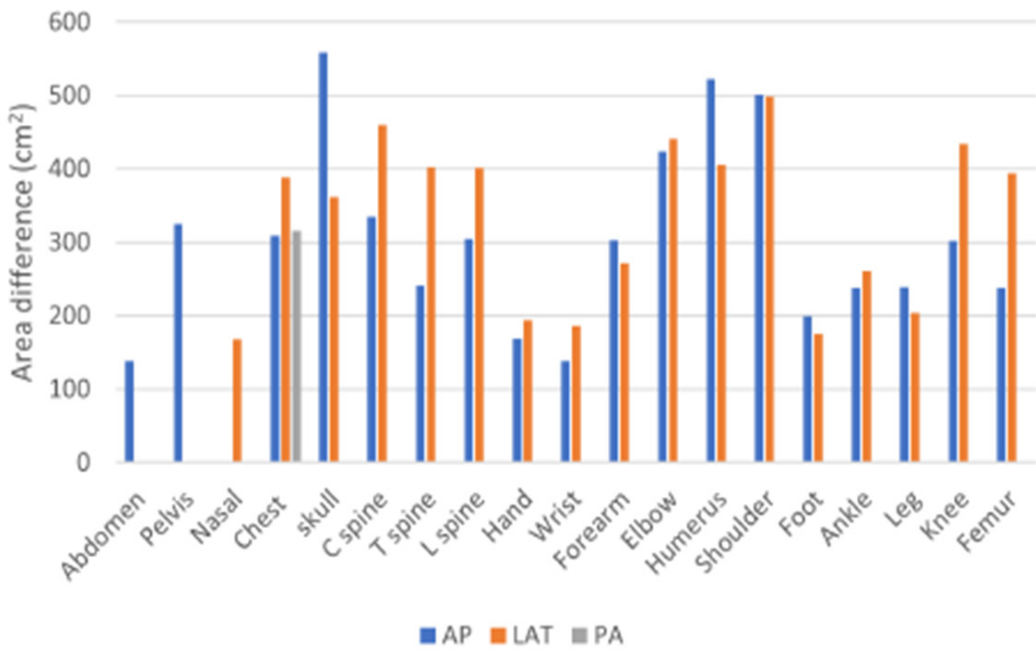

Figure 4: Discrepancy in the area between electronic collimation and the radiation field. (AP: Anteroposterior, PA: Posteroanterior, LAT: Lateral)

