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Experimental Evaluation of Optimization in Cr and Dr Digital Radiography Systems: A Study with Anthropomorphic Phantom

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Place and Duration of Study: Sample: The experimental optimization study was conducted at a radiology clinic in Santa Maria, RS, Brazil between June 2022 and December 2022.
In this study, we verified the efficiency of two digital radiography image acquisition systems (CR and DR) for a radiographic system.
Methodology: We used an anthropomorphic phantom that represents the anatomy of the pelvis region of an adult patient. For image acquisition and dosimetric measurements, the radiographic system and two clinical use image digitization systems were used, and the dosimetric measurements were obtained through a radiation detector. For optimization of the exam, five different exposure techniques were used. With ImageJ software it was possible to obtain the signal and noise values for image quality (IQ) from regions of interest (ROI) defined in the image anatomy. The signal-to-noise ratio (SNR) was calculated. The percentage deviation (D%) was chosen to

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compare the readings against the reference technique, which is used by radiology professionals in the clinic for pelvic examination.

Results: The results obtained in this study point out that the DR system offers a constant SNR and a better visualization of tissues at low contrast when compared to the CR system. It was found that by raising the X-ray tube voltage and reducing the current product by time (70 kV and 32 mAs) to (100 kV and 5 mAs) one can optimize the pelvis radiographic examination for DR system, i.e., the KERMA in the incident air (K_{AR}) was reduced from 2.9 mGy to 0.5 mGy (-76.3%) at the patient's pelvis surface. Average dose reduction in organs from 3.07 to 0.94 mGy (-69.5%) in the testes, 0.69 to 0.33 mGy (-52.2%) in the ovaries, 1.20 to 0.51 mGy (-57.3%) in the prostate, 0.14 to 0.07% (-46.4%) mGy in the bone marrow and 35.3% and 62.2% reduction (0.45 to 0.17) mSv the total effective dose of the exam with IQ higher by 11%.

Keywords: Signal-to-noise ratio; computed radiography; digital radiography.

1. INTRODUCTION

Digital radiographic images share similarities and characteristics, regardless of the image acquisition technology; in other words, they are digital approximations of an analog projection of anatomy. However, the significance of optimizing radiation dose in patients during radiographic examinations remains a significant concern [1].

Recent research on reducing radiation dose in patients undergoing radiographic examinations focuses mainly on optimizing exposure techniques in digital systems (SD) as a means to implement the ALARA philosophy (ALARA stands for "As Low As Reasonably Achievable") [2,1].

Abbeyquaye et al. [3] studies emphasized the importance of optimizing radiographic examinations of the pelvic region, as they concluded that the patient may be exposed to an effective dose (ED) 20 times higher when compared to an examination of the chest. Although the average ED per examination in all plain radiographs is relatively low, for pelvic region examinations, it still represents higher values compared to other sites [4]. Certain dense and thick regions and structures of the human body, such as the pelvis and abdomen, suffer from relatively high exposure interruptions, or that result in higher radiation doses, in order to assess penetration and acquire a more accurate image for purposes diagnosis [5]. This implies that the reproductive organs are necessarily exposed to the primary X-ray beam during pelvic radiography, which carries a potential cancer risk for generations [5].

According to Tompe and Sargar [6], optimizing exposure techniques aims to reduce the potential damage that radiation can cause. They also highlight that exposure techniques with a constant 10% increment in voltage (kV) associated with a 50% reduction in the product of current and time (mA.s) can produce an X-ray beam with adequate image quality for clinical purposes, providing a lower radiation dose to the patient.

The parameter used as a variable in this study is the image quality, meaning that increasing the voltage (kV) and reducing the product of current and time (mA.s) of the X-ray beam results in a change in standard image quality. A Quantitative Image (QI) measure was defined by the signal-to-noise ratio (SNR), which is the ratio between the signal obtained from regions of interest (ROI) and its respective noise (signal fluctuation within the ROI). This metric proved to be effective in determining QI when comparing the same simulator object or anthropomorphic phantom [6].

Estimating the average absorbed dose (D) of internal organs and effective dose (ED) of a radiographic examination is experimentally challenging. However, the PCXMC 2.0 program [7] is recognized as a reliable method for dose estimation in internal organs, such as dose in the gonads (DG) and bone marrow dose (BMD), as well as the patient's .

