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Establishing national clinical diagnostic reference levels and achievable doses for CT examinations in Brazil: A prospective study

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ABSTRACT

Purpose: Diagnostic reference levels (DRL) and achievable doses (AD) are important tools for radiation dose optimization. Therefore, a prospective study was performed which aimed to establish a multi-parametric, clinical indication based – DRL(DRL_{CI}) and clinical indication – AD (AD_{CI}) for adult CT in Brazil.

Methods: The prospective study included 4787 patients (50 ± 18 years old; male:female 2041:2746) at 13 Brazilian sites that have been submitted to head, paranasal sinus, cervical spine, chest, or abdomen-pelvis CT between January and October 2021 for 13 clinical indications. The sites provided the following information: patient age, gender, weight, height, body mass index[BMI], clinical indications, scanner information(vendor, model, detector configuration), scan parameters (number of scan phases, kV, mA, pitch) and dose-related quantities (CT dose index volume- $CTDI_{vol}$, dose length product- DLP). Median(AD) and 75th(DRL) percentile $CTDI_{vol}$ and DLP values were estimated for each body region and clinical indications. Non-normal data were analyzed with the Kruskal-Wallis test.

Results: In majority of Brazilian sites, body region and clinical indications based DRLs were at or lower than the corresponding DRLs in the US and higher than Europe. Although radiation doses varied significantly for patients in different body mass index groups ($p < 0.001$), within each body region, there were no differences in radiation doses for different clinical indications ($p > 0.1$). Radiation doses for 7/13 clinical indications were higher using iterative reconstruction technique than for the filtered back projection.

Conclusions: There was substantial variation in Brazil DRL_{CI} across different institutions with higher doses compared to the European standards. There was also a lack of clinical indication-based protocol and dose optimization based on different clinical indications for the same body region.

Abbreviations

ACR	American College of Radiology
AD	Achievable doses
AEC	Automatic exposure control
ALARA	As low as reasonably achievable
BMI	Body mass index
CBR	Brazilian College of Radiology
CT	Computed tomography
$CTDI_{vol}$	CT dose index volume
DIR	Dose Index Registry
DLP	Dose length product
DRL	Diagnostic reference levels (DRL)
DRL_{CI}	DRLs based on clinical indications
ESR	European Society of Radiology
EUCLID	European Commission funded the European study on clinical diagnostic reference levels for x-ray medical imaging
ICRP	International Commission on Radiation Protection
TCLE	Free and Informed Consent Form

1. Introduction

Imaging, in particular radiography and CT, plays huge role in management of a variety of acute and chronic diseases from head to toe in both the developing and underdeveloped countries worldwide [1,2]. While the value and standing of CT in modern medicine are not disputed, with swaths of applications from head to toe and from infections to cancer imaging, the issues stemming from unjustified applications and suboptimal scan protocols have raised concerns over associated radiation doses and the potential risks of radiation-induced cancers [3]. The national and international regulatory bodies and organizations have issued guidelines against imaging overuse and have stressed on the need for optimizing scan protocols [4,5]. Several technologic developments over the last two decades enable users to optimize scan protocols and parameters for radiation dose reduction. Notable developments that help optimize radiation doses include automatic exposure control, automatic tube potential selection, 3D camera-based patient centering and positioning, dose-efficient detectors, and improved reconstruction techniques such as with iterative and deep-learning methods [6,7].

Besides the referral and appropriate use guidelines, as well as the optimization of scan protocols, CT radiation dose monitoring is also considered critical for ensuring that the principle of as low as reasonably achievable (ALARA) is honored [8–10]. Toward that goal, the International Commission on Radiation Protection (ICRP) introduced and urged the adoption of diagnostic reference levels (DRL) to establish benchmark radiation doses for diagnostic imaging [8–10]. Several subsequent studies reported on anatomic region-specific DRL, which represents the 75th percentile of dose distribution at an institutional, regional, or national level [11–14]. The main purpose of DRLs, and later, the concept of the achievable doses (AD – set at 50th percentile of dose distribution) from the National Council on Radiation Protection and Measurements (NCRP), is to help improve radiation dose optimization and reduction [15]. With the radiation dose monitoring software, sites can use larger datasets of CT scanners and protocols to create local or regional DRLs and ADs to identify which scanners/protocols/patient types (adult versus children, large versus average or small size patients) require adjustment to acquisition protocols and radiation doses. Such local DRLs and ADs can also help convince radiologists and technologists on the need for dose optimization and reduction policies.

Due to differences in diagnostic requirements for various clinical indications, scan factors, techniques, and associated radiation doses within each anatomic region can vary and offer an additional opportunity for establishing DRLs based on clinical indications (DRL_{CI}) [16]. For example, some clinical indications can and must be imaged with substantially lower radiation doses (such as head CT for shunt patency, paranasal sinus CT before endoscopy, chest CT for lung nodule follow-up or lung cancer screening, and abdomen CT for urinary calculi and colonography) versus other indications such as for cancer staging, esophageal leaks, chest trauma, and focal liver and pancreatic lesions. Therefore, DRL_{CI} can help ensure that radiation doses are stratified and optimized within each body part to ensure that there are no more than necessary radiation doses based on the specified diagnostic need rather than a single protocol and dose fit all indications without DRL_{CI}. The European Commission funded the European study on clinical diagnostic reference levels for x-ray medical imaging (EUCLID) reported DRL_{CI} for 10 frequent clinical indications for CT in various anatomic regions [17]. Subsequent studies from the US and other parts of the world have embraced the DRL_{CI} concept to spur dose optimization, which accounts for both the clinical indication and anatomic region of interest [13]. In collaboration with the Brazilian College of Radiology (CBR) and multiple academic sites from multiple states in Brazil, we conducted a

prospective study on establishing the first multi-parametric, multi-site clinical indication-based DRL DRL_{CI} for the head, paranasal sinus, cervical spine, chest, and abdomen-pelvis CT examinations in Brazil.