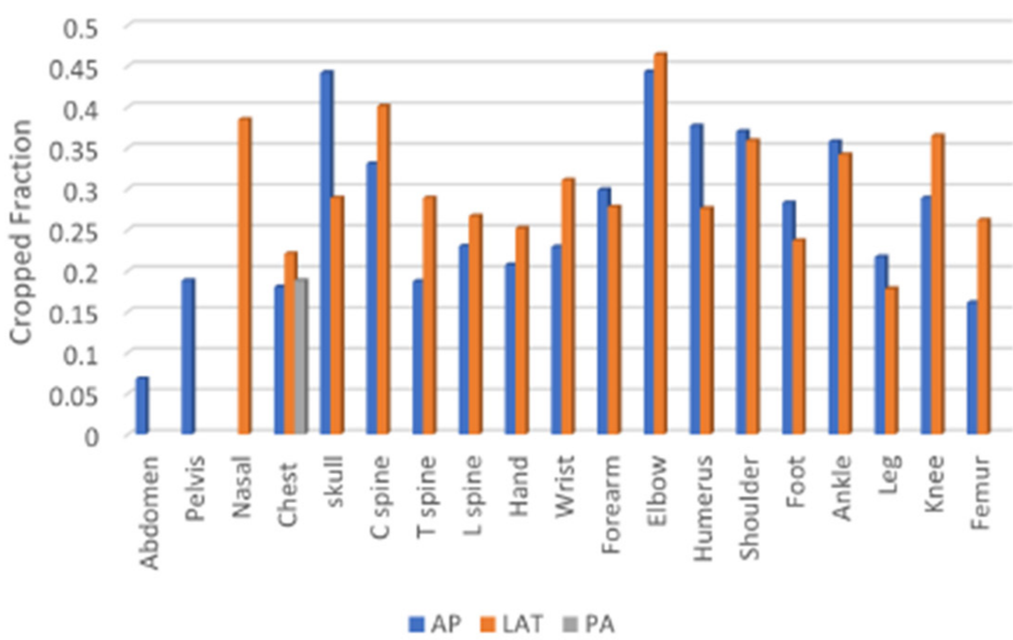

Figure 5: Cropped fraction for the 36 radiographic projections. (AP: Anteroposterior, PA: Posteroanterior, LAT: Lateral)

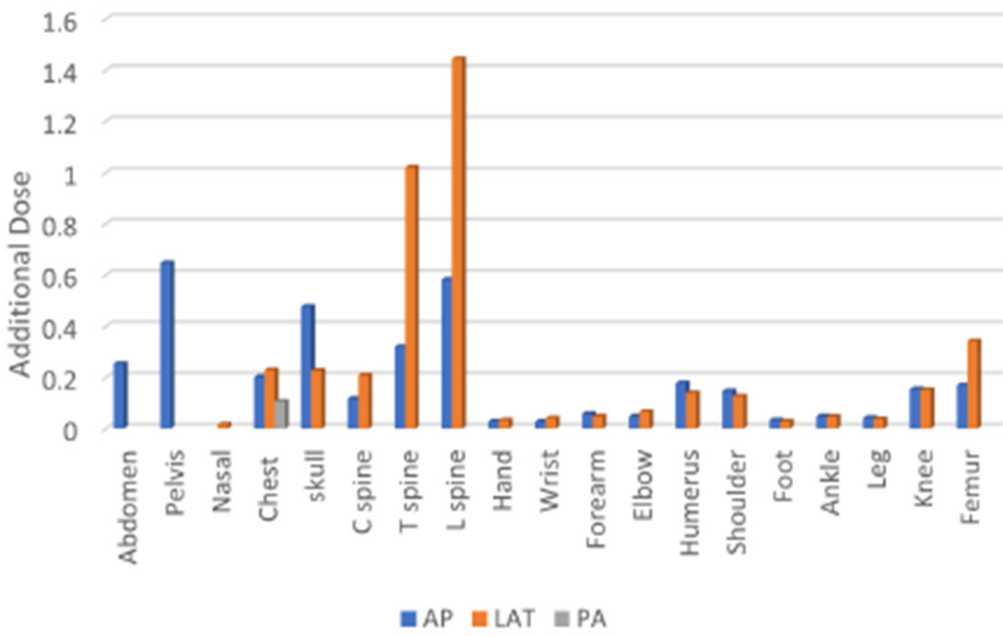

Figure 6: Additional dose amounts in the 36 radiographic projections. (AP: Anteroposterior, PA: Posteroanterior, LAT: Lateral)

elbow and abdominal exhibit the highest and lowest additional dose at 50.78% and 5.55%, respectively. These findings emphasize the importance of the collimation of the primary beam during radiographic protocols, leading to reducing patient dose while maintaining image quality.

Discussion

Medical imaging advancements prioritize balancing optimal image quality with reduced radiation doses [15]. The forthcoming study focuses on the assessment of radiation doses and the cropped fraction for 36 radiographic projections, which revealed that 82% of the images were cropped. The lateral projection of the knee exhibited the highest cropping rate at 96.2%, whereas the abdominal projection demonstrated the lowest at 36%, showing a tendency among radiologic technologists to crop the images substantially. Additionally, the significant differences between the area of the radiation field and electronic collimation underscored the importance of precise collimation as an effective factor in managing patient dose. Neglecting precise collimation can lead to increased long-term risks associated with radiation exposure [16, 17].

In the current study, the cropped fraction, as a key index in assessing the collimation of the radiation beam, indicates the extent of non-essential information that a radiologic technologist has eliminated during electronic collimation. The present study revealed a significant amount of cropping (>40%) in lateral projections of the cervical spine, skull, and elbow. Notably, the elbow had the highest cropped fraction (46.6%), showing that lateral elbow X-rays require precise collimation to minimize radiation exposure to surrounding tissues. Proper collimation ensures a clear image of the elbow while protecting non-target areas from unnecessary radiation.

The challenges in positioning patients'

elbows, especially those with trauma, could account for this discrepancy. To ensure accurate imaging, the elbow center must be positioned in the middle of the patient couch. However, the elbow often does not reach the correct position, due to patients' restricted arm movement and the distance from the couch edge to its center. Consequently, radiologic technologists may widen the radiation field to ensure that the elbow joint is fully captured within the radiation field. These findings emphasize the need for developing and implementing improved collimation techniques and strategies.

Conversely, the anterior abdominal projection showed the least amount of cropping, with only 6.8% requiring adjustments, showing imaging the abdomen and extremities, like legs and femurs in adults, often necessitates an entirely open radiation field on one or both sides. As a result, electronic image cropping is generally less necessary for these projections.

In the present study, the obtained results are consistent with those of Satharasinghe's 2020 study, which examined six anatomical regions namely, the neck, chest, sinus, abdomen, lumbar vertebrae, and shoulder regarding the extent of cropping performed in a private healthcare facility equipped with a GE Healthcare Digital Radiography system. The study revealed that the cervical vertebrae and the abdomen had the highest and lowest cropped fractions at 0.55 and 0.059, respectively. These data further underscored the varying requirements for electronic collimation across different anatomical projections, highlighting the importance of tailored radiographic practices to optimize patient safety and image quality [8]. Figure 2 illustrates that the radiation field in the abdominal radiography of most adult patients is typically maximized, which is essential to encompass the area from the diaphragm superiorly to the pubic symphysis inferiorly, as well as the entire width of the patient's abdomen laterally. Consequently, the need for electronic image cropping in these projections is minimal, revealing the necessity to cover such a comprehensive anatomical region for accurate diagnostic imaging [8].

It should be noted that a high cropped fraction will lead to an increase in the percentage of unnecessary doses for that projection. Based on the results obtained, the highest percentage of unnecessary dose was at 50.78%, for the lateral projection of the elbow, and the lowest percentage of unnecessary dose was at 5.55%, for the abdomen. However, the additional radiated area is air, which cannot lead to an increase in the effective dose to the patients in many images [18, 19].

In this study, the dose assessment index was the DAP, affected by exposure parameters and the radiated area's size. In the lumbar spine lateral projection, high exposure parameters are used due to the significant thickness of the body part and the presence of muscular and bone tissue in this area. Since the area of the imaging region is also large in this projection, the highest DAP was observed at 5.24 dGy.cm^2. Conversely, the nasal bone's lateral projection, which covers a small area with less thickness, registered the lowest DAP at 0.04 dGy.cm^2. Therefore, radiation collimation should be precise in the lumbar spine lateral projection. Improper collimation can lead to unnecessary radiation exposure. In this study, omitting collimation for the specific projection in question led to an additional dose of 1.444 dGy.cm^2. Accurate collimation minimizes radiation exposure to surrounding tissues, reducing the overall radiation dose a patient receives and enhancing patient safety.

Despite a higher cropped fraction compared to the lumbar vertebrae in the nasal projection, the unnecessary dose is less than all projections at 0.017 dGy.cm^2, showing the importance of electronic collimation for projections with higher exposure parameters. Figure 3 displayed the extent of image cropping in the lateral projections of the nasal and lumbar spine. Junina et al. investigated X-ray collimation practices across three healthcare facilities: a university hospital and two clinics. All three locations used the same X-ray system (Adora, NRT, Hasselager, Denmark). In summary, the study focused on seven commonly used projections: shoulder, lumbar vertebrae, chest, hip, knee, foot, and hand [14].

Table 3 presents a significant difference in all radiographic imaging projections concerning the area of collimation and radiation exposure (P-value<0.05). For projections, a normal distribution was shown, including the lateral cervical spine, chest AP, and lateral, lumbar, thigh, knee, leg, heel and foot sole, skull, shoulder, and arm. The t-student test was employed for statistical analysis. In contrast, for projections with a non-normal distribution, the Mann-Whitney test was utilized to evaluate the differences.

Electronic collimation was mainly used to eliminate shadows caused by scatter radiation on the image before delivering it to the patient or radiologist, which was performed manually on some devices and automatically on others. Therefore, the image sent to the PACS should be a few millimeters away from the periphery of the initial radiation field. i.e., the Silver Line is visible [3]. In this way, radiologists were aware of any unnecessary radiation exposure to the patient, which is the best way to prevent unnecessary radiation exposures.

The electronic collimation, instead of properly adjusting X-ray collimation, will not only lead to unnecessary radiation exposure to the patient but also reduce the quality of the image. While patients have the right to access all the information, cropping X-rays may sometimes be necessary. Radiologic technologists crop images to minimize radiation exposure to non-target tissues, ultimately prioritizing patient safety [10].

This study had several limitations: 1) despite the lack of data on radiologic technologists, measures were taken to minimize errors, such as increasing the sample size for each imaging projection and limiting the review to five images per examination daily. Additionally, skull and thoracic spine projections are less frequently requested due to limited access to CT scan devices, resulting in smaller sample sizes for these projections. Future studies should aim to examine a larger sample size for these specific projections to strengthen the robustness of the findings. According to the results, the cropped fraction is considerable for all projections; therefore, measures should be taken toward proper X-ray collimation. This study recommends several strategies to ensure optimal collimation and minimize the risk of inappropriate collimation practices, as follows: 1) comprehensive training programs for radiologic technologists to enhance their knowledge and skills required for informed decisions about electronic collimation because these training emphasize the importance of anatomical landmarks, clinical judgment, and patient-specific conditions in optimizing collimation and 2) regular quality control assessments, leading to improving electronic collimation and image quality and reducing unnecessary doses [19].

Conclusion

The advent of electronic image cropping has diminished the precision of radiologic technologists in collimating the primary radiation field, resulting in decreased image quality and increased patient dose. This study demonstrated that proper collimation can reduce the average DAP by 29.01%.

The findings underscore the critical importance of precision in collimating the primary beam to minimize unnecessary patient radiation exposure across 36 different projections. Radiologic technologists play a pivotal role in ensuring optimal X-ray imaging. By accurately confining the radiation field to the targeted organ through collimation, they can achieve multiple benefits.

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Authors' Contribution

P. Hejazi conceived the idea. The paper was written by AM. Esmaeilian and S. Aliakbari. The study was designed by P. Hejazi. The experiment was carried out by AM. Esmaeilian. Results and Analysis were carried out by AM. Esmaeilian and M. Jadidi. The research work was proofread and supervised by S. Aliakbari and P. Hejazi. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The Ethics Committee of Semnan University of Medical Sciences approved the protocol of the study (Ethic cod: IR.SEMUMS.REC 1401.304).

Conflict of Interest

None

References

1. Seeram E. Digital Radiography: Physical Principles and Quality Control. Springer; 2019.
2. Wiemker R, Dippel S, Stahl M, Blaffert T, Mahlmeister U. Automated recognition of the collimation field in digital radiography images by maximization of the Laplace area integral. In: Medical Imaging 2000: Image Processing 2000; San Diego, CA, United States: SPIE; 2000. p. 1555-65.
3. Shetty CM, Barthur A, Kambadakone A, Narayanan N, Kv R. Computed radiography image artifacts revisited. *AJR Am J Roentgenol.* 2011;**196**(1):W37-47. doi: 10.2214/AJR.10.5563. PubMed PMID: 21178029.
4. Takeuchi H, Chuang KS, Huang HK. Dual energy imaging in projection radiography. In: Application of Optical Instrumentation in Medicine XIV and Picture Archiving and Communication Systems; Newport Beach, CA, United States: SPIE; 1986. p. 39-48.
5. Kruse JJ, Herman MG, Hagness CR, Davis BJ, Garces YI, Haddock MG, et al. Electronic and film portal images: a comparison of landmark visibility and review accuracy. *Int J Radiat Oncol Biol Phys.* 2002;**54**(2):584-91. doi: 10.1016/s0360-3016(02)02955-3. PubMed PMID: 12243839.
6. International Commission on Radiological Protection. Managing patient dose in digital radiology. A report of the International Commission on Radiological Protection. *Ann ICRP.* 2004;**34**(1):1-73. doi: 10.1016/j.icrp.2004.02.001. PubMed PMID: 15302167.
7. Carter C, Veale B. Digital radiography and PACS E-Book. Elsevier Health Sciences; 2018.
8. Satharasinghe D, Jeyasugiththan J, Jeyasuthan M, Amalaraj T, Abeyweera AL, Wanninayake WMNMB, Pallewatte AS. Impact of Collimation on Radiation Exposure in Adult and Paediatric Digital X-Ray Imaging. *Radiat Prot Dosimetry.* 2021;**197**(1):19-27. doi: 10.1093/rpd/ncab155. PubMed PMID: 34718821.
9. Uffmann M, Schaefer-Prokop C. Digital radiography: the balance between image quality and required radiation dose. *Eur J Radiol.* 2009;**72**(2):202-8. doi: 10.1016/j.ejrad.2009.05.060. PubMed PMID: 19628349.
10. Bomer J, Wiersma-Deijl L, Holscher HC. Electronic collimation and radiation protection in paediatric digital radiography: revival of the silver lining. *Insights Imaging*. 2013;**4**(5):723-7. doi: 10.1007/s13244-013-0281-5. PubMed PMID: 23982805. PubMed PMCID: PMC3781259.
11. Long BW, Rollins JH, Smith BJ. Merrill's atlas of radiographic positioning and procedures e-book. Elsevier Health Sciences; 2018.
12. Tsalafoutas IA. Electronic collimation of radiographic images: does it comprise an overexposure risk? *Br J Radiol.* 2018;**91**(1086):20170958. doi: 10.1259/bjr.20170958. PubMed PMID: 29544343. PubMed PMCID: PMC6223295.
13. International Atomic Energy Agency. Handbook of Basic Quality Control Tests for Diagnostic Radiology. Vienna: IAEA; 2023.
14. Guðjónsdóttir J. The unnecessary dose behind cropped radiographs. *Radiography Open*. 2019;**5**(1):1-10. doi: 10.7577/radopen.3611.

15. Aldrich JE, Duran E, Dunlop P, Mayo JR. Optimization of dose and image quality for computed radiography and digital radiography. *J Digit Imaging*. 2006;**19**(2):126-31. doi: 10.1007/s10278-006-9944-9. PubMed PMID: 16511674. PubMed PMCID: PMC3045190.
16. Zetterberg LG, Espeland A. Lumbar spine radiography--poor collimation practices after implementation of digital technology. *Br J Radiol*. 2011;**84**(1002):566-9. doi: 10.1259/bjr/74571469. PubMed PMID: 21606070. PubMed PMCID: PMC3473630.
17. Karami V, Zabihzadeh M. Beam Collimation during Lumbar Spine Radiography: A Retrospective Study. *J Biomed Phys Eng.* 2017;**7**(2):101-6. PubMed PMID: 28580331. PubMed PMCID: PMC5447246.
18. Vañó E, Miller DL, Martin CJ, Rehani MM, Kang K, Rosenstein M, et al. ICRP Publication 135: Diagnostic Reference Levels in Medical Imaging. *Ann ICRP.* 2017;**46**(1):1-144. doi: 10.1177/0146645317717209. PubMed PMID: 29065694.
19. Pazanin A, Skrk D, O'Driscoll JC, McEntee MF, Mekis N. Optimal collimation significantly improves lumbar spine radiography. *Radiat Prot Dosimetry.* 2020;**189**(4):420-7. doi: 10.1093/rpd/ncaa057. PubMed PMID: 32363403.