Considering that the image quality criteria used in SD are not the same as those in the screen-film system, digital radiography images can be taken with high kVp and low product of current and time (mA.s) independent of radiation exposure, resulting in a lower radiation dose to the patient however computerized radiology (CR) is widely employed in clinical practice for diagnostic imaging. Nevertheless, it is important to note that medical technology is constantly evolving, and new technologies such as Digital Radiology System (DR) have been emerging since then [8].

The objective of this study is to compare two digital radiography systems (CR and DR) by assessing the impact of optimizing exposure techniques on image quality and possible reduction of radiation dose to the patient. Finally, a relationship between dose and image quality will be presented for each digital system.

2. MATERIALS AND METHODS

The experimental optimization study using an anthropomorphic phantom comparing the digital systems was used, a solid-state detector and carried out in a radiology clinic in Santa Maria, RS, Brazil.

The following equipment was used in the research:

Radiographic System: The radiographic system used in the study is in compliance with current regulations and is routinely used for clinical purposes. It is capable of producing X-ray images with various exposure parameters.

Computed Radiography (CR) System: The CR system utilized in the study is designed for digital image acquisition. It uses a reusable imaging plate (IP) that captures X-rays and stores the latent image. The IP is then processed to obtain digital radiographic images.

Digital Radiography (DR) System: The DR system employed in the study is a direct digital imaging system. It consists of a digital detector panel that directly captures X-ray photons and converts them into digital signals, resulting in real-time digital images.

Air Kerma (K_{AR}) Detector: To measure the Air Kerma (KAR), an Unfors X1 radiation detector was used. This detector was calibrated at the Federal University of Pernambuco (UFPE) in the Department of Nuclear Energy's Ionizing Radiation Metrology Laboratory in Brazil. It is capable of quantifying the air kerma, which is a measure of the radiation exposure in the air.

Anthropomorphic Phantom: For the experimental measurements, an anthropomorphic phantom was utilized. The simulator was designed and developed specifically by students of the Medical Physics course at the Universidade Franciscana (UFN) and consists of reproducing the image of the pelvis, it was validated by the study by Gomes et al, 2022 [9]. It accurately represents the anatomical structures of the abdomen region, including the lumbar spine and pelvis, and is covered with acrylic resin to simulate a typical adult. In Table 1 the systems with the brand and model used in the research are listed.

The anthropomorphic phantom used for the measurements was developed by students from the Medical Physics course at the Universidade Franciscana (UFN). The phantom is internally composed of a skeletal structure representing the abdominal region (lumbar spine and pelvis) and is covered with acrylic resin molded to resemble a typical adult. The choice of this phantom was based on the fact that the imaging techniques used to obtain images are the same as those applied in human pelvic radiography. Additionally, the phantom reproduces images similar to those of a human pelvis, making the experiment closely resemble a real radiographic examination [9].

2.1 Acquisition of Images and Air Kerma Measurement

Table 2 shows the values of voltage and current that were selected on the control panel of the radiographic equipment. According to the experimental design, of High kVp techniques, 15% or 10-kVp rules, are well-known dose reduction methods. Traditionally, the use of high tube potential (i.e. increased kVp) is associated with decreased radiographic contrast and overall image quality. Recent studies suggest contrast and image quality are not heavily reliant on kVp with digital systems. This study aims to assess the effects of the high tube potential technique on clinical radiographic image quality when using digital systems, to validate high kVp as a dose saving technique [10]. Voltage increment was set at intervals of 10, followed by a corresponding 50% reduction in mAs. Technique 2 was kept as the standard, as it is used as a reference for pelvic examinations in the clinic. The electrical current value was kept constant at 200mA, representing a large focal spot typically used for pelvic region examinations.

Fig. 1-A illustrates the irradiation geometry for obtaining the image of the phantom, where the source-to-image receptor distance (SID) is 100 cm, and the source-to-phantom surface distance (SPSD) is 20 cm. Fig. 1-B illustrates the irradiation geometry for obtaining the air kerma measurements. The sensitive area of the detector is positioned on the central ray of the collimator of the equipment.

Table 1. Description of the equipment used in the research

System	Brand	Model
radiographic	Philips Health Care	Compacto Plus DR 800
Computed Radiology (CR)	Carestream	Direct View Classic CR
Image Plate (PI)(35X43)	Carestream	-
Radiologia Digital Direta (DR) (PI)(35x43)	Imex Medical Group	Trimax TX 65
radiation detection	RaySafe Xi	Unfors
Software	*ImageJ*	Ver. 1.8.0_112
Software	*PCXMC*	Ver. 2.0

**Source: Author's construction (2023)*

Table 2. Electrical parameters used for each technique

Electrical parameters	Technic 1	Technic 2	Technic 3	Technic 4	Technic 5
Voltage (kV)	60	70	80	90	100
Current product time (mA.s)	80	40	20	10	5

**Source: Author's construction (2023).*

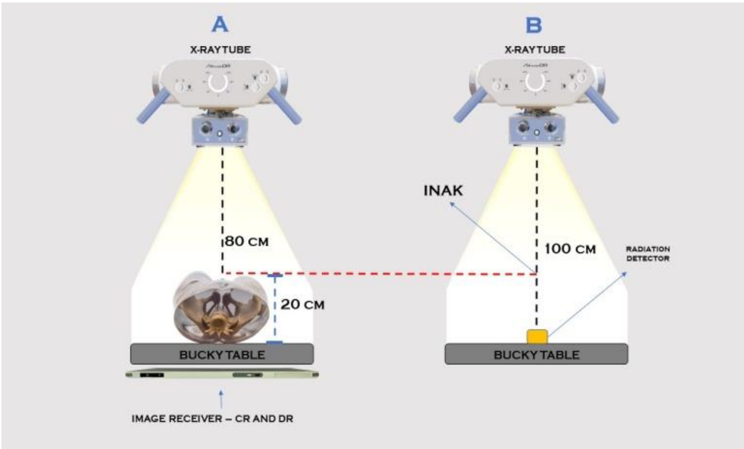


Fig. 1. Geometry of irradiation
**Source: Author's construction (2023)*

Computed Radiology System (CR)

Direct Digital Radiology System (DR)

Fig. 2. The exposure geometry for simulator object imaging and K_{AR} measurement.
**Source: Author's construction (2023)*

Ilustration of the irradiation geometry for imaging the phantom, where the image focus-receiver distance (DFR) is 100 cm from the focal point of the equipment, and the source-surface distance (DFS) of the phantom is 20 cm.

2.2 Dose Assessment

Incident air kerma (INAK) is the K_{AR} obtained with the radiation detector at a distance of 20cm representing the phantom surface [11].

$$\mathrm{INAK} = \mathrm{K\_AR} \times (\mathrm{DFR}/\mathrm{DFS})^2 \quad (1)$$

As shown in Fig. 3, the X-ray tube was positioned at a source-to-receptor distance (SID) of 100 cm from the focal spot of the equipment, and the irradiation field size was set to 40 cm x 40 cm. Subsequently, the phantom was positioned with the tube fixed in the initial position to perform acquisitions using both CR and DR image receptors, followed by post-processing, quality evaluation, and data analysis.

2.3 Image Quality

In the literature, no material was found that classifies a visual scale to validate the quality assessment of anteroposterior (AP) pelvic examinations, as mentioned in the article by Mraity HAAB et al. Therefore, in this study, we quantitatively evaluated the quality using descriptors such as signal-to-noise ratio (SNR) and its relationships. The software ImageJ was employed to obtain these values through Regions Of Interest (ROI) analysis [11].

2.4 Selection Criteria

As there are no reference values to define the quality image (QI) descriptor limits, we considered the values measured in the reference images acquired with Technique 2 as such. The deviation percentage (D%) was chosen to compare the acquired images to the reference image acquired at 70 kV and 40 mAs. This specific technique is commonly used in quality control dose. The deviation percentage was calculated using Equation 2 to assess the deviation from the reference image::

$$\mathrm{D}(\%) = ((\mathrm{New\ Value})/(\mathrm{Standard\ Dev.})) - 1 \quad (2)$$

2.5 Signal and Noise Evaluation

To determine the signal and noise in the obtained images, six Regions Of Interest (ROIs) were selected for each technique in each image. The ROIs were placed as follows: the first one at the level of the lumbosacral transition (L5/S1), the second one at the right iliac wing, the third one at the left iliac wing, the fourth one at the right femoral neck, the fifth one at the left femoral neck, and the sixth one at the lateral edge of the image without anatomical structures. The last ROI represents the background of the image and is used to identify the noise for calculating the signal-to-noise ratio. All ROIs have a circular shape and the same area (13.684 mm²).

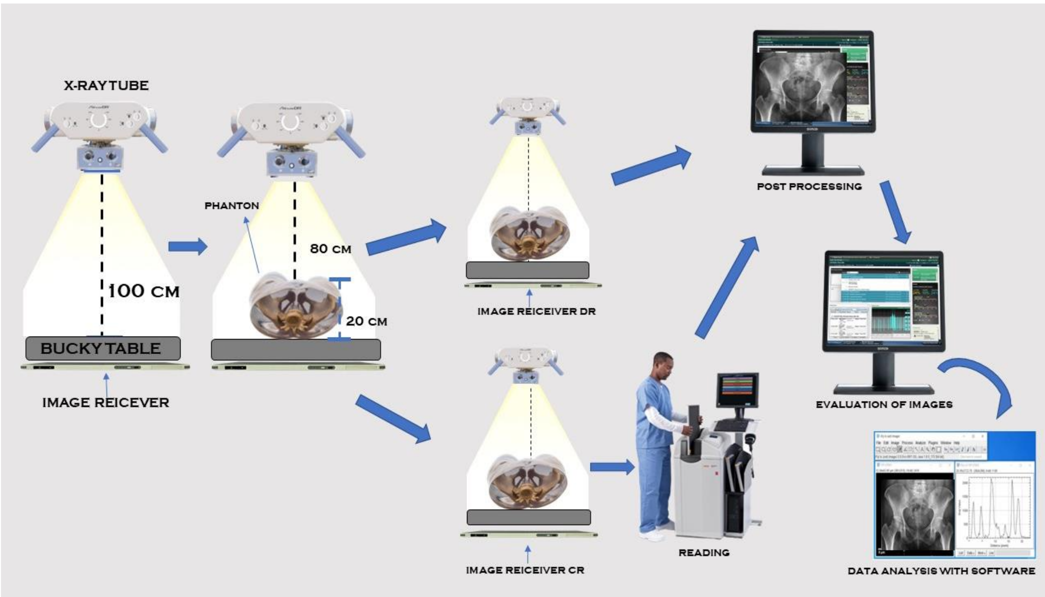


Fig. 3. Stages of the methodology
**Source: Author's construction (2023)*

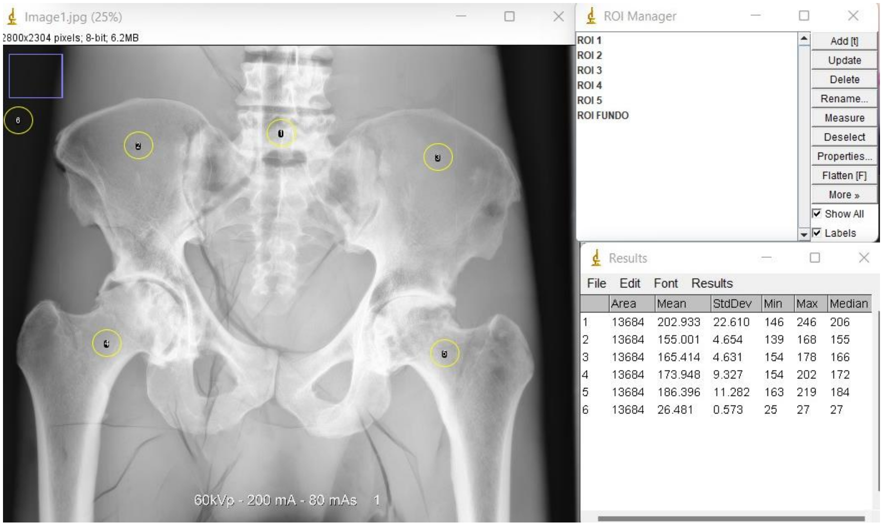


Fig. 4. Shows the location of the ROIs on the reference image using the ImageJ software. The illustration depicts Technique 1 from the DR system

**Source: Author's construction (2023)*

For each image, the signal value (mean pixel value) of each ROI and the noise (respective standard deviation) will be evaluated, following the methodology of Mraity HAAB et al. [12], to obtain a comprehensive analysis of image quality. To facilitate the analysis, the average of the ROIs will be calculated to obtain a single value per image. By doing so, we can obtain a single signal-to-noise ratio (SNR) value per image, making it easier to assess image quality.

According to Equation 3 from Mraity HAAB et al. [12], the average of the signal values of ROIs 1 to 5 will be divided by the average value of the background ROI (ROI 6) to obtain the SNR value for each exposure technique.

$$SNR = (\text{Signal Average ROIs } 1;\ 2;\ 3;\ 4 \text{ e } 5)/(\text{Background Noise ROI } 6) \quad (3)$$

2.6 Estimation of Absorbed Dose and Effective Dose (ED)

The effective dose (ED) is the weighted sum of the equivalent doses in all tissues and organs of the body [13]. The PCXM 2.0 software [6], which utilizes the Monte Carlo method, was used to calculate the radiation dose to the internal organs and the effective dose (ED) for the patient adjusted to the radiographic examination. The dose was estimated for the main internal organs in the pelvic region and the effective dose based on the input data, including the selected voltage, anode angle of 12 degrees, and the total collimator-scatter radiation (CSR) corresponding to the selected voltage.

3. RESULTS AND DISCUSSION

3.1 Imagem Digitalization

Each image provides a two-dimensional representation formed by a matrix of small elements called pixels. In digital imaging, each pixel represents the smallest unit in the image, and columns and rows of pixels make up the matrix [14].

The wider latitude range of digital radiography allows for minimizing patient exposure while producing diagnostic-quality images within an acceptable range of exposure indicators indicated by the manufacturer. The image quality and contrast did not show statistically significant differences between the images acquired with different techniques for the same imaging system. However, a difference between the systems was visibly apparent, with lower contrast observed in the DR system, showing better depiction of regions outside the phantom's anatomy.

The characterization of the X-ray beam and dosimetry results showed that for each technique used, an increase in voltage by a factor of 10 and a 50% reduction in current resulted in a significant reduction in air kerma (K_{AR}), as shown in Fig. 6A.

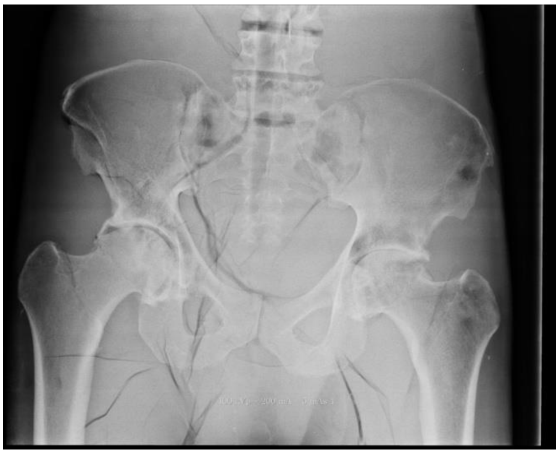
DR **CR**

Technic 1 **Technic 1**

Technic 2 **Technic 2**

Technic 3 **Technic 3**

Technic 4 **Technic 4**



Technic 5 **Technic 5**

Fig. 5. Displays the 10 radiographs obtained from the phantom for each respective technique in the DR system (5 images in the right column) and CR system (5 images in the left column). Visually, it can be observed that there is lower contrast in the DR images, indicating better visualization of regions outside the phantom's anatomy
**Source: Author's construction (2023)*

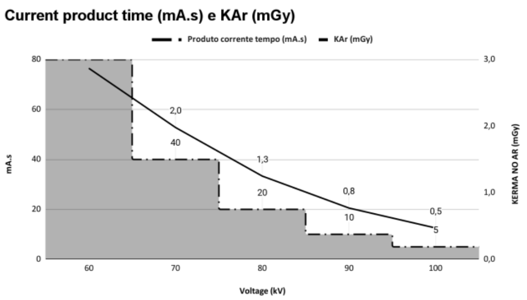


Fig. 6A

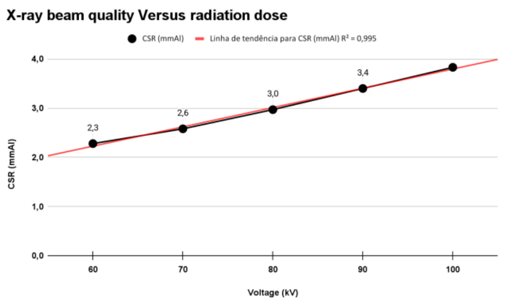


Fig. 6B

Fig. 6. Results of dosimetric measurements
**Source: Author's construction (2023)*

According to Fig. 6B, it is demonstrated that the quality of the X-ray beam, as expected, increases the Collimator-Scatter Radiation (CSR) with an increase in voltage. Consequently, for more penetrating beams, there is an increase in CSR to achieve a lower Air Kerma (K_{AR}). The increase in kVp with the reduction in mAs showed a linear relationship with the increase in 10 kVp increments.

Diop, Adji Yaram et al. [15] concluded in their studies that there is a need to standardize the exposure technique for digital radiographic examinations and highlighted the importance of conducting actual patient dose measurements. Other studies have shown that radiology professionals have the opportunity to reduce medical exposures by 20% to 50%, depending on the technology employed. Therefore, their challenge lies in considering both Image Quality (QI) and radiation dose in image acquisition [6,15].

3.2 Signal and Noise Evaluation

In Tables 3 and 4, the values obtained using the ImageJ software are presented, and they correspond to the reference image shown in Fig. 4.

In comparison with the standard deviation readings between the ROIs for the DR and CR equipment, there is a very close match between them. However, in terms of signal readings, there are differences. For example, at 60 kV, ROI 1, the signal reading for DR is 56.62% compared to CR.

Using the ImageJ software as shown in Fig. 4 with the ROI tool, it is possible to analyze the differences between the obtained radiographs. Tables 5 and 6 represent the values of K_{AR}, SNR, and the voltage used for each technique, along with the respective percentage deviation relative to the reference Technique 2.

Indeed, while an increase in peak kilovoltage (kVp) can significantly reduce the patient's radiation dose, it also increases the penetration and scattered radiation of the X-ray beam, which may alter the contrast of the radiograph.

3.3 Absorbed Dose and Effective Dose

The fundamental physical quantity used in radiological protection is the absorbed dose (DT), which can be described as the average energy deposited in a specific organ or tissue (T). Dosimetry in radiology is of paramount importance for quality control and radiological protection.

Table 3. ROI Readings for DR

Technics	Signal						Noise
	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6	Standard Dev.
Technic 1	202,9	155,0	165,4	173,9	186,3	26,4	8,8
Technic 2	202,3	157,5	168,1	175,1	188,1	25,9	8,5
Technic 3	203,1	163,3	173,1	179,8	192,2	25,7	7,9
Technic 4	203,4	168,9	177,3	184,1	195,4	25,9	7,4
Technic 5	206,1	176,5	183,7	190,4	200,6	25,0	6,8

Source: Author's construction (2023)

Table 4. ROI Readings for CR

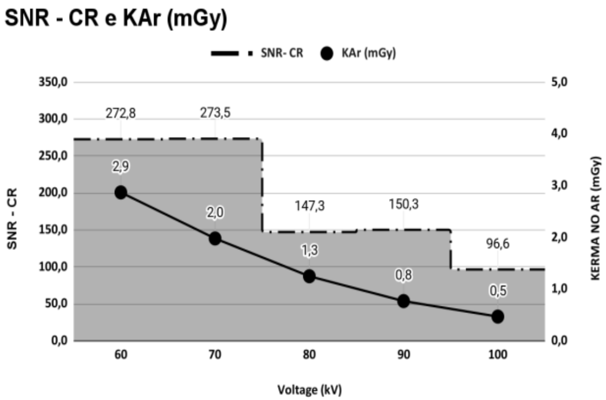
Technics	Signal						Noise
	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6	Standard Dev.
Technic 1	88,0	122,6	187,1	123,4	160,3	0,0	7,2
Technic 2	92,5	126,9	179,1	124,1	161,0	0,05	6,7
Technic 3	98,3	132,3	171,9	131,0	160,6	0,94	6,3
Technic 4	109,8	140,1	176,1	137,9	173,1	0,98	6,0
Technic 5	114,2	144,7	172,1	144,5	168,1	1,55	5,9

Source: Author's construction (2023)

Table 5. Relates technique, radiation dose, and the respective percentage deviation

Electrical parameters			Radiation Dose			Image Quality		
Technic	**Voltage**	**Corrente**	**K_{AR}**	**INAK**			**CR**	**DR**
	kV	**mA.s**	**mGy**		**D%**	**SNR**	**D% SNR**	**D%SNR**
Technic 1	60	80	2,9	7,2	45,2%	272,8	-0,3%	-3,0%
Technic 2	70	40	2,0	5,0	-	273,5	-	-
Technic 3	80	20	1,3	3,2	-35,5%	147,3	-46,2%	2,7%
Technic 4	90	10	0,8	2,0	-61,3%	150,3	-45,0%	4,1%
Technic 5	100	5	0,5	1,2	-74,2%	96,6	-64,7%	11,0%

**Source: Author's construction (2023)*
for the CR and DR systems



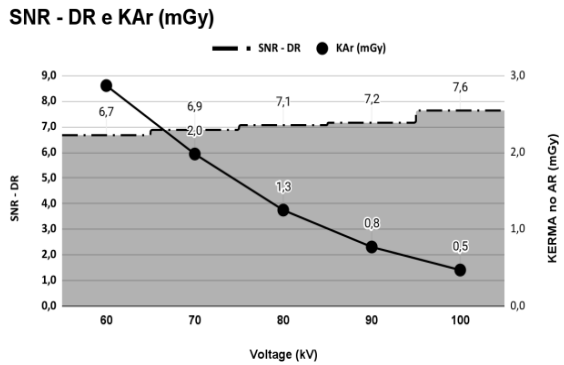


Fig. 7. Graphical representation of SNR and K_{AR}

**Source: Author's construction (2023)*

Table 6. PCXMC simulation values

	Testicle		Ovary		Prostate		Bone Marrow		Effective Dose	
	(mGy)	**D%**	**(mGy)**	**D%**	**(mGy)**	**D%**	**(mGy)**	**D%**	**(mSv)**	**D%**
Technic 1	3,96	29,9%	0,70	0,1%	1,28	7,4%	0,13	3,6%	0,52	15,6
Technic 2	3,07	-	0,69	-	1,20	-	0,14	-	0,45	-
Technic 3	2,16	-29,7%	0,59	-14,4%	0,97	-18,6%	0,13	-10,1%	0,35	-22,2
Technic 4	1,45	-52,9%	0,46	-33,8%	0,73	-39,2%	0,10	-27,5%	0,25	-44,4
Technic 5	0,94	-69,5%	0,33	-52,2%	0,51	-57,3%	0,07	-46,4%	0,17	-62,2

**Source: Author's construction (2023)*

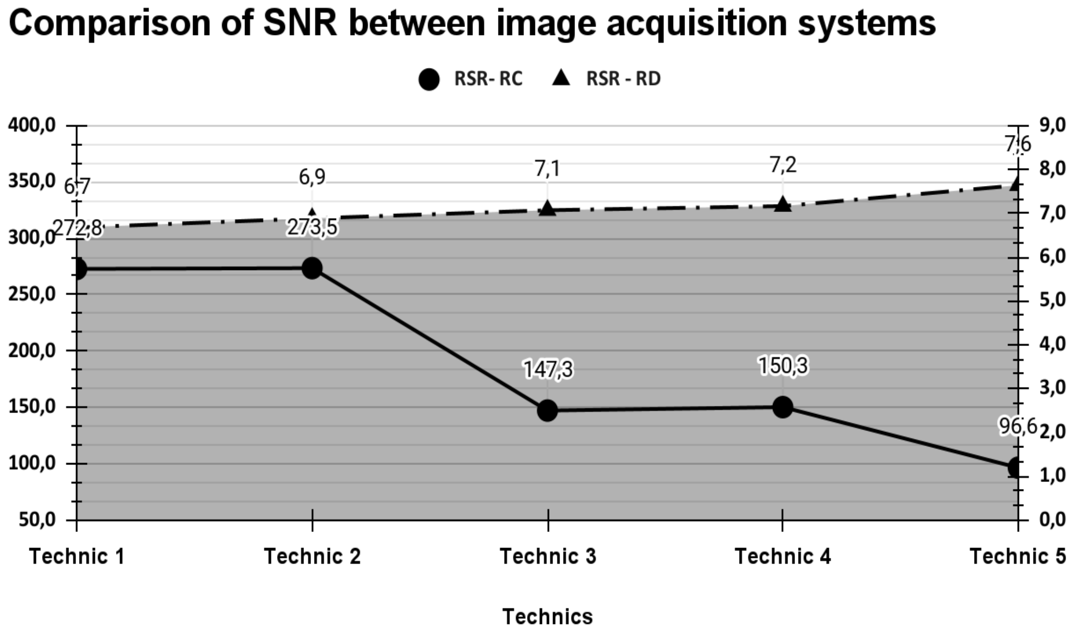


Fig. 8. Comparison of SNR

**Source: Author's construction (2023)*

The absorbed dose is emphasized for the main organs in the pelvic region (testicles, prostate, ovaries, and bone marrow) in mGy, and the effective dose in mSv for pelvic radiographic examinations according to ICRP 103, as shown in Table 6.

The study conducted by Abbeyquaye et al. [16] concluded that patients could be exposed to an effective dose (ED) of 0.28 mSv. In this optimization study of exposure techniques for pelvic examinations, the obtained ED reductions were 0.52 mSv for Technique 1, 0.45 mSv for Technique 2, 0.35 mSv for Technique 3, 0.25 mSv for Technique 4, and 0.17 mSv for Technique 5. These results indicate a substantial reduction in effective dose compared to other studies. For instance, Masjedi et al. (2020) reviewed Radiation Protection Reports of the European Commission No. 154 and 180 and found average effective dose values of 0.85 mSv and 0.68 mSv, respectively, which are higher than the values found in this study. Fig. 8 compares the Signal-to-Noise Ratio (SNR) of the systems and demonstrates that the SNR of the DR system remains nearly constant with an increase in voltage, whereas the SNR of the CR system remains constant for Techniques 1 and 2, then exhibits a significant drop, and finally remains constant again for Techniques 3 and 4. In contrast, the SNR of Institution A shows a negative linear relationship, as there is a gradual loss of SNR from Technique 1 to Technique 5.

4. CONCLUSION

In conclusion, the study demonstrated that by increasing the tube voltage and reducing the current-time product (from 70 kV and 32 mAs to 100 kV and 5 mAs), the radiographic examination of the pelvis for the DR system can be optimized. This optimization resulted in a significant reduction in the surface air kerma (K_{AR}) from 2.9 mGy to 0.5 mGy (-76.3%) at the patient's pelvis. The average dose to the organs was also reduced from 3.07 to 0.94 mGy (-69.5%) for the testicles, 0.69 to 0.33 mGy (-52.2%) for the ovaries, 1.20 to 0.51 mGy (-57.3%) for the prostate, and 0.14 to 0.07 mGy (-46.4%) for the bone marrow. The total effective dose of the examination was reduced by 35.3% and 62.2% (from 0.45 to 0.17 mSv), with an 11% improvement in Image Quality (QI) for the DR system.

For the CR system used in the study, there was a significant reduction in SNR due to technique optimization. Specifically, for techniques 3, 4, and 5, the dose was reduced by 36.9%, 61.1%, and 76.3%, respectively, with a reduction in image quality (SNR) by 46.2%, 45.0%, and 64.7%, respectively. The results indicate that increasing the tube voltage and optimizing the exposure technique can lead to a considerable reduction in patient radiation dose without compromising image quality for the DR system. However, for the CR system, the reduction in dose comes at the expense of a decrease in image quality due to its limitations in detecting photons efficiently and the signal-to-noise ratio. This study highlights the importance of optimizing exposure techniques and considering both dose reduction and image quality for radiographic examinations, especially for the advancement and adoption of digital radiography systems.

CONSENT

As per international standard or university standard, patient(s) written consent has been collected and preserved by the author(s).

ETHICAL APPROVAL

As per international standard or university standard written ethical approval has been collected and preserved by the author(s).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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