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Typical values statistical analysis for adult chest and abdomen-pelvis CT examinations

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ABSTRACT

The use of DRLs has been extensively documented in the literature as a tool for protocol optimization across different x-ray imaging modalities in different countries. It recognizes the importance of developing and validating methods capable of correlating DRL quantities ($CTDI_{vol}$, DLP and SSDE) with the technical parameters employed in CT studies. Such correlations must be supported by robust statistical methodologies in order to ensure the adoption of adequate optimization decisions. The aim of this work was to apply the Generalized Additive Model (GAM) statistical analysis in adult non-contrast chest and abdomen-pelvis CT typical values. These patient cohorts were statistically evaluated to identify correlations with key-parameters associated to the demographic patient information and machine dependent data, taking into account patients' effective diameters, *d*, and body mass indexes (BMI). GAM was implemented considering each anatomical region in order to correlate the log-transformed DRL quantities (DRLq's) as outcomes given different key predictors related to image acquisition and patient characteristics. A total of 956 CT patient data were collected in this retrospective single-center study. Demographic variables demonstrate that age is not or it is just weakly-correlated to the DRLq's resulting from chest procedures, but it is strongly correlated when considering abdomen-pelvis examinations. Gender is correlated to the DRLq's for chest examinations adopting *d* as a key predictor but it is only correlated with DLP adopting the BMI as a key predictor. The level of accuracy provided by the GAM was adequate for interpreting the large fluctuations of the DRLq's, technical parameters and demographic data observed for the studied patient cohorts. Our results reflect the importance of a comprehensive statistical evaluation of typical values. The domain of this technique is important to different CT imaging chain stakeholders and its application can be a key tool for decision-making process to effective optimization strategies.

1. Introduction

The concept of diagnostic reference level (DRL) was introduced by the International Commission on Radiological Protection (ICRP) (ICRP, 1996). The ICRP 135 (ICRP, 2017) provided guidelines and updates to previous publications for the practical application of the DRLs. This publication defines a typical value as "the median of the distribution of the data for a DRL quantity for a clinical imaging procedure". The publication emphasizes that this median is associated with the distribution of a dose-related quantity from a particular healthcare facility, and that these typical values (TVs) can be used as a guide to encourage optimization initiatives. It is a fundamental action for improving patient safety and allows the evaluation of the DRL quantities (DRLq) for comparison with periodic patient dose audits (Vano et al., 2020). In this sense, the TVs can assist decision makers in the referred single facility since they provide potential comparators linked to new technologies or techniques (ICRP, 2017).

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Abbreviations

AAPM	American Association of Physicists in Medicine
BMI	Body mass index
$CTDI_{vol}$	volume CT dose index
DLP	dose-length product
DRL	diagnostic reference level
d	effective diameter
DRLq	DRL quantities ($CTDI_{vol}$, DLP and SSDE)
GAM	Generalized Additive Model
HCFMUSP	Hospital das Clínicas, Faculdade de Medicina, Universidade de São Paulo
ICRP	International Commission on Radiological Protection
IQR	inter-quartile range
IR	Iterative reconstruction
mAs-cs	current-time product at the central slice
P-IRLS	Penalized Iteratively Reweighted Least Squares
RDSR	Radiation Dose Structured Report
SSDE	size-specific dose estimate
TV	Typical value

The ICRP 135 alerts for practical difficulties on setting up DRLs, reinforcing the need of connecting them to well defined clinical and technical requirements, according to the medical imaging task. The use of DRLs have being found in the literature as a tool for protocol optimization considering different x-ray imaging modalities and strategies in different countries (Abuzaid et al., 2020; Alashban and Shubayr, 2022; Albahiti et al., 2022; Almujally et al., 2023; Dalah and Bradley, 2023; Kawooya et al., 2022; Osman et al., 2023; Rawashdeh et al., 2023; Ria et al., 2022; Roch et al., 2020; Sulieman et al., 2020; Ukoha et al., 2023; van der Molen et al., 2013). In a recent paper, Damilakis et al. (2023) reported the relevance of the determination of local DRLs for defined clinical tasks in order to identify x-ray units requiring further optimization. However, the actions required to the establishment of consistent data collections for composing trustable local DRLs are dependent on institutional initiatives. This kind of implementation is still not well established in all medical facilities, especially in low- and middle-income countries (Benmessaoud et al., 2023; Meyer et al., 2017; Ukoha et al., 2023). These limitations are more relevant considering DRL data collections associated to specific clinical indications (Oliveira Bernardo et al., 2023; Brat et al., 2019; Dalah et al., 2022; Damilakis et al., 2023; Hasan et al., 2022; Lajunen, 2015; Paulo et al., 2020; Ukoha et al., 2023; Zeinali-Rafsanjani et al., 2023).

The relevance and novelty of the present work is based on the importance of establishing and validating methods to correlate DRLq's ($CTDI_{vol}$, DLP and SSDE) to technical parameters adopted in CT studies. The implemented approach provides quantitative comparisons associated with the available CT technologies, which is especially useful considering situations where national or regional DRLs are still not determined. The work is motivated by the increased concern to implement optimized CT protocols that seek to reduce the radiation dose to the patient without reducing image quality and losing diagnostic information (Ria et al., 2019; Samei et al., 2018; Tsapaki et al., 2006).

When a healthcare facility decides to evaluate the TVs of a given radiological procedure and use the results of this survey to conduct an optimization process of the referred clinical protocols, they generally face a myriad of technical and demographic information to take into account. The overarching objective remains to balance optimal image quality while minimizing radiation doses, but the diversity of the patient cohort anatomies and body habitus are fundamental ingredients for an effective optimization process. In the domain of CT studies, stakeholders are confronted with a complex interplay among acquisition parameters, reconstruction algorithms and radiation doses that, combined, must synergistically converge to yield diagnostically adequate images. In this case, the use of robust statistical tools that could answer the question "what the main parameters that affect the DRLqs for a specific CT protocol applied on a given patient cohort?" is valuable to focus the attention on the correct points of the image chain.

In the present work, we demonstrate that the Generalized Additive Model (GAM) is capable of connecting the intricate relationships inherent to CT studies in real patient cohorts. This demonstration was done correlating the response of this model to different patients attributes, with particular emphasis placed on size descriptors such as effective diameter and body mass index, adopted as key-predictors given the influence of these parameters on the CT dose delivery mechanisms.

In this study, the application of the GAM as an effective tool to be used for CT procedures optimization purposes is exemplified using TVs stratified into adult patient size groups for CT examinations performed in a reference hospital. The cohorts of patients imaged in each CT machine were statistically evaluated in order to identify possible correlations with some key-parameters associated with the CT protocols. The proposed statistical method contributes with the development of decision tools to identify key-parameters on the CT machines that stakeholders (radiologists, medical physicists and technicians) must focus on implementing effective optimization processes.

2. Materials and methods

2.1. Design of the study

Data from no-contrast chest and abdomen-pelvis CT examinations were retrospectively analyzed. The study was approved by the Institutional Board Review (CAAE 27912619.6.0000.0068) of the Hospital das Clínicas, Faculdade de Medicina, Universidade de São Paulo (HCFMUSP), São Paulo, Brazil, and informed consent was not required.

The design of the study was composed of five parts: (i) identification of the most frequent examinations performed in the institution and the most representative patient cohorts in order to maximize the impact of the results in future optimization actions; (ii) establishment of a methodology for data management using the available tools to accurately correlate the patient studies, demographic data and corresponding dose metrics; (iii) evaluation of the effective diameter, *d*, of the patients in order to allow the determination of the corresponding SSDEs; (iv) elaboration of a database associating technical (kV, mAs, pitch, AEC model, reconstruction method, etc.) and dosimetric data ($CTDI_{vol}$, DLP and SSDE), demographic information (age and gender) and patient size-dependent data (BMI and *d*) in order to establish the TVs and their statistical correlation with these variables; and (v) implementation of a robust statistical method to the establishment of the correlation between the technical, dosimetric, demographic and patient-size dependent data previously mentioned.

2.2. Patient cohort stratification

The study included examinations performed on adult patients (>18 years old) using four CT scanners: SCANNER 1 - Discovery 750 HD (GE Healthcare, USA); SCANNER 2 - Aquilion CXL (Canon Medical Systems Corporation, Otawara, Japan); SCANNER 3 and SCANNER 4 – Brilliance 64 (Philips Medical Systems, Netherlands). Considering the pandemic period during the data collection and the fact that the HCFMUSP is a regional reference center which received patients of all ages, an increase on the number of chest CTs was registered in the Hospital routine (Carvalho et al., 2022; Homayounieh et al., 2020). The age group of patients who underwent abdomen-pelvis exams was from 19 to 93 years old, with a median of 52 years old, while for chest examinations was from 18 to 94 years old with median 55 years old.

2.3. Database management

Teamplay® platform (Siemens Healthineers, Forchheim, Germany) was used to select DICOM diagnostically validated image series corresponding to the cohorts of interest for the present study and their corresponding Radiation Dose Structured Reports (RDSR). These studies were sent to the institutional PACS (IntelliSpace PACS-Enterprise, Philips, Eindhoven Netherlands) and eFilm Workstation 3.1 (Merge Healthcare, Milwaukee, USA) was used to select the images of interest in each series. Patient demographic and dose data were extracted from the DICOM Header using ImageJ (National Institute of Health, Bethesda, USA). Table 1 summarizes the acquisition parameters of the studied protocols. The following demographic and technical parameters were also registered: gender, age, mAs at central slice (mAs-cs), pitch, slice thickness and the use or not of iterative reconstruction.

2.4. Assessment of dose-related quantities and image quality evaluation

It is important to emphasize that all image series included in the study provided adequate diagnostic information in terms of contrast, spatial resolution and noise characteristics in order to be used for the regular clinical purposes. As recommended at ICRP 135 (ICRP, 2017), all four CT equipment are regularly submitted to quality control (QC) tests according to local regulations in order to balance image quality and patient doses. These QC tests are performed by clinically qualified medical physicists, using x-ray detectors calibrated in accredited laboratories and the QC protocols designed in accordance with well-established and validated methods. Therefore, the dose quantities used for this TVs evaluation are representative of the regular operation of CT systems at this reference hospital.

This study adopted the $CTDI_{vol}$ and DLP values presented in the RDSRs as dose quantities to the establishment of the TVs. The reference phantom size for all $CTDI_{vol}$ data was 32 cm. SSDE were estimated according to the AAPM Report No. 204 (AAPM, 2011) as the product of the $CTDI_{vol}$ and a size-dependent factor published in this report. The uncertainties associated with each evaluated quantity were estimated. It was considered the accuracy presented on the RDSR, and the typical uncertainties estimated during CQ measurements. The maximum $CTDI_{vol}$ uncertainty was 4.1%, and the maximum DLP uncertainty was 1.5%, considering 95% confidence level ($k = 2$). A 20% uncertainty was associated with the quantity SSDE (AAPM, 2011).

2.5. Statistical analyses

In the present work, a statistical model was proposed to examine the association between DRLqs as dependent variables (outcomes) and demographic and technical quantities as independent variables (key predictors, scalar variables or covariates). This model allows to evaluate the significance of the functional relationship between the covariates and the outcomes.

The implementation of statistical analysis was based on the following steps. Standard descriptive statistics of the categorical data were used to analyze the sample's characteristics for each DRLq according to the anatomical region, CT scanner, weight, height, effective diameter, gender and age. The normality of DRLq and their corresponding log-transformed distributions were tested using the Kolmogorov-Smirnov test. As previously reported in the literature (Taylor et al., 2017), the distribution of these quantities differs significantly from the normal. It was identified that the log-transformed distributions adopted in the present work are consistent with the normal distribution considering $p < 0.001$. After that, in data exploring step it was investigated the interactions between the variables. It was verified that the DRLqs are strongly dependent on the patient size descriptors (*d* and BMI), being this dependency non-linear and distinct according to the CT scanner. Finally, based on the findings of the exploring statistical analysis, the key-parameters and covariates were chosen from the dataset and the GAM (Costa et al., 2023; Hastie and Tibshirani, 1986; Wood, 2017) was implemented to model the relationship between dependent (DRLq) and independent (technical and demographics data) variables.

GAM is an extension of the linear models that allows introducing nonlinearities in individual variables by smoothing functions which relate univariate response variables to multiple predictors (Muncy et al., 2022; Mundo et al., 2022; Stasinopoulos and Rigby, 2007). Adopting these smoothing functions, it is possible to get a proper model fit to non-polynomial curves. The covariates included in the GAM allows for identifying the significance of different categories since several splines could be fitted. The resulting GAM generates a smoothed fit to the data as described in details on the following.

The application of the GAM allowed the identification of the level of significance of each variable on the resulting DRLq (outcomes). The method allows to calculate the p-values associating each key predictor with the studied DRLq as well as to plot distributions of the input data versus the corresponding model outcomes.

The GAM implementation considered each anatomical region in order to correlate the log-transformed DRLq's as outcomes to the scalar

Table 1
The main acquisition parameters of the examination's protocols evaluated for each CT scanner.

	SCANNER 1		SCANNER 2		SCANNER 3		
						SCANNER 4	
	Abdomen-pelvis	**Chest**	**Abdomen-pelvis**	**Chest**	**Abdomen-pelvis**	**Chest**	**Chest**
Protocol identification	Abdomen no-contrast	Chest routine	Abdomen no-contrast	Chest routine no-contrast	Abdomen no-contrast	Chest routine	Chest parenchyma mediastinum
Tube voltage (kV)	120; 140	120; 140	120	120	120	120	120; 140
Pitch	1.375	1; 1.375	0.828	1.250	0.829 - 0.984[4]	0.767; 0.797	0.828 - 0.922[4]
Automatic tube current modulation[1]	Auto+SmartmA	AutomA; Auto+SmartmA	SureExposure 3D	SureExposure 3D	ZDOM	ZDOM	ZDOM; ZDOM_ACS
Iterative reconstruction	SS50[2]	SS50[2]	AIDR 3D STD[3]	AIDR 3D STD[3]	---	---	---

[1] AutomA, ZDOM and ZDOM_ACS are automatic tube current modulation modes that use corrections in the longitudinal (z) direction. Auto+SmartmA and SureExposure 3D combine longitudinal (z) and angular (xy) corrections.
[2] SS50 means that 50 % of the reconstruction were from iterative data
[3] Standard Iterative reconstructions (STD), which uses a standard deviation of 10 (this was established by the manufacture).
[4] Pitch range.

variables gender, age, mAs at central slice (mAs_{cs}), pitch, slice thickness, iterative reconstruction (IR) and effective diameter as key predictors. The adopted covariates were the individual patient identification number and the scanner identification.

Considering the response variable (outcomes) μ_i as the logarithm of the DRL quantity ($CTDI_{vol}$, DLP and SSDE) of the i^{th} examination, the GAM implemented in this study can be described for each CT scanner s = 1, …, N to account for potential nonlinear associations between variables, as

$$\mu_i = \beta_0 + \sum_{j=1}^{6} \beta_j F_{i,j} + f(d_i) \quad (1)$$

The firsts two terms represent a sum of linear functions of the scalar variables and $f(d_i)$ represents the smoothing function. In equation (1), $F_{i,1} = 1$ for male patients and $F_{i,1} = 0$ for female patients, $F_{i,2}$ is the patient age, $F_{i,3}$ is the mAs value at central slice, $F_{i,4}$ is the pitch value, $F_{i,5}$ is the slice thickness, and $F_{i,6} = 1$ if iterative reconstruction is used and $F_{i,6} = 0$ otherwise in the i^{th} examination. In addition, GAM allows to accommodate functional variables, $f(\bullet)$, which account to the effective diameter values (d_i) for each CT machine as

$$f(d_i) = \sum_{s=1}^{N} g_s(d_i) G_{i,s} \quad (2)$$

Where N is the number of CT machines, $G_{i,s}$ is a binary variable which is equal to 1 when the CT machine used in the examination of the i^{th} patient is CT_s, where $s = 1 \cdots N$, and it is 0 otherwise

Finally, the values β_0 and β_j ($j = 1..6$) are parameters to be estimated by the model and $g_s(d_i)$ are functions which can be estimated by a linear combination of B-spline functions, represented by

$$g_s(d_i) = \sum_{k=1}^{K} b_k(d_i) \theta_{sk} \quad (3)$$

In this case, K is the number of cubic spline functions, b_k are the k^{th} base functions of the applied B-splines on a given observed d_i, and θ_{sk} are the parameters of each base-function b_k. An alternative evaluation was also implemented replacing d by the BMI in order to evaluate the response of the model using this variable.

GAM presented in equation (1) was fitted by adjusting the parameters β and θ, using the Penalized Iteratively Reweighted Least Squares (P-IRLS) method. The accuracy of the model was evaluated considering the determination coefficient, R^2, which allows the estimation of the proportion of the data variability resulting to the fitting model. All statistical analyses were performed using R Software version 4.1.2 (The R Foundation for Statistical Computing). The authors adopt $p < 0.05$ to represent statistical significance.

3. Results

Table 2 presents the number of collected exams by CT scanner and patient gender, as well as total and median age. The 50th percentile and IQR of the evaluated DRLq considering each patient size are presented in Table 3.

Fig. 1 presents the percent distributions of the patients for each size group, considering the anatomical region. Fig. 2 presents the distributions of both cohorts in terms of their d and scanner used. The most frequent patient size groups at the facility were 25–33 cm, for both studied protocols. To the definition of the TVs, the standard-sizes of the patient cohorts in terms of their d was established as 29–31 cm for chest examination and 27–30 cm for abdomen-pelvis examinations.

The distributions of the DRL quantities ($CTDI_{vol}$, DLP and SSDE) considering different scanners are shown in Figs. 3 and 4 for Chest and Abdomen-pelvis protocol, respectively. It can be observed a large variability in the DRLq among different scanners. In particular, the higher DRLq values were observed for Scanner 4 and Scanner 1 for Chest and Abdomen-pelvis protocols, respectively. It is worth to mention that the box-plots presented in Figs. 3 and 4 include all the dataset and some

Table 2
– Demographic distribution of collected data by CT scanner. Median and min-max values of patient's age and weight, height and BMI are presented.

Protocol	Scanner	Number of exams per scanner				Median and range (max-min) of weight, heigh and BMI		
		Total	Female	Male	Median age (min-max)	Weight (kg)	Height (cm)	BMI (kg/m^2)
Chest	**SCANNER 1**	158	89 (56%)	69 (44%)	56 (18-83)	70 (40-115)	175 (155-190)	23.9 (16.5-37.6)
	SCANNER 2	101	58 (57%)	43 (43%)	55 (21-86)	70 (45-125)	175 (155-190)	22.9 (16.5-36.5)
	SCANNER 3	144	83 (58%)	61 (42%)	52 (20-83)	65 (40-125)	175 (150-190)	22.9 (16.5-36.5)
	SCANNER 4	234	96 (41%)	138 (59%)	55 (18-94)	75 (35-135)	175 (155-190)	24.2 (12.9-39.4)
	Total	**637**	**327 (51%)**	**312 (49%)**	**55 (18-94)**	**70 (35-135)**	**175 (150-190)**	**23.1 (12.9-39.4)**
Abdomen-pelvis[a]	**SCANNER 1**	104	67 (64%)	37 (36%)	54 (21–86)	75 (40-130)	170 (150-190)	25.4 (17.8-45.0)
	SCANNER 2	103	59 (57%)	44 (43%)	51 (20–89)	75 (40-120)	170 (150-190)	24.9 (16.5-34.3)
	SCANNER 3	112	60(54%)	52 (46%)	52 (19–93)	70 (40-120)	170 (150-190)	25.1 (16.5-33.2)
	Total	**319**	**186(58%)**	**133 (42%)**	**52 (19–93)**	**75 (40-130)**	**170 (150-190)**	**25.2 (16.5-45)**

[a] CT 4 was used as emergency dedicated equipment and during the COVID's pandemic period there wasn't significate sample for abdomen-pelvis protocols.

Table 3
Summary of the 50th percentile and IQR of the evaluated DRLq considering each patient size distribution.

Protocol	d (cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SSDE (mGy)
Chest	21-25	5.0 [4.3-6.6]	197 [177-269]	7.7 [6.5-10.1]
	25-29	6.7 [5.4-8.8]	267 [216-346]	9.1 [7.5-11.6]
	29-33	9.7 [8.5-11.1]	393 [341-452]	11.5 [10.4-13.1]
	33-37	13.6 [11.3-13.7]	543 [456-608]	14.0 [11.0-14.6]
Abdomen-pelvis	21-25	5.8 [5.2-6.5]	304 [257-339]	8.9 [8.5-10.0]
	25-29	8.1 [6.8-14.6]	421 [362-751]	10.8 [9.5-21.1]
	29-33	10.8 [9.1-18.4]	611 [498-941]	12.9 [11.5-21.5]
	33-37	18.5 [13.3-22.4]	997 [737-1212]	19.6 [13.7-22.5]

*It was considered 4.1% and 1.5% as $CTDI_{vol}$ and DLP uncertainties, respectively, with 95% confidence level (k = 2). A 20% uncertainty was considered for the quantity SSDE, according to the AAPM Report N° 204 (AAPM, 2011). The methods for obtaining the uncertainties were described in item 2.4.

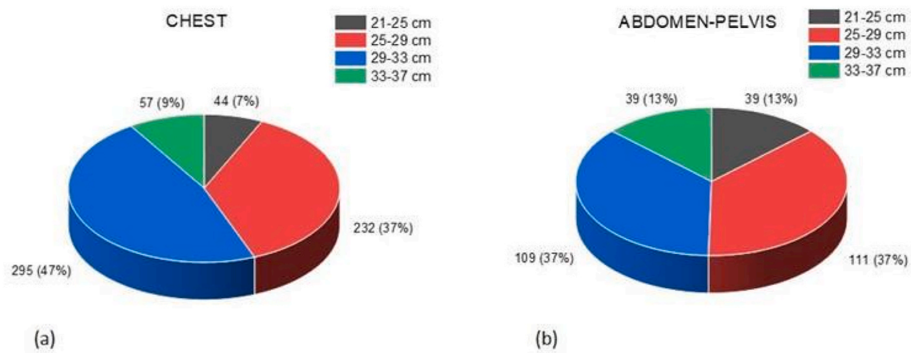

Fig. 1. Distribution of patients into each size groups for the (a) chest and (b) abdomen-pelvis cohorts.

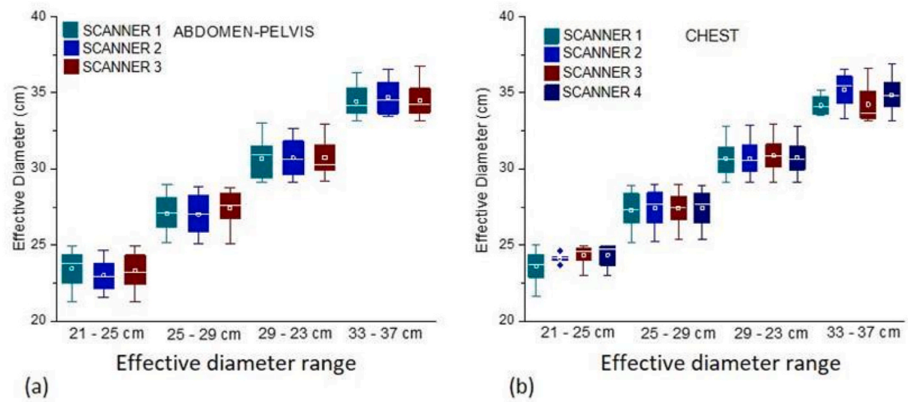

Fig. 2. Distributions of chest (a) and abdomen-pelvis (b) patients in the four ranges of effective diameters.

Table 4
Significance levels (p-value) of each scalar variable adopted at the applied GAM, considering the functional variables, $f(\bullet)$, as a function of the effective diameter values (d) or BMI. Values of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $p > 0.05$ represent strong, intermediate and no statistical significance, respectively

	Protocol	Scalar variables	Significance levels (p-value)										
			Age	Gender	mAs-cs	Pitch	IR	Slice Thickness	SCANNER				R^2
									1	2	3	4	
d	**Chest**	**CTDI**	0.041	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.803
		DLP	0.124	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.763
		SSDE	0.021	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.04	< 0.01	< 0.01	< 0.01	0.716
	Abdomen-pelvis	**CTDI**	< 0.01	0.885	< 0.01	0.936	< 0.01	0.099	< 0.01	< 0.01	< 0.01	-	0.938
		DLP	< 0.01	0.020	< 0.01	0.406	0.196	0.026	< 0.01	< 0.01	< 0.01	-	0.917
		SSDE	< 0.01	0.885	< 0.01	0.936	< 0.01	0.099	< 0.01	0.308	< 0.01	-	0.917
BMI	**Chest**	**CTDI**	0.040	0.239	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.784
		DLP	0.021	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.734
		SSDE	0.024	0.232	< 0.01	< 0.01	< 0.01	< 0.01	0.416	< 0.01	< 0.01	0.011	0.700
	Abdomen-pelvis	**CTDI**	< 0.01	0.787	< 0.01	0.429	< 0.01	0.558	0.021	< 0.01	< 0.01	-	0.933
		DLP	< 0.01	0.034	< 0.01	0.938	< 0.01	0.217	0.050	< 0.01	< 0.01	-	0.909
		SSDE	< 0.01	0.755	< 0.01	0.707	< 0.01	0.170	0.160	0.336	< 0.01	-	0.912

variation on DRLq distribution among the scanner can be also be caused by the differences between the patient size distributions, as shown in Fig. 2.

Table 4 presents significance levels (p-value) representing the statistical significance of the studied variables according to their influence in each DRLq. These significance levels of each scalar variable adopted at the applied GAM, considering the functional variables, $f(\bullet)$, as a function of *d* or BMI. Values of $p \leq 0.01$ represents strong statistical significance, $0.01 < p \leq 0.05$ represents intermediate statistical significance, and $p > 0.05$ no statistical significance. Using a table like this, it is possible objectively to identify what demographic or technical variables into the studied cohort are strongly-correlated, weakly-correlated or uncorrelated with the dosimetric variables of interest. Most of the CT scanners demonstrate significance on the estimation of all DRLq, since the smoothing functions adopted for all scanners, which accommodate functional variables to account to the effective diameter *d,* are significant on the GAM fitting.

Figs. 5 and 6 illustrate the DRLq estimated for each CT scanner as function of the effective diameter, *d,* considering the Chest and Abdomen-pelvis protocols, respectively. For an easier visualization of the variability, the trend lines and the respective 95% confidence interval are also included. Except for Chest protocol and Scanners 1 and 4, the DRLq increase as *d* increases, showing that *d* is a key-predictor on the

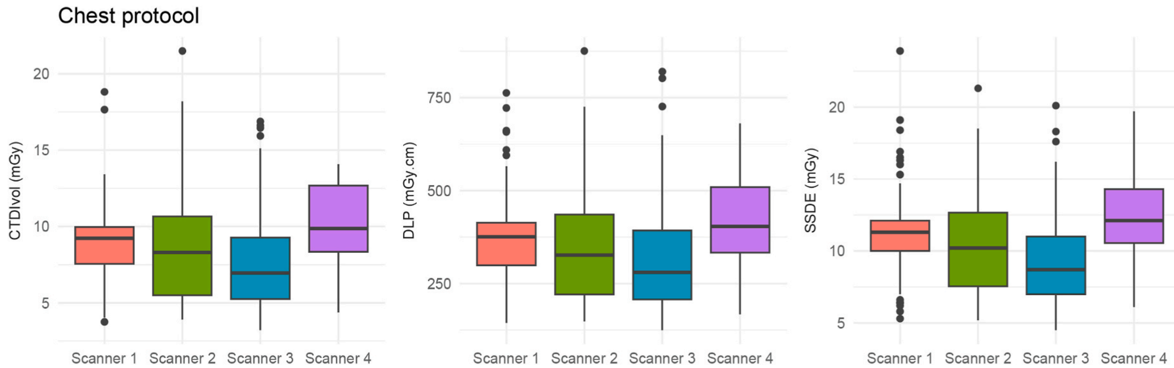

Fig. 3. *Box-plot* of the distribution of the DRL quantities ($CTDI_{vol}$, DLP and SSDE) for different scanners. Chest protocol.

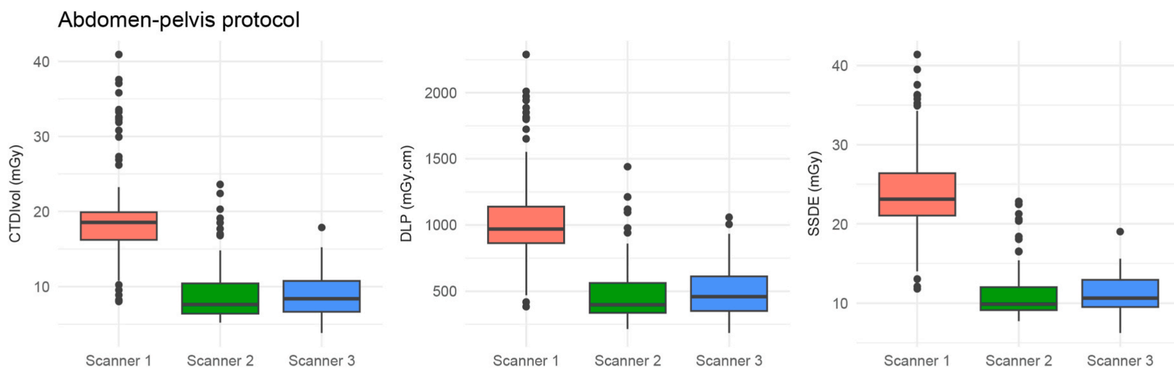

Fig. 4. *Box-plot* of the distribution of the DRL quantities ($CTDI_{vol}$, DLP and SSDE) for different scanners. Abdomen-pelvis protocol.

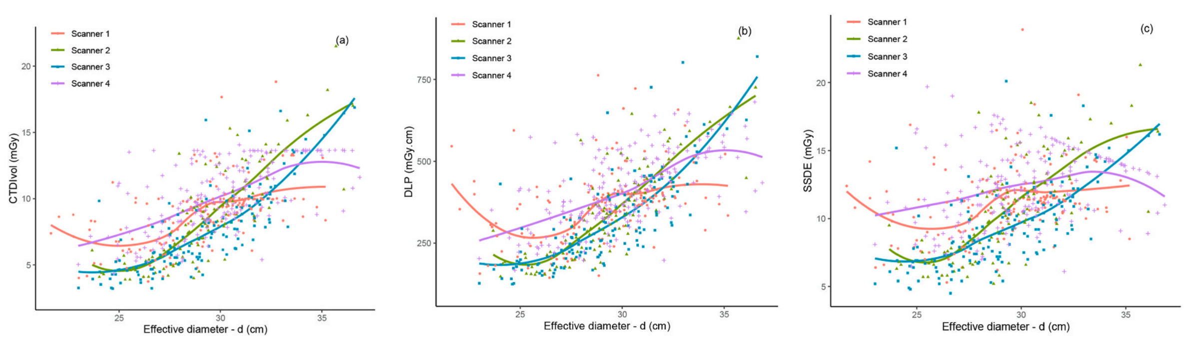

Fig. 5. DRL quantities ($CTDI_{vol}$, DLP and SSDE) as a function of the effective diameter for different scanners. Chest protocol.

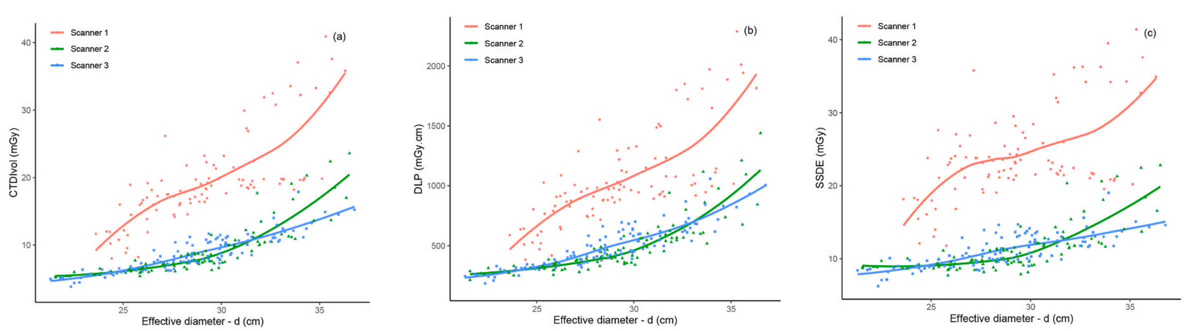

Fig. 6. - DRL quantities ($CTDI_{vol}$, DLP and SSDE) as a function of the effective diameter for different scanners. Abdomen-pelvis protocol.

DRLq evaluation. However, there is a non univocal relationship between DRLq and the patient size descriptor, being a large variability observed among the CT scanners. In addition, the variability of the DRLq values between CT scanner and effective diameter is larger in Chest protocol compared to Abdomen-pelvis one. Similar results were obtained considering BMI values as patient size descriptor.

The Supplemental Material present more examples of the statistical analysis implement in this work, including the statistical summary of the data and the detailed results of the GAM. A summary of the main findings of the GAM method is presented on the following.

For chest studies, the resulting accuracies (R^2) of the model were 0.803, 0.763 and 0.716 for fitting respectively the $CTDI_{vol}$, DLP and SSDE values. The alternative evaluation replacing the *d* by BMI as key predictor in the chest cohort resulted in a similar level of significance of all variables. However, in this case, all CT scanners demonstrate be significant on all DRLq, except by SCANNER 1 which was not significant on SSDE outcome. For this alternative implementation, the R^2 estimated for fitting respectively the $CTDI_{vol}$, DLP and SSDE values was estimated as 0.784, 0.734 and 0.7. The deviance explained by the models for both *d* and BMI was above 70.8%.

For the abdomen-pelvis cohort, the accuracy R^2 for fitting respectively the $CTDI_{vol}$, DLP and SSDE were estimated in 0.938, 0.917 and 0.917. The deviance explained by the model was above 92.1%. The adoption of the alternative implementation of the GAM considering the BMI resulted in similar results for all key predictors, except by the use of iterative reconstruction which is significant for all DRLq. All scanners are significant in estimating $CTDI_{vol}$. However, SCANNER 1 demonstrated to be not significant to the estimation of the DLP, while only SCANNER 3 is significant for SSDE estimation. In this case, the R^2 describing the $CTDI_{vol}$, DLP and SSDE fittings were 0.933, 0.909 and 0.912, respectively. The deviance explained by the model was above 91.5%.

4. Discussion

The determination of TVs is important when national DRLs are not available and when the facility performs a large number of exams. However, establishing TVs in practice is challenging. The results obtained depend on the size and homogeneity of the sample and its demographic characteristics. Additionally, the establishment of TVs must be implemented and constantly updated in clinical practice, aiming for the patient's radiation safety and an adequate quality diagnostic practice (Smith-Bindman et al., 2022). The use of the TVs associated with statistical tools is demonstrated in the present study as a comprehensive method for protocol optimization, supporting objective and assertive decision making. Besides that, the clinical image quality evaluation is crucial for the final decision in an optimization process, which was not performed in this study.

Although these practices are well established in developed countries (Roch et al., 2020), in low and middle-income countries these kinds of initiatives are still recent (Meyer et al., 2017). International, regional and local organizations have been publishing guidelines and harmonized results of consistent data collection (European Commission, 2014; Granata et al., 2018; Schegerer et al., 2021; Tsapaki et al., 2021; Vassileva et al., 2015). Investigators also alert to the limitations of these data surveys (Rehani, 2015) and for the need of data supported by adequate statistical analysis and sample size (Sohrabi et al., 2019; Taylor et al., 2017).

The current investigation exemplifies the utilization of the GAM statistical methodology adopting technical and demographic variables in order to clearly discern the critical components within the CT image acquisition process that must be prioritized for protocol optimization purposes. A representation of these findings, such as the p-values provided in Table 4, may emphasize the technical parameters meriting attention for effective optimization endeavors. For example, if the variable associated to the patient size is the effective diameter and the aim is to optimize adult thorax protocols, all technical variables (mAs-cs, pitch, IR and slice thickness) must to be considered for dose reduction purposes, almost independently of gender and age of the patients. An exception includes discernible correlations between gender and DLP, indicative of potential disparities in the selected scan length utilization across genders in chest CT studies. In this case, the strategy must be focused on radiographer training initiatives, transcending mere technical or reconstruction parameter adjustments.

On the other hand, considering the abdomen-pelvis protocols, the most important technical factor to be considered is the mAs-cs, associated with the proper choice and calibration of the system's tube current modulation (TCM). In this case, it is imperative that the clinically qualified medical physicist and the radiologists work collaboratively in order to balance the best TCM available choice that produces images with diagnostic quality while minimizing radiation exposure. Furthermore, the patient age is also a correlated factor and may be considered in training programs of the radiographers' teams.

In terms of the demographic variables (age and gender) the model demonstrates that age is not or is weakly-correlated to the DRLq's results from chest procedures but strongly correlated when considering abdomen-pelvis examinations adopting *d*. Gender, on the other hand, is correlated to the DRLq's for chest examinations adopting *d* as a key predictor but it is only correlated with DLP adopting the BMI as a key predictor. This can be associated with the presence of the breast on the determination of the effective diameter, which may result in different values of *d* for patients with similar BMIs considering male or female patients. In all other cases, gender is not or weakly-correlated to the DRLq's.

In the studied sample, the model provides a quite evident conclusion that the mAs at the central slice is an important parameter for all DRLq's for both cohorts independently of the key predictor adopted. However, pitch, IR and the slice thickness demonstrate only be correlated to chest studies in both cases of the key predictors. Pitch and slice thickness are not or just weakly-correlated for abdomen-pelvis studies. Finally, the use of IR demonstrates be importantly correlated to the DRLq's, except to the DLP for abdomen-pelvis studies adopting the effective diameter as a key-predictor.

The level of accuracy provided by the GAM can be considered adequate for interpreting the fitting of DRLq since a large fluctuation of these DRLq, exposure parameters and demographic data are observed for that patient cohort. In particular, for abdomen-pelvis protocol the goodness of fit of the models is smaller than for chest-protocol, considering both *d* and BMI as key predictors. This behavior can be related with the larger variation of the DRLq for a same patient's characteristic compared to the chest protocol.

Although the sample size and generalizability facilitate the demonstration of the efficacy of the statistical methodology proposed in the present work, some few limitations of the study can be mentioned. Notably, the method's application was restricted to cohorts derived exclusively from abdomen-pelvis and chest CT examinations from a single healthcare institution. To augment the applicability and comprehensiveness of the proposed statistical framework, future investigations should contemplate its deployment in a multi-center study. This kind of approach would offer insights into diverse facets of correlations between CT technical parameters and demographic variables, thereby enriching the understanding of these associations. The applications in specific cohorts, such as pediatric patients, can also be interesting for particular optimization purposes. Additionally, the evaluation was done in a limited spectrum of CT machines from the three major vendors. Studies considering a broader array of CT system models and incorporating emerging technologies, such as photon-counting CT, could potentially reveal novel interesting results. The incorporation of state-of-the-art reconstruction algorithms, including those based on artificial intelligence, may also delineate alternative pathways for optimizing imaging protocols.

The ICRP 147 publication (ICRP, 2021) recognizes that the best way to estimate the risk to individuals submitted to medical procedures using ionizing radiation is the adoption of organ/tissue doses and specific dose risk models. Therefore, connections between organ doses and measurable quantities determined using controlled cohorts and its associations with technical factors normally adopted in the clinical practice may support the development of models to identify patient-specific risks (Costa et al., 2023).

5. Conclusions

GAM demonstrates to be flexible and accurate in both evaluated cohorts to identify and test the significance of the relationship regarding demographic and technical parameters which may drive the focus of future dose optimization processes. The model demonstrates that mAs-cs and use of iterative reconstruction impact all DRLq in both anatomical regions. However, IR, pitch and slice thickness are important only in chest examinations.

The authors understand that the outputs of the proposed methodology may contribute to the establishment of current (Fu et al., 2021) and new (Samei et al., 2022) risk-associated metrics applied to imaging modalities (Ria et al., 2021) and can also support further investigations associating DRLs and organ doses (Costa et al., 2023).

The evaluation of demographic data can be use just to characterize the population submitted to the examinations and their association with the DRLq's. However, the careful identification of the technical parameters more or less influential on the DRLq's may drive the effort to effective optimization actions. Close collaborations between stakeholders is essential and determinant of the effectiveness of the presented technique for CT protocol optimization.

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Statistics and biometry

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Informed consent

Written informed consent was waived by the Institutional Review Board.

Ethical approval

Institutional Review Board approval was obtained.

Study subjects or cohorts overlap

Some study subjects or cohorts have been previously reported in Costa et al. Insights into Imaging (2023) 14:60 https://doi.org/10.1186/s13244-023-01403-y.

Methodology

- retrospective
- experimental
- performed at one institution

CRediT authorship contribution statement

Paulo Roberto Costa: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jullianna Cristina de Oliveira Castro:** Data curation, Formal analysis, Resources. **Isabella Paziam Fernandes Nunes:** Data curation, Formal analysis, Resources. **Denise Yanikian Nersissian:** Data curation, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Márcio Yamada Sawamura:** Data curation, Resources, Writing – review & editing. **Hilton Leão Filho:** Data curation, Resources, Writing – review & editing. **Alessandra Tomal:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radphyschem.2024.111669.

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