2. Methods

We performed a multicenter, quantitative, prospective study. Individual participating sites obtained local ethical committees' approval for contributing the study data on consecutive patients who underwent head, paranasal sinus, cervical spine, chest, and abdomen-pelvis CT examinations. We do not have any financial disclosures related to the study. All coauthors had access to the study data and the manuscript.

2.1. Study sites and population

The CBR contacted several imaging sites in 26 states in Brazil. Of these, 13 sites from seven states in Brazil submitted data for the study. The participating sites included 6/13 sites public hospitals, 7/13 private centers and hospitals, and 5/13 university/teaching hospitals.

The inclusion criteria were patients older than 18 years; availability of clinical indication for CT; patients' body weight and height; CT services in hospital or outpatient clinics settings; agreement with the terms in the Free and Informed Consent Form (TCLE); agreement with terms of confidentiality of data; national quality control requirements updated, availability of a research radiologist, technologists or medical physicists for data recording; capability and approval for sending technical data of included variables. As per the guidance document for DRLs, we requested each site to contribute data from at least 20–30 patients for each clinical indication [9]. The exclusion criterion was an insufficient number of CT examinations for a given clinical indication (that is <15 patients/clinical indication) (Fig. 1).

2.2. Clinical indications

Participating sites contributed data on 13 common clinical indications for the head, paranasal sinuses, cervical spine, chest, and abdomen-pelvis CT. These clinical indications represent the most frequent reasons for ordering different body part CT in Brazil. All CT examinations were performed between January and October 2021. Table 1 shows the representation of the clinical indications included in our study per anatomical region. These clinical indications represented the most common indications for ordering CT in different body parts [13]. Although not common, head CTA protocol was included due its

Table 1
Represents the clinical-indications included in our study per anatomical region.

Body regions	Clinical indications
Head (n = 1475)	Brain Trauma
	Headache
	Stroke
Head CTA (n = 34)	CT Angiography
Paranasal sinus (n = 565)	Sinusitis
Cervical spine (n = 204)	Trauma
Chest (n = 1312)	Covid
	Cancer
	Pneumonia
	Pulmonary embolism
Abdomen (n = 857)	Appendicitis
	Renal stone
Chest and abdomen (n = 340)	Cancer

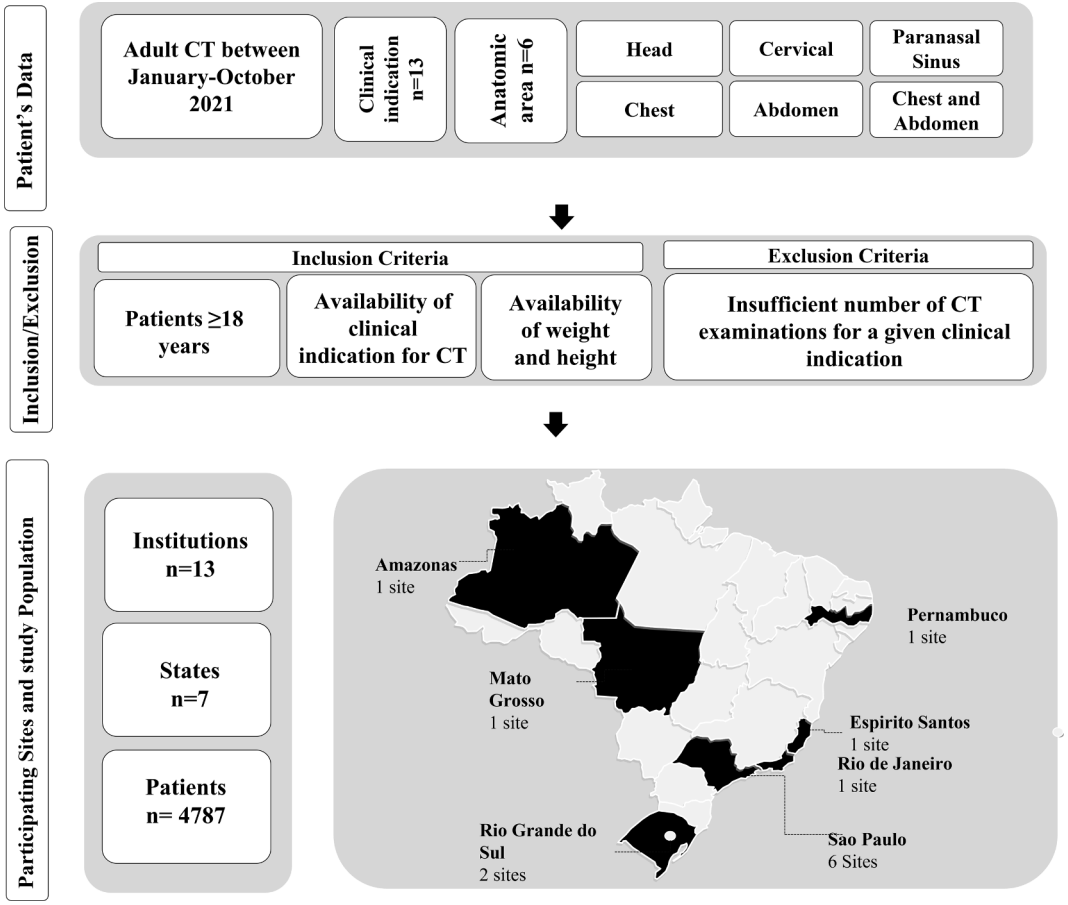

Fig. 1. Flow diagram summarizing the study dates and components of the CT data from various institutions in Brazil.

association with multiphase imaging and higher radiation doses compared to routine head CT and paranasal sinus CT examinations.

2.3. Survey component

Before the data collection phase, we surveyed the participating sites to obtain information on the most common clinical indications, basic demographics, scanner name, vendor, number of detector rows, year of installation, and the sites' technical ability to collect and share data for the project. We created and shared a fillable Google Forms document to collect this information. Most survey data were filled by CT technologists or research radiologists.

2.4. Collected data elements

We requested each site to provide data from at least 20–30 CT examinations per clinical indication. Sites either uploaded their data on a web-based platform or filled out an MS-Excel® worksheet with labeled columns. We requested the sites not to record or share patient health information such as patient name, date of birth, medical record number, and examination accession number. On the patient level, we collected the following information: age, gender, body weight, body height, and the clinical indications for CT. From the weight and height information, we estimated the body mass index (BMI) and classified patients into four categories (underweight patients: <18.5 kg/m^2; normal BMI: 18.5–24.9 kg/m^2; overweight: 25.0–29.9 kg/m^2; obese BMI: ≥ 30 kg/m^2) [18,19].

We also requested scan factors-related information, including the technique of tube current selection (fixed tube current versus automatic exposure control [AEC]), average tube current, tube potential, gantry rotation time, pitch, scan length, prospective section thickness, reconstruction technique (filtered back projection or iterative reconstruction), anatomic scan start and end locations, and number and name of scan phases. Participants were requested to enter CT dose index volume ($CTDI_{vol}$) and dose length product (DLP) separately for each scan phase. Since most sites' scanners do not provide the dose for planning radiographs, we did not collect that data.

In addition, we requested one radiologist from each site to comment on whether the image quality of the included CT examination was acceptable or unacceptable for diagnostic interpretation.

2.5. Data verification

To verify data accuracy, we created common MS-Excel® worksheets for each protocol from all sites and reviewed each dose level to exclude any potential errors in data recording, such as multiphase CT without phase-specific doses or sites with too few examples for any specific clinical indication. A senior radiologist (MKK, 23 years of experience in CT protocol and radiation dose optimization) and a post-doctoral research fellow (LK) performed the data verification.

2.6. Statistical analysis

Data were analyzed in Microsoft Excel (Microsoft Office 365) and IBM®SPSS® statistical software version 26 (IBM Corporation, New Orchard Road Armonk, NY). For multi-phase CT, we added the DLP to derive the total DLP and obtained the median $CTDI_{vol}$ for the entire exam. Next, we estimated the 50th (AD) and 75th (DRL) for $CTDI_{vol}$ and DLP for each of the five body regions (head, paranasal sinuses, cervical spine, chest, and abdomen-pelvis), and separately for each of the 13 clinical indications. Data were represented in tabular and box-whisker plots. We numerically compared the $CTDI_{vol}$ and DLP for each body region and clinical indication with the corresponding doses from the US and European Union data [13,14,17,20]. We performed Kolmogorov–Smirnov test to determine the distribution of the data. Kruskal Wallis and Man-Whitney tests were used to compared the non-normal distributed data as median and the radiation doses between different parameters (BMI, reconstruction techniques, automatic/fixed tube potential). A p-value less than 0.05 was considered statistically significant.

3. Results

3.1. Survey

Of the 13 participating institutions, nine had one CT scanner, 4 had two or more CT scanners. Among the 21 multidetector-row CT scanners (16–192 rows) at these sites, there were 9 scanners from Siemens Healthineers (SOMATOM Definition Flash, SOMATOM Definition Force, SOMATOM Definition AS, SOMATOM Go, and SOMATOM Drive), 7 from Philips Healthcare (Brilliance 64, Access, and MX16] and 5 from Canon Medical Systems (Aquilion Prime, CETF Alexion).

3.2. Patient data

Following data verification, the study included 4787 adult patients with a mean age of 50 ± 18 years. There were 2746 female patients (2746/4787, 57 %) and 2041 male patients (2041/4787, 43 %). The distribution of patients in different BMI groups was underweight: 56/4787 patients (1.2 %); normal BMI 1555/4787 (33.1 %); overweight: 1948/4787 (41.5 %); obese BMI: 1134/4787 (24.2 %). The number of patients for different body regions and clinical indications are presented in Table 2. Radiologists from each site deemed all CT examinations as diagnostically acceptable from the image quality perspective.

3.3. Anatomic region-specific DRLs

The DRL and AD for different body regions versus the corresponding values from the US and European publications [22; 23] are summarized in Table 3. The DRL and AD for most body regions and clinical indications were lower than the corresponding values from the US and higher than Europe (Table 3 and 4). The distribution of sites with $CTDI_{vol}$ below or at the US or European DRL was CT head (84 % – 11/13 sites), paranasal sinuses (9/10 sites), cervical spine (7/7 sites), chest (10/12 sites), and abdomen-pelvis (7/8 sites). The corresponding distribution of sites for DLP values below or at the US or European DRL was head (4/13 sites), paranasal sinuses (1/10 sites), cervical spine (4/7 sites), chest (1/12 sites), and abdomen-pelvis (2/8 sites) (Table 4).

There were significant differences between radiation dose quantities (both $CTDI_{vol}$ and DLP) for patients in different BMI categories ($p < 0.001$) for cervical spine, chest, and abdomen-pelvis CT, but not for head and paranasal sinuses where the anatomic variations between patients are minimal ($p > 0.05$). Fig. 2 presents the 50th and 75th percentile $CTDI_{vol}$ according to patients' BMI groups. There were significant differences in the body region-based radiation doses among different sites ($p < 0.001$).

3.4. DRL_{CI}

The DRL_{CI} and AD_{CI} for the different clinical indications included in our study are summarized in Table 4 [13]. There were significant differences between radiation dose quantities (both $CTDI_{vol}$ and DLP) for patients in different BMI categories ($p < 0.001$) for all clinical indications of the chest and abdomen-pelvis CT. Fig. 2 presents the C-DRL and AD_{CI} for different clinical indications of chest and abdomen CT according to patients' BMI categories. There were significant differences in clinical indication-based radiation doses among different sites ($p < 0.001$). Site-wise DRL_{CI} and AD_{CI} for different clinical indications are summarized in the appendix (Table 5).

Most of the clinical indications except head CTA (63 %, 27/40 with > 2–4 phases) had a single-phase non-contrast or post-contrast CT [head trauma: 98 % (n = 322/328), headache: 89 % (n = 799/889), stroke: 98 % (n = 255/258), paranasal sinus screening: 100 % (n = 565/565) cervical spine trauma: 100 % (n = 204/204), suspected COVID-19: 93 %

Table 2
Tabular summary of CT patients' demographics and clinical indications.

Body regions	Clinical indications	Count	Participating Sites	Age (years)	Male: Female	BMI (kg/m^2)
Head (n = 1475)	Brain Trauma	328	12/13	56 ± 22	145: 183	25 ± 5
	Headache	889	9/13	48 ± 19	316: 573	25 ± 8
	Stroke	258	12/13	62 ± 20	109: 149	26 ± 7
Head CTA (n = 34)	CT Angiography	34	4/13	56 ± 15	10: 24	20 ± 2
Paranasal sinus (n = 565)	Sinusitis	565	10/13	43 ± 15	221: 344	26 ± 6
Cervical spine (n = 204)	Trauma	204	7/13	47 ± 16	97: 107	27 ± 5
Chest (n = 1312)	Covid	518	9/13	51 ± 16	265: 253	28 ± 5
	Cancer	71	8/13	61 ± 15	28: 43	26 ± 5
	Pneumonia	621	12/13	51 ± 18	286: 335	28 ± 5
	Pulmonary embolism	102	7/13	57 ± 17	39: 63	28 ± 5
Abdomen (n = 857)	Appendicitis	126	9/13	35 ± 13	40: 86	27 ± 6
	Renal stone	731	11/13	44 ± 14	351: 380	28 ± 5
Chest and abdomen (n = 340)	Cancer	340	10/13	59 ± 14	134: 206	27 ± 5

Age in years ± standard deviation, BMI in Kg/m^2 ± standard deviation

Table 3
AD and DRL for $CTDI_{vol}$ and DLP for different body regions benchmarked with US and European levels. We recommend the summarized CTDIvol and DLP as the DRLs for Brazil [22,23].

Body Region	Brazil				US [21]				Europe [20]			
	$CTDI_{vol}$ (mGy)		DLP (mGy.cm)		$CTDI_{vol}$ (mGy)		DLP (mGy.cm)		$CTDI_{vol}$ (mGy)		DLP (mGy.cm)	
	AD	DRL	AD	DRL	AD	DRL	AD	DRL	AD	DRL	AD	DRL
Head CT (n = 1475)	29	45	614	942	49	56	811	962	–	47	–	790
Paranasal sinus CT (n = 565)	15	19	228	353	20	28	421	562	–	12	–	160
Cervical spine CT (n = 204)	16	23	394	547	20	28	421	562	–	16	–	400
Chest CT (n = 1210)	8	11	298	409	9	12	334	443	–	9	–	290
Abdomen CT (n = 126)	9	12	443	632	13	16	639	781	–	10	–	530
Chest abdomen CT (n = 340)	8	13	628	1345	12	15	779	947	–	–	–	660

Clinical indication-based CT protocols doses are summarized in table 3 (Head CTA, CT pulmonary angiography and renal stone CT).

Table 4
AD_{CI} and DRL_{CI} ($CTDI_{vol}$ and DLP) for different clinical indications benchmarked with US and European levels.

Body Region	Clinical Indication	Data				US [13]				Europe [13]			
		$CTDI_{vol}$ (mGy)		DLP (mGy cm)		$CTDI_{vol}$ (mGy)		DLP (mGy cm)		$CTDI_{vol}$ (mGy)		DLP (mGy cm)	
		AD_{CI}	DRL_{CI}	AD_{CI}	DRL_{CI}	AD_{CI}	DRL_{CI}	AD_{CI}	DRL_{CI}	AD_{CI}	DRL_{CI}	AD_{CI}	DRL_{CI}
Head	**Head Trauma**	26	37	601	769	–	–	–	–	–	43	–	920
	Headache	29	45	616	955	–	–	–	–	–	–	–	–
	Stroke	30	53	617	998	50	56	899	1072	38	43	691	829
	Head CTA	19	26	633	1181	–	–	–	–	–	–	–	–
Paranasal Sinus	**Sinusitis**	15	19	228	353	19	27	311	446	18	38	265	707
Cervical spine	**Trauma**	16	23	394	547	19	24	421	609	11	14	256	358
Chest	**Covid-19**	8	12	320	454	–	–	–	–	–	–	–	–
	Lung cancer	6	10	249	419	9	12	336	478	4	5	130	215
	Pneumonia	8	10	285	379	–	–	–	–	–	–	–	–
	Pulmonary embolism	11	15	376	582	11	15	420	594	4	6	138	206
Abdomen	**Appendicitis**	9	12	443	632	12	15	645	880	9	12	433	625
	Renal stones	10	13	535	717	–	–	–	689	–	6	–	290
Chest and Abdomen	**Cancer**	8	13	628	1345	–	–	–	–	–	10	–	870

(n = 485/518), cancer: 80 % (n = 57/71), pneumonia: 97 % (n = 607/621), pulmonary embolism: 67 % (n = 69/102), appendicitis: 95 % (n = 120/126) and renal calculus: 92 % (n = 678/731)].

Most CT examinations, regardless of clinical indications, were performed with AEC (Fig. 3). When compared across CT examinations for the same clinical indications t at different sites, radiation doses with AEC were significantly lower than for fixed tube current for three clinical indications (head CT for trauma, stroke, and headache) and significantly higher than fixed tube current for the remaining two indications (head CTA, sinus screening CT) ($p < 0.001$). Most sites (12/13) without the automatic tube potential selection techniques used a manually selected fixed tube potential. As noted in Fig. 4, radiation doses for 5/13 clinical indications imaged with the automatic tube potential selection technique were higher than those with a fixed tube potential ($p < 0.001$).

When compared across identical clinical indications/protocols, for 7/13 clinical indications, $CTDI_{vol}$ for CT exams with iterative reconstruction was significantly higher than those with filtered back projection ($p < 0.001$) (Fig. 5) although there was no difference in patients' BMI in CT exams with or without iterative image reconstruction ($p > 0.05$). For the remaining clinical indications, iterative reconstruction did not make any difference in radiation doses compared to CT examinations reconstructed with the filtered back projection technique ($p > 0.05$).

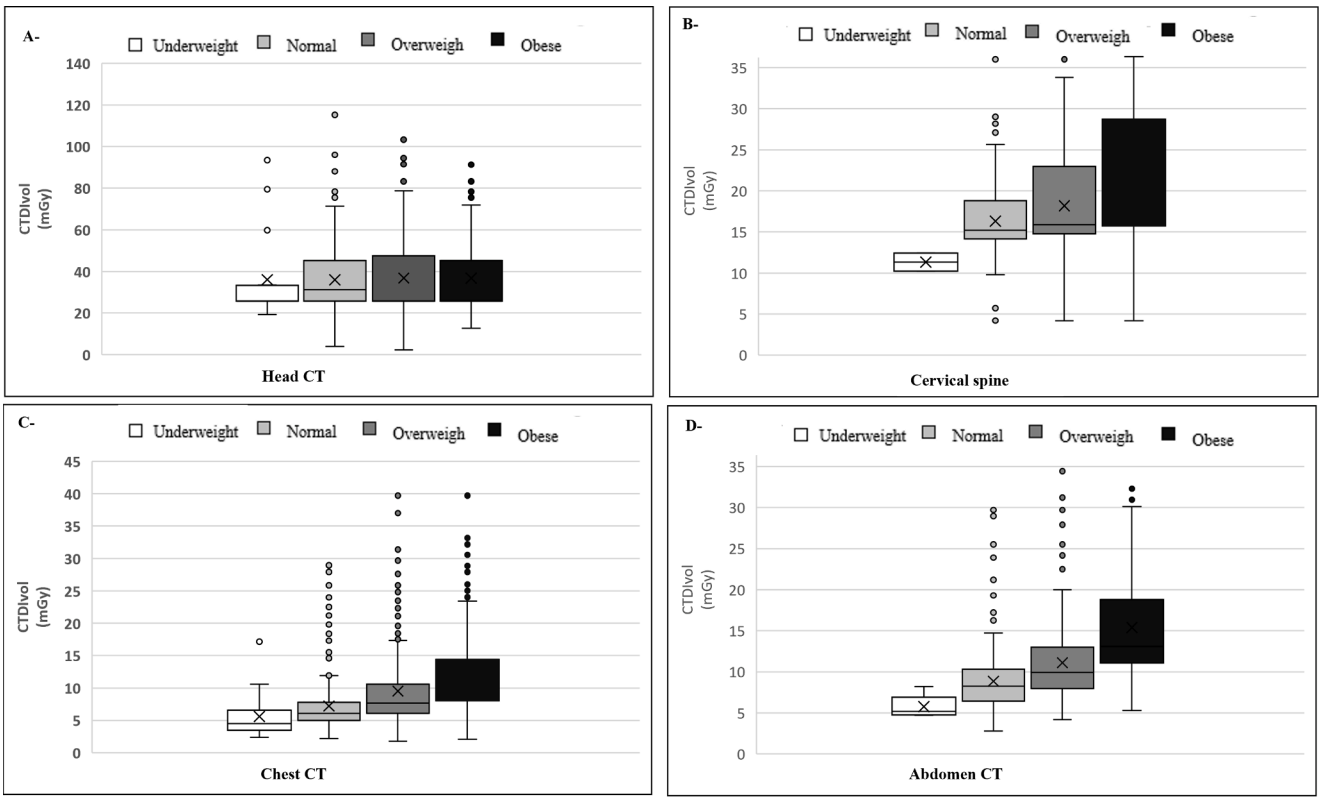

Fig. 2. Box and whisker plots illustrating variation in CTDIvol (y-axis) per body habitus for (A) head, (B) cervical spine, (C) chest, and (D) abdomen-pelvis CT examinations.

4. Discussion

We report that DRL and AD for different body regions and clinical indications in most sites in Brazil were lower than the corresponding values from the US and higher than Europe [20–22]. Statistical comparison with other studies is not feasible since the other study data are not available for comparison. Versus prior publications from the US and EU [20–22], our study provides both ADCI and DRLCI for more clinical indications. Our study highlights the underutilized opportunity to reduce radiation doses for chest CT examinations, particularly when compared to European data. Doses for lung cancer, pulmonary embolism, and kidney stones were almost two-fold higher in Brazil (Table 4). Due to high inherent tissue contrast, these indications must be scanned at lower radiation doses. Our study also highlights the lack of advanced CT technologies in the participating sites, which can help reduce radiation doses while retaining or improving image quality (such as wider, efficient detector array scanners, iterative reconstruction, and automatic tube potential selection techniques).

The major clinical implication of our study is the establishment of Brazilian DRL and AD for different body regions and 13 clinical indications. Since our DRL and AD are lower than most corresponding DRL from the US [20–22], we believe that our DRL_{CI} will help other sites in Brazil, beyond those included in our project, optimize radiation doses based on clinical indications. Another implication of our study applies to the participating sites, which need to adjust scan protocols and radiation doses for different clinical indications within the same body region. In fact, a lack of change in scan factors with identical radiation doses across different clinical indications in the same body region suggests that most sites do not have dedicated, pre-saved scan protocols for different clinical indications. This finding defeats the essence of DRL_{CI}, which is to encourage users to modify scan protocols based on different image quality requirements for different clinical indications. Thus, radiation doses for chest CT in suspected COVID-19 or pneumonia should be lower than for cancer work-up, since high image noise in reduced dose CT does not affect the visibility of lung findings. Likewise, kidney stones too can be assessed in images with much higher noise acquired with lower radiation dose than lesions in the liver, spleen, and pancreas.

Our study highlights impressive DRL for most clinical indications versus other studies [12,25] but also draws attention to the overall lack of advanced, modern CT scanners at the participating sites. Fewer than 10 % of CT examinations were performed with either iterative reconstruction or automatic tube potential selection techniques, which have been available on most CT scanners for the past several years. At sites with iterative reconstruction techniques, radiation doses with their use were higher than with filtered back projection for 7/13 clinical indications, which suggests improper use of the newer, advanced image reconstruction techniques. Thus, the availability of modern techniques does not guarantee optimized CT protocols and radiation doses. Sites should modify scan factors (such as tube potential and/or current) to reduce radiation dose when using iterative reconstruction technique versus filtered back projection. After completing our study and data analysis, the CBR organized online educational sessions for all participating sites to help them improve their scanning practices. We reviewed individual dose data with each site, and where needed, we advised them to adjust scan protocols and optimize radiation doses based on clinical indication. We emphasized the need for dedicated scan protocols and modifications in scan factors to adjust dose based on the clinical need for specified indications. If the users do not modify scan factors as per clinical need, the automatic exposure control and automatic tube potential selection technique will only adapt the tube current and potential according to the body region and size, without exploiting the opportunity of adapting these factors and radiation doses based on clinical need. Furthermore, a lack of scan factor modification can also negatively influence diagnostic quality of the exam such as with lack of low tube potential use for certain indications (for example, CT angiography) which not only reduces dose but also improves contrast enhancement.

Table 5
Site-specific ADCI and DRLCI (CTDIvol in mGy and DLP in mGy cm) for different clinical indications.

Body Region	Clinical indications	Radiation	Sites												
			A	B	C	D	E	F	G	H	I	J	K	L	M
Head	Head Trauma	$CTDI_{vol}$	26 (26)	53 (50)	60 (60)	91 (75)	78 (78)	51 (51)	36 (34)	54 (54)	52 (31)	–	45 (45)	32 (30)	29 (28)
		DLP	603 (590)	1149 (1020)	1088 (1052)	1809 (1631)	1597 (1479)	1317 (1237)	711 (667)	962 (962)	1071 (657)	–	1068 (1068)	595 (564)	581 (502)
	Headache	$CTDI_{vol}$	26 (26)	–	60 (60)	–	–	51 (51)	36 (34)	54 (54)	52 (52)	42 (42)	45 (45)	–	30 (29)
		DLP	601 (581)	–	1052 (998)	–	–	1195 (1122)	721 (680)	930 (914)	1227 (1097)	1664 (895)	1046 (1001)	–	870 (545)
	Stroke	CTDIvol	26 (26)	50 (34)	60 (60)	79 (71)	78 (64)	36 (36)	35 (34)	54 (54)	31 (31)	–	45 (45)	48 (32)	48 (31)
		DLP	607 (588)	1020 (704)	1052 (963)	1620 (1460)	1558 (1143)	933 (933)	703 (673)	941 (941)	617 (600)	–	1091 (1091)	891 (584)	1000 (831)
	Head CTA	$CTDI_{vol}$	26 (26)	–	7 (6)	–	–	–	–	–	24 (17)	–	–	–	37 (32)
		DLP	1181 (1133)	–	476 (476)	–	–	–	–	–	1226 (914)	–	–	–	692 (593)
Paranasal Sinus	Sinusitis	$CTDI_{vol}$	19 (19)	12 (7)	15 (15)	28 (25)	37 (32)	–	2 (1)	19 (19)	31 (22)	–	10 (10)	–	7 (3)
		DLP	365 (344)	236 (124)	215 (191)	503 (440)	638 (603)	–	31 (27)	277 (271)	682 (484)	–	176 (166)	–	117 (54)
Cervical Spine	Trauma	$CTDI_{vol}$	27 (21)	–	6 (5)	30 (24)	13 (13)	–	16 (15)	13 (13)	–	–	–	–	17 (17)
		DLP	687 (498)	–	139 (97)	803 (549)	271 (271)	–	407 (372)	275 (275)	–	–	–	–	324 (324)
Chest	Covid-19	$CTDI_{vol}$	26 (26)	–	10(7)	23(19)	9 (8)	14(12)	–	11(11)	–	7(6)	–	12(11)	29(28)
		DLP	603 (590)	–	356 (241)	888 (714)	355 (299)	506 (432)	–	377 (343)	–	286 (230)	–	492 (444)	581 (502)
	Lung Cancer	$CTDI_{vol}$	26 (26)	–	5 (5)	–	10 (9)	14 (12)	–	–	7 (5)	6 (6)	–	11 (10)	30 (29)
		DLP	601 (581)	–	188 (188)	–	689 (435)	533 (470)	–	–	272 (176)	372 (232)	–	427 (373)	870 (545)
	Pneumonia	$CTDI_{vol}$	26 (26)	23 (18)	9 (6)	23 (18)	11 (8)	16 (15)	8 (7)	11 (11)	–	6 (6)	10 (10)	10 (8)	48 (31)
		DLP	607 (588)	1049 (487)	346 (194)	948 (819)	402 (277)	640 (373)	306 (25)	359 (359)	–	230 (217)	374 (341)	384 (314)	1000 (831)
	Pulmonary Embolism	$CTDI_{vol}$	26 (26)	16 (15)	14 (14)	21 (21)	–	–	–	–	11 (10)	–	–	9 (7)	37 (32)
		DLP	1181 (1133)	618 (478)	14 (14)	1853 (1674)	–	–	–	–	333 (301)	–	–	341 (270)	692 (593)
Abdomen	Appendicitis	$CTDI_{vol}$	15 (13)	16 (16)	13 (12)	30 (26)	9 (7)	–	10 (8)	–	–	–	10 (10)	8 (8)	7 (6)
		DLP	919 (689)	753 (753)	1013 (654)	1567 (1320)	467 (325)	–	514 (413)	–	–	–	537 (537)	403 (338)	369 (272)
	Renal stones	$CTDI_{vol}$	16 (13)	14 (10)	11 (8)	30 (25)	–	15 (13)	10 (9)	12 (12)	16 (7)	–	7 (6)	12 (11)	9 (8)
		DLP	904 (669)	671 (487)	573 (383)	1729 (1334)	–	1173 (718)	559 (459)	594 (583)	923 (394)	–	375 (295)	638 (594)	558 (422)
Chest and Abdomen	Cancer	$CTDI_{vol}$	18 (15)	12 (11)	9 (7)	30 (24)	8 (6)	18 (14)	13 (13)	–	5 (5)	–	–	11 (11)	6 (5)
		DLP	3995 (3131)	1563 (870)	1070 (825)	1597 (1305)	630 (403)	2437 (1727)	748 (748)	–	567 (389)	–	–	2344 (2344)	530 (490)

The values represent DRLCI (ADCI).

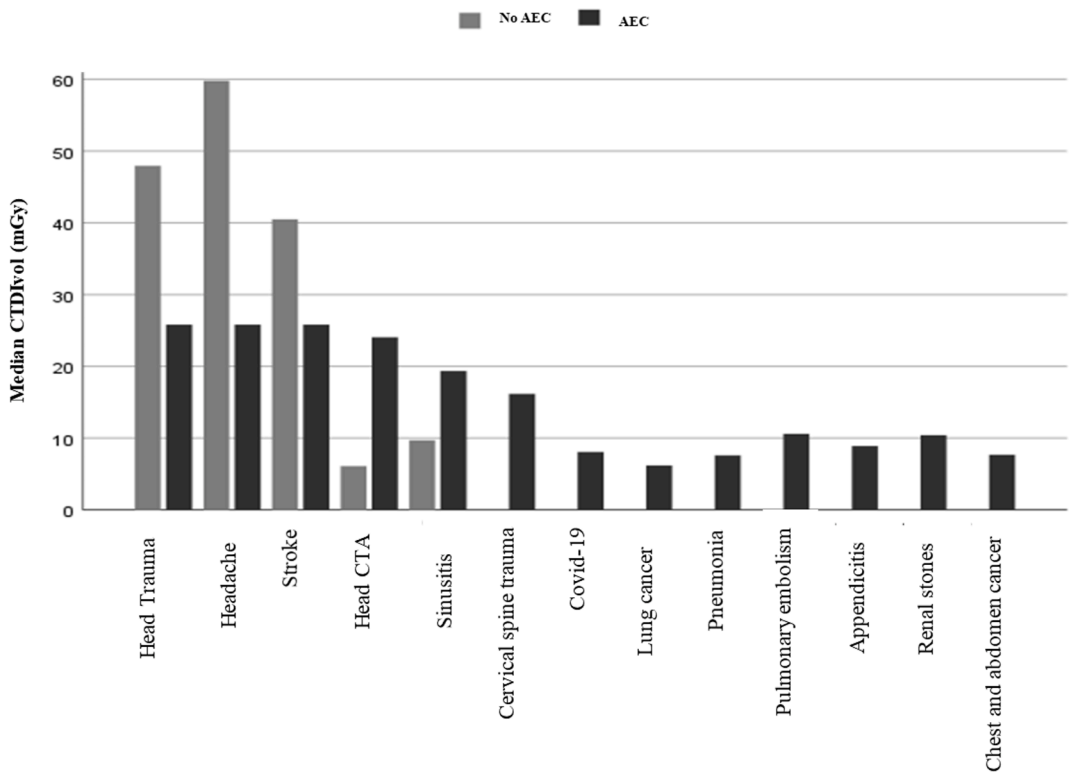

Fig. 3. The bar diagram illustrates the median CTDIvol (y-axis) for CT examinations performed with either automatic exposure control (AEC with IR and automatic kV selection - black bars) or fixed tube current (no AEC without IR and automatic kV selection - gray bars) techniques when comparing across CT protocols /clinical indications. Note that CT for most clinical indications in the chest and abdomen used AEC.

There are limitations to our study. First, there was a heterogenous distribution of CT datasets across different sites due to variations in practices and protocol usage across the participating sites. The lack of proper tracking or documentation of clinical indications at some sites could also contribute to the heterogeneity in case distribution. Second, although we included data from multiple sites from diverse regions, the number of participating sites represents a small fraction of imaging sites in Brazil. The participation of additional sites could have led to different conclusions regarding radiation doses. Third, several sites recorded the data manually due to a lack of radiation dose monitoring software; manual data entry can lead to errors. During the data verification step, we excluded erroneous or deficient cases. Fourth, there is a lack of a formal online order entry system that requires referring physicians to enter clinical indications for CT. A lack of reliable documentation for clinical indications can make it hard to create clinical indication-driven CT protocols and radiation dose optimization. Fifth, we did not include pediatric data in our project since there are separate clinical indications, concerns, and considerations in children undergoing CT. Sixth, there were a limited number of patients for each clinical indication. Although we followed previously published guidelines and requested data on a minimum of 20–30 CT exams per clinical indication, stratified data analysis by patient size (BMI categories) can reduce the effect size considerably. To undertake larger, comprehensive, and ongoing studies, we have created an online data portal for sites to contribute CT radiation dose data (**https://www.nrdbrasil.com.br/**). Through this site, we are planning to provide educational lectures on DRL_{CI} and CT practices and we will re-evaluate the data to assess its impact. The portal can help on continued monitoring of doses across multiple additional imaging sites and regions in Brazil and Latin America (through the Latin Safe initiative). For sites with inadvertently higher radiation doses, the portal will enable us to evaluate how radiation doses change following recommendations for optimization. Seventh, we did not measure the anterior-posterior diameter of the chest and abdomen-pelvis which is a more accurate and optimal parameter compared to patients' BMI. Eighth, weight and height were not measured; they were self-reported and can be inaccurate. Also, variations in scan length can lead to variations in DLP and we did not measure the scan lengths for each scan phase. The scan start and end locations recorded in our study, however, did not reveal a change in anatomic coverage between different scan phases. Although our protocols are stratified based on clinical indications rather than CT with and without contrast administration as in the US data, we believe that our dose comparison is still valid since there was no change in doses in most participating Brazilian sites for different clinical indications (for non-contrast and post-contrast CT) in the same body region.

Finally, CT technology continues to evolve rapidly, and imaging sites could and should adjust their protocols. The dynamic and evolving nature of technology and scanning techniques makes it harder to establish DRL from a limited period or snapshot data. We applaud the efforts of organizations such as the American College of Radiology (ACR) to create and maintain the Dose Index Registry (DIR) and the European Society of Radiology (ESR) to perform constant surveillance of radiation doses [24]. We hope developing countries and regions such as Brazil and Latin America can emulate such models and develop registries and infrastructures to support ongoing, inclusive, and comprehensive radiation dose surveillance.

5. Conclusion

In conclusion, our multicenter study establishes the national diagnostic reference levels and achievable doses in Brazil for 13 clinical indications for the head, paranasal sinuses, cervical spine, chest, and abdomen-pelvis CT examinations. At the same time, our study brings forth a paucity of modern scanners and scanning techniques at several participating sites in our national study. Our study brings forth the positive and negative aspects of CT radiation doses in Brazil. Through

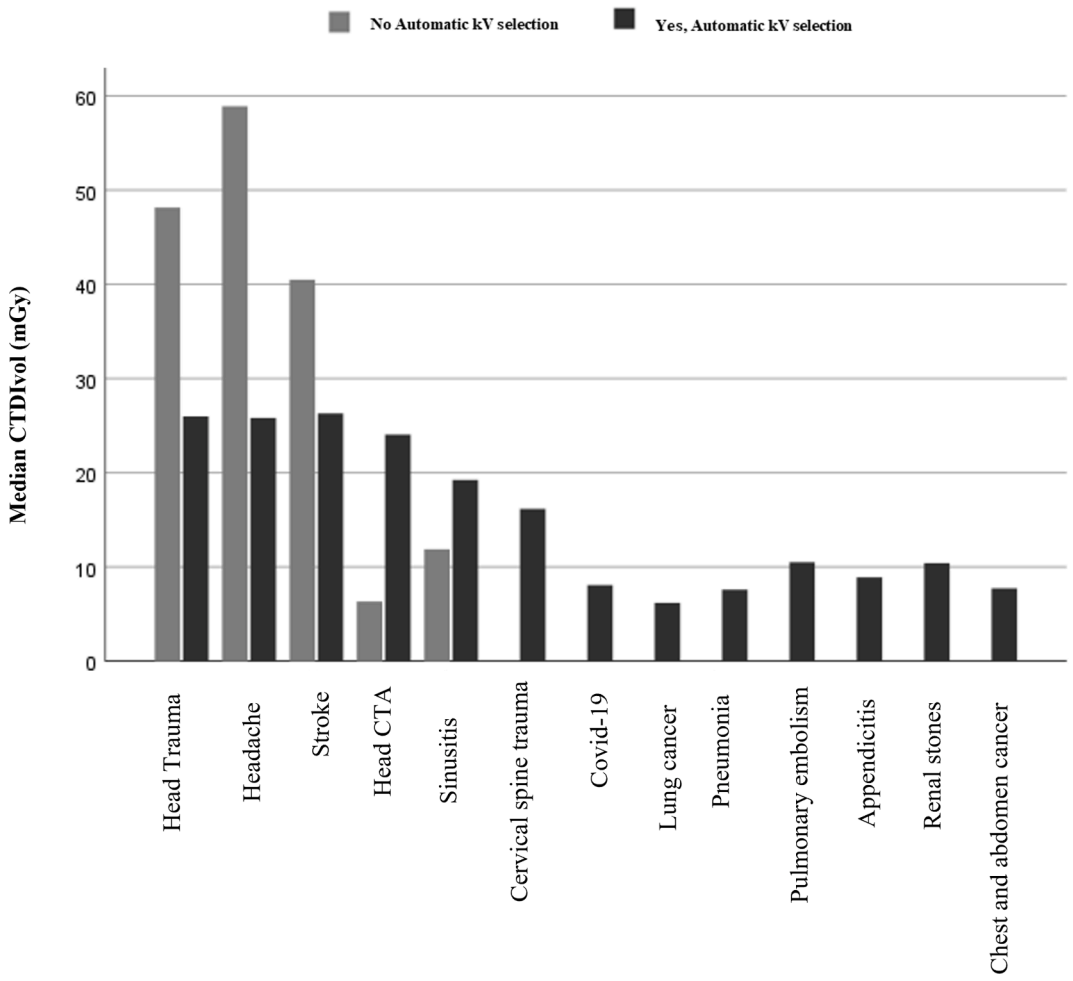

Fig. 4. Clinical indications-based median CTDIvol (y-axis) for CT examinations performed with either fixed tube potential (grey bars) or automatic tube potential selection (black bars) techniques.

ongoing outreach and educational efforts, we believe that the current study guides a path forward towards a more complete evaluation of radiation doses across an additional array of clinical indications, sharing of information on modifying scan factors per body region and clinical indications, and a mechanism via abovementioned web portