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Characterization of X-ray Beams: Determination of $K_{a,e}$ for Comparison with DRLs

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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

Aims: The aim of this experimental study was to quantify the entrance surface air kerma ($K_{a,e}$) of X-ray beams in radiographic examinations, and the obtained values were compared with national and international Diagnostic Reference Levels (DRLs).

Place and Duration of Study: Sample: Department of Medical Physics and Radiology, Franciscan University (UFN), between June 2023 and August 2024.

Methodology: Initially, the main quality control (QC) tests were applied to characterize the radiographic equipment. During the evaluation of the X-ray beam, a dosimetric set was used, and for the same QC geometry, Air Kerma Rate (K_{AIR}) measurements were obtained to determine the output of the X-ray tube. Under the same conditions, a phantom without water and the same filled with water were used to determine the backscatter factor (BSF), which was then used to estimate the $K_{a,e}$ for the main radiographic examinations.

Results: The results of this study are consistent with other studies and identified the region/anatomy with the highest radiation exposure, highlighting the importance of its optimization and verifying that continued professional training should be integrated into best practices to ensure greater safety in procedures. The results obtained evidence the necessity for adjustments in image acquisition protocols, as the $K_{a,e}$ values found in this study, although within the limits established by the national DRLs, exceed the reference values of countries such as the United Kingdom and Japan in the areas of the skull, abdomen, and lumbar spine. This discrepancy highlights the importance of the periodic review and update of DRLs, in accordance with international recommendations and the technological evolution of equipment. Dose optimization is an ongoing process that involves the evaluation of image quality, the appropriate selection of technical parameters, and the implementation of specific dose protocols. The continuous training of radiology professionals is essential to ensure the correct application of imaging techniques and the minimization of patient exposure to ionizing radiation.

Conclusion: This study shows the importance of evaluating radiation dose in diagnostic imaging and the need for a multidisciplinary approach to dose optimization. Implementing quality assurance programs, updating DRLs, and providing ongoing training for professionals are essential to ensure patient safety and high-quality diagnostic imaging. The methodology adopted in this study can contribute to the ongoing education of radiology professionals, promoting the correct application of imaging techniques and reducing patient exposure to ionizing radiation.

Keywords: X-ray beam; Air Kerma; DRLs.

1. INTRODUCTION

The characterization of the X-ray beam (kVp, mAs, filtration, focus-skin distance), the patient's anthropometric characteristics (thickness, beam projection) and the anatomical region of interest allows an estimation of skin entrance dose ($K_{a,e}$) [1]. Currently, the comparison of values obtained with Diagnostic Reference Levels (DRLs) makes it possible to identify opportunities to reduce the dose of ionizing radiation, contributing to safe and efficient radiological practice [2].

DRLs are reference values established by the International Commission on Radiological Protection (ICRP) for the amount of radiation used in imaging examinations, such as radiography and computed tomography [1,2]. These indicators are recommended for identifying unusually high radiation doses in typical diagnostic radiology procedures [2]. However, exceeding a DRL does not necessarily imply that the exam is inadequate, nor does meeting a DRL guarantee that the practice is correct, as image quality (IQ) must also be considered [3].

These values serve as a benchmark to assess whether the radiation dose applied in an examination falls within an acceptable range, thereby contributing to the safety of both patients and healthcare professionals, as exposure to ionizing radiation, even at low doses, can pose health risks [2,3].

Other studies, such as those by Alvarez *et al.* [4] and Diop *et al.* [5], highlight that DRL values account for various factors, including beam geometry, the anatomical region of the patient, tissue thickness, and the contribution of scattered radiation. The optimization of radiation protection, therefore, requires radiology professionals to balance dose and image quality, considering both DRLs and diagnostic needs.

The application of the ALARA principle (As Low As Reasonably Achievable) is fundamental in this context, aiming to reduce the patient's radiation dose to the lowest possible level without compromising image quality.

To achieve this balance, it is necessary to adopt practices such as the appropriate selection of technical parameters, precise collimation, and dose reduction techniques, including filtration and image processing. In this regard, DRLs act as an essential tool for managing good radiological protection practices, provided they are properly understood and applied by radiology technicians and technologists [1-3].

Considering the principle of ALARA radiological protection, this study aims to characterize the X-ray beams used in radiographic examinations, focusing on the estimation of $K_{a,e}$. The results will be compared with Brazilian and international DRLs.

2. MATERIALS AND METHODS

The study was conducted in the radiodiagnosis laboratory of the undergraduate programs in Radiology and Medical Physics, as part of the research carried out during the Quality Control and Radiodiagnosis courses at the Universidade Franciscana (UFN).

2.1 Equipments

In this study, radiographic equipment from Intecal brand and model MAAF was used, operating in a voltage range (kV) between 40 and 120 and current between 100 and 630 mA, coupled with a high-frequency generator. For the X-ray beam measurements, a dosimetry set from RADCAL, model 9015, calibrated in a reference laboratory, was used.

2.2 Methodology

The research was conducted in 5 stages, which are represented in a flowchart in Fig. 1.

2.3 Quality Control (QC) of Equipment

Before the start of the study, QC procedures for the radiographic equipment were carried out according to current guidelines and regulations [6,7] to ensure accurate and reliable results. Performing these procedures helps identify any technical failures and/or deviations in the operating parameters of the radiographic equipment.

2.4 Air KERMA Measurements

The test was conducted for nine selected kV values on the control panel of the radiographic equipment, using the same radiation field size (25 cm x 25 cm). In each stage, three readings were recorded for each kV value, while keeping the electric current (mA) and the product of current and time (mA.s) in the tube constant, as shown in Table 1.

To obtain the measurements of K_{AIR}, a dosimetry set and a phantom object (PO) consisting of a plastic box measuring 39 x 26.5 x 22.0 cm³ (length, width, and height, respectively) filled with water were used to simulate the patient on the table. A radiation field of 25 cm x 25 cm was opened, the distance between the tube focal point and the table was adjusted to 100 cm, and the Source-to-Image Distance (SID) used was 80 cm.

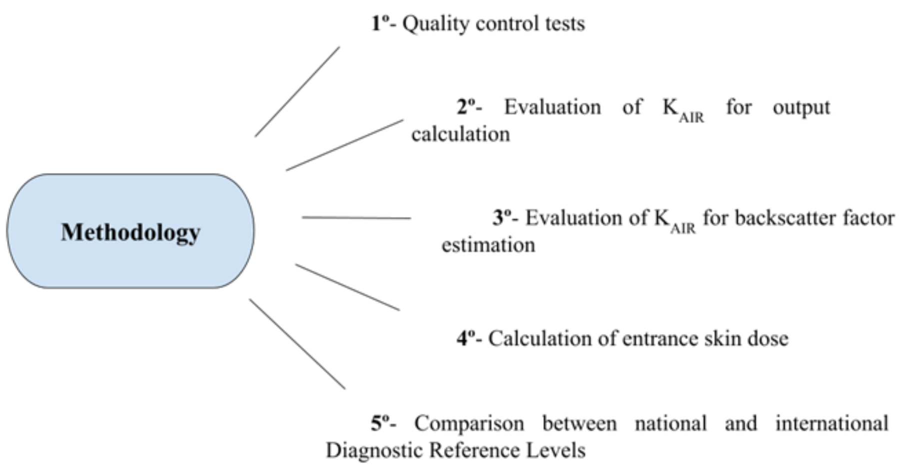

Fig. 1. Representation of the methodology in the form of a flowchart

Table 1. Selected electrical parameters for Air KERMA measurements

Electrical Factors	Selected Electrical Parameters								
Voltage (kV)	40	50	60	70	81	90	102	109	120
Electric current (mA)	200								
mA.s	40								

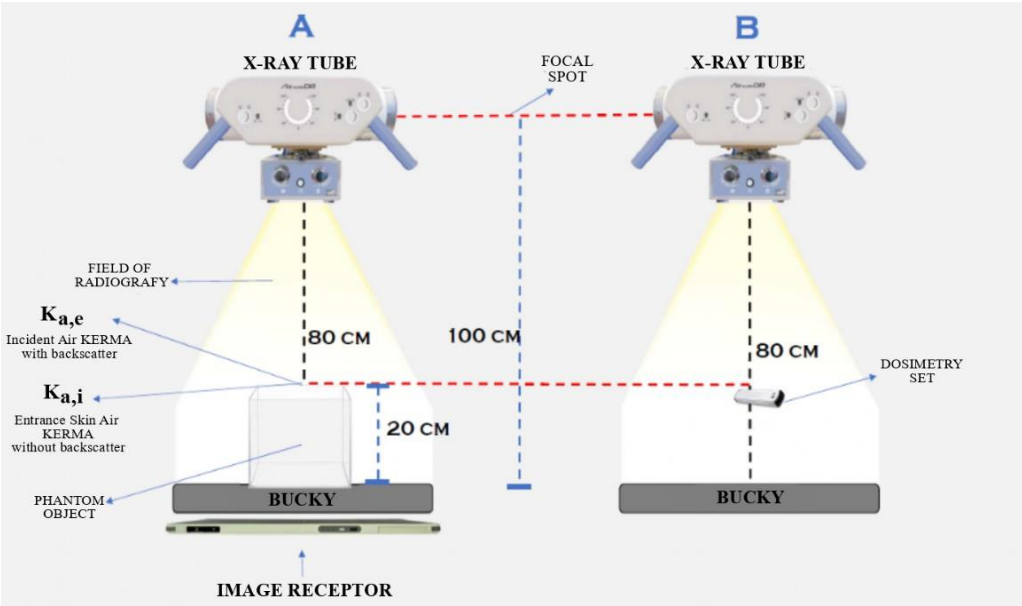

Fig. 2. Illustration of the geometry adopted for measurements of K_{AIR}, $K_{a,i}$, $K_{a,e}$, and backscatter (BSC)

Fig. 2 depicts the X-ray tube, typical beam geometry for obtaining the typical radiographic examination, and identification of the main parameters used for medical exposure measurements.

During the radiographic examination, the X-ray beam consists partly of primary radiation, which penetrates a specific region of the patient and registers information of the internal anatomy of interest on the detector due to transmitted radiation. Additionally, it includes scattered radiation (backscatter), which contributes to the overall radiation dose received by the patient [8].

The output value was determined by the ratio between the average K_{AIR} readings obtained for each kV and mA.s value used. Furthermore, potential differences between the nominal and actual values of kV and mA.s across the entire operating range of the radiographic equipment were also checked, according to Equation 1.

$$Output = \frac{K_{AIR}}{mA.s} \quad (1)$$

2.5 Measurements of the Backscatter Factor (BSF)

To perform the measurement of the BSF, it was necessary to position and align the radiation detector appropriately, as illustrated in Fig. 2(A), with the dome positioned over the table at 80 cm. For each kV value, three readings of K_{AIR} were taken, resulting in a total of 27 readings. Subsequently, the plastic box was filled with water to a thickness of 20 cm during the measurement, as depicted in Fig. 2(B). Again, three readings of K_{AIR} were taken for each voltage value, totaling an additional 27 readings with the addition of water.

Due to the relevance of BSF in calculating $K_{a,e}$, it was decided to calculate the ratio between the average of K_{AIR} readings obtained with the dosimetry set with and without water, according to Equation 2:

$$BSF = \frac{K_{AIRwater}}{K_{AIRair}} \times \frac{\left[\frac{\mu tr}{\rho}\right]_{water}}{\left[\frac{\mu tr}{\rho}\right]_{air}} \quad (2)$$

where $K_{AIR_{water}}$ represents the reading on the surface of the phantom filled with water, $K_{AIR_{air}}$ the reading at the same position without water, and $\left[\frac{\mu tr}{\rho}\right]$ refers to the mass energy transfer coefficient in water and air.

2.6 Evaluation of Entrance Skin Dose ($K_{a,e}$)

$K_{a,e}$ evaluations play a crucial role during QC tests to verify compliance with DRLs, ensuring that radiation doses used in diagnostic procedures are appropriate while minimizing adverse health effects. Furthermore, these evaluations are of utmost importance to enhance the quality and safety of radiological procedures, identifying opportunities to reduce radiation dose without compromising IQ or diagnostic information obtained [9].

According to ICRP Publication 135 of 2017 [1], the radiation metric used as a measure of DRLs should be easily measurable or available, such as $K_{a,e}$ in diagnostic radiology. In this study, $K_{a,e}$ was calculated through the assessment of output, determined in units of mGy/mA.s, at a FSD of 80 cm. According to Metaxas et al. [10], with this value, it should be corrected for the desired FSD using the inverse square law equation (Equation 3):

$$K_{a,e}(mGy) = Output\ \left(\frac{mGy}{mA.s}\right) \times \left(\frac{80}{FSF}\right)^2 \times (mA.s) \times BSF \qquad (3)$$

where Output (mGy/mA.s) is the average of the K_{AIR} values obtained from the X-ray equipment, which increases with the square of the approach distance (FDD/FSD)², where FSD is represented by FDD minus the patient's thickness (in the region being radiographed) and depends on the protocol of each examination. Finally, due to the proportionality between tube output and mA.s, the last step to estimate $K_{a,e}$ is to multiply the X-ray tube output by the selected mA.s value on the control panel of the respective exposure technique and by the BSF.

2.7 Selection Criteria

It was chosen to use the percentage deviation (D%) to compare the acquired values with the DRLs, according to equation 4:

$$D(\%) = \left[\left(\frac{measured\ value\ of\ K_{a,e}}{reference\ value\ of\ DRL}\right) - 1\right] \times 100 \qquad (4)$$

3. RESULTS AND DISCUSSION

Periodic assessment of the X-ray beam during Quality Control tests, conducted by Medical Physics professionals, possibly with the inclusion of other radiology professionals, can improve the safety of both patients and professionals, ensuring a more effective approach to radiological protection practices.

In Table 2, the types of tests applied for the evaluation of the radiographic equipment, along with the respective measured values and achieved results, are listed.

It can be observed in Table 2 that the constancy values of the radiographic equipment showed an error of less than 7% in the worst case, which is below the 10% accepted as the limit by legislation, ensuring good reproducibility of the equipment. The minimum limit for the half-value layer (HVL) at 80 kV is 2.9 mmAl, and since 3.19 mmAl was found, the results were considered acceptable in accordance with the current legislation [6,7].

Table 2. Summary of Quality Control test results for the digital image radiographic equipment [6,7]

TEST	Reproducibility		
	Exposure	**Time**	**kVp**
Obtained values	4.20%	1.72%	3.90%
Tolerance	≤10%	≤10%	≤5%
Result	Conform	Conform	Conform
Test	**Accuracy**		**HVL (mmAl)**
Obtained values	-6.48%	-5.02%	3.19
Tolerance	≤10%	≤10%	2.9
Result	Conform	Conform	Conform
Test	**Output**		
	Linearity		**µGy/mA.s**
Obtained values	5.68%		48.77
Tolerance	≤20%		-
Result	Conform		Conform

Table 3 lists the selected values of voltage and the product of current by time (kV and mA.s) with the measured average values of KERMA in air and water, as well as the average calculated values of standard deviation (SD), output value (mGy/mA.s) and Backscatter Factor (BSF).

As expected, it can be observed in Table 3 that the contribution of scattered radiation increases as the voltage (kV) increases, meaning that the increase in the primary beam energy results in an increased probability of scattered radiation occurrence [11]. This happens because, with higher energy, the radiation is less likely to be attenuated within the patient's body and more likely to escape, resulting in greater lateral scattering, backscattering, and forward scattering [12].

According to Diop *et al.* [5], after obtaining the K_{AIR} values for each kV and a fixed mA.s value in the spreadsheet, the output curve (output value) for the X-ray tube can be obtained. Other studies by Tompe & Sargar [13] highlighted that the intensity of the X-ray beam produced in a radiographic tube can be affected by the applied voltage due to two main factors: the number of electrons released and the energy of the photons.

Fig. 3 graphically represents the output values (mGy/mA.s) as a function of the voltage selected on the X-ray equipment control panel.

Table 3. Summary of Quality Control test results for the digital image radiographic equipment [6,7]

Selected Values		Measured Values				Calculated Values	
Current.time (mA.s)	Voltage (kV)	Readings in air Average (mGy)	SD	Readings in water Average (mGy)	SD	Output (mGy/mA.s)	BSF Air/ Water
40	40	1.62	0.31%	1.75	0.06%	0.040	1.08
	50	2.93	0.06%	3.25	1.36%	0.073	1.11
	60	4.37	0.57%	4.93	0.60%	0.109	1.13
	70	5.93	0.49%	6.77	0.61%	0.148	1.14
	81	7.61	0.83%	8.82	0.59%	0.190	1.16
	90	8.95	0.87%	10.46	0.58%	0.224	1.17
	102	10.88	4.04%	12.93	2.65%	0.272	1.19
	109	12.10	3.06%	14.33	1.73%	0.302	1.18
	120	13.85	3.61%	16.46	4.62%	0.346	1.19

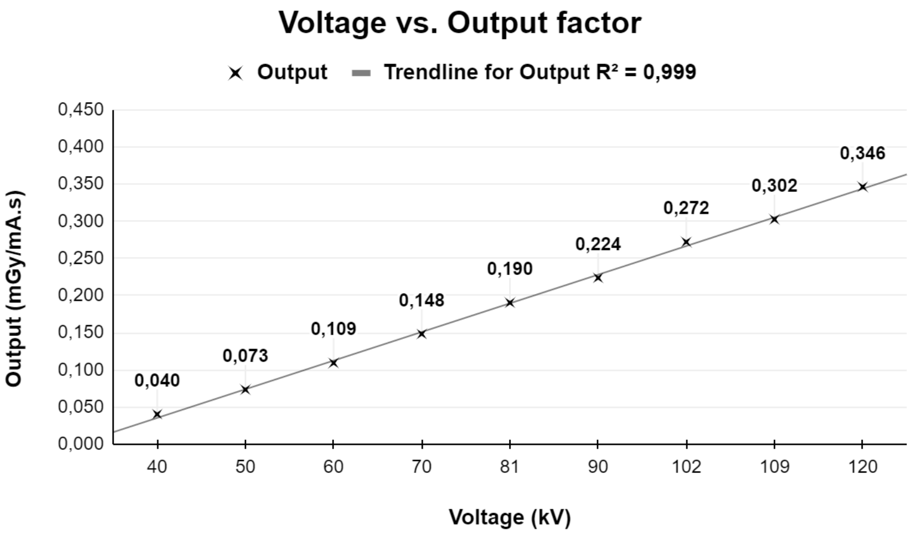

Fig. 3. The output curve of the radiographic tube

It is observed in the graph of Fig. 3 that the linear upward trend of the radiographic tube's output (mGy/mA.s) as a function of kV. With the obtained values of yield (mGy/mA.s) and BSF for this study, it was possible to calculate the $K_{a,e}$ values for a typical individual using Equation 3, whose information on region, projection, and thickness was obtained according to ANVISA (from portuguese *Agência Nacional de Vigilância Sanitária*)'s technical manual for radiodiagnosis [14].

If scattered radiation is detected by the image receptor, it affects the image and can be a significant cause of its degradation. Scattered radiation creates a grayscale in the image in areas that do not correspond to the anatomical projection, and this can significantly reduce the contrast in the radiograph [12].

Table 4 presents a comparison between the estimated $K_{a,e}$ values obtained in this study and the Reference Levels established by RDC 330/52 for different radiographic exams in various projections and body regions.

When comparing the $K_{a,e}$ values obtained in this study with the DRLs established by RDC 330/52, we can observe a significant variation in many cases. For example, for the anteroposterior (AP) skull radiographic exam, the estimated $K_{a,e}$ value is 4.30 mGy, while the DRL established by RDC 330/52 is 5 mGy. This results in a discrepancy of -14.00% compared to the DRL.

These differences highlight the importance of monitoring and optimizing radiation doses used in radiographic procedures to ensure they comply with standards set by regulatory authorities. When $K_{a,e}$ values exceed DRLs, it may indicate excessive patient exposure to radiation, increasing the risk of adverse health effects.

In the case of the lateral (LAT) projection of the skull, the $K_{a,e}$ estimate resulted in a percentage deviation of -14%, indicating an underestimation compared to the established DRL. However, in other projections, such as the posteroanterior (PA) chest and lateral lumbar spine, there are significantly higher percentage deviations, indicating a substantial reduction in $K_{a,e}$ values compared to the established DRLs.

Suliman's studies [15] conducted a retrospective analysis through image analysis and found that the average $K_{a,e}$ (mGy) values for radiographic exams of PA chest, LAT chest, AP abdomen, AP pelvis, AP lumbar spine, and LAT lumbar spine were 0.13, 0.27, 0.70, 1.06, 2.33, and 4.18 mGy, respectively. Our study's results are consistent with chest findings; however, for the abdomen, pelvis, and lumbar spine regions, the values were higher.

Additionally, comparing the obtained doses with the DRLs emphasizes the importance of periodically reviewing and updating DRLs to ensure they align with current clinical practices and evolving imaging technologies. If doses consistently exceed recommended values, it may indicate a need to review radiological practices. This will help ensure patient safety and the quality of radiographic procedures, contributing to more effective and safer clinical practice.

Table 4. Comparison of the $K_{a,e}$ estimate with the reference levels established by RDC 330/52 [6,7]

RADIOGRAPHIC EXAMINATION			TECHNIQUE		DOSIMETRY		
Region	**Incidence**	**Thickness[a] (cm)**	**kV**	**mA.s**	**$K_{a,e}$[b] (mGy)**	**DRLs[c] (mGy)**	**D%**
Skull	AP	19	81	20	4.30	5	-14.00%
	LAT	15	70	20	2.99	3	-0.33%
Chest	PA	23	102	2	0.17	0.4	-57.50%
	LAT	32	120	5	0.60	1.4	-57.14%
Abdomen	AP	23	81	20	4.76	10	-52.40%
Pelvis	AP	23	81	20	4.76	10	-52.40%
Lumbar	AP	23	81	25	5.95	10	-40.50%
Spine	LAT	30	102	50	21.14	30	-29.53%
	LJ	20	70	40	15.78	40	-60.55%

[a]Radiographic thicknesses, considering a typical adult patient (weight from 60 kg to 75 kg and height from 1.60 m to 1.75 m); [b]$K_{a,e}$ is considered the best indicator of deterministic effects, such as the death of a large number of cells, which can lead to tissue collapse, causing it to cease its functions in the organism; [c]Reference levels for radiographic diagnostic imaging, in terms of Entrance Surface Dose, for a typical adult patient.

Table 5. Comparison of the $K_{a,e}$ estimate with international reference levels

$K_{a,e}$ (mGy) versus DRL (mGy)							
Region (Incidence)	**Our study**	**France[a]**	**United Kingdom[b]**	**Germany[c]**	**Sweden[d]**	**Italy[e]**	**Japan[f]**
Skull (AP)	4.30	-	-	-	-	-	3
Skull (LAT)	2.99	-	-	-	-	-	2
Chest (PA)	0.17	0.3	0.15	0.3	0.3	0.4	0.3
Chest (LAT)	0.60	-	-	-	-	-	-
Abdomen (AP)	4.76	5	2	5	5	5	3
Pelvis (AP)	4.76	-	-	-	-	-	3
Lumbar (AP)	5.95	10	5	10	10	10	4
Lumbar (LAT)	21.14	30	11	30	30	30	11
Lumbar (LJ)	15.78	-	-	-	-	-	-

[a]Talbot; Rehel (2004), [b]Wall (2005), [c]Diop (2022), [d]Hart; Hillier; Wall (2009), [e]Compagnone; Pagan; Bergamini, (2005), [f]Yonekura (2015, p.12) [5,16-20].

However, assessing the quality of radiographic images and their suitability for the clinical objective is a complex process that requires the expertise of a radiologist and, therefore, goes beyond the scope of this study.

Table 5 presents a comparative analysis between the $K_{a,e}$ (mGy) values obtained in this Brazilian study and the internationally recognized Diagnostic Reference Levels (DRLs). The comparison covers the most frequent anatomical regions in clinical practice, considering different radiographic projections common between countries.

The analysis of the results presented in Table 5, which relates the average $K_{a,e}$ values obtained in this study with international DRLs, shows variations compared to the DRLs adopted in other countries. For example, for the AP projection skull radiographic exam, the estimated $K_{a,e}$ value was 4.30 mGy, whereas in some countries like Japan, the corresponding DRL is 3.0 mGy. This indicates a discrepancy of approximately 30% compared to the Japanese standard. Similarly, for other body regions and different radiographic projections, such as the chest, abdomen, and lumbar spine, the $K_{a,e}$ values estimated in this study show variations relative to the DRLs adopted in different countries. For example, for the chest in the PA projection, the estimated $K_{a,e}$ value is 0.17 mGy, while in some countries like the United Kingdom, the corresponding DRL is 0.3 mGy.

These differences highlight the importance of evaluating and comparing locally obtained $K_{a,e}$ values with international reference standards. This allows the identification of areas where radiation doses may be above or below acceptable limits, enabling the implementation of corrective measures to ensure safe and effective radiological practice.

4. CONCLUSION

The results obtained demonstrate the need for adjustments in imaging acquisition protocols, as the $K_{a,e}$ values found in this study, although within the limits established by national DRLs, exceed the reference values of countries such as the United Kingdom and Japan in the areas of the skull, abdomen, and lumbar spine. The methodology adopted in this study can contribute to the ongoing education of radiology professionals, promoting the correct application of imaging techniques and reducing patient exposure to ionizing radiation. Furthermore, this study emphasizes the importance of evaluating radiation dose in diagnostic imaging and the need for a multidisciplinary approach to dose optimization and radiological safety.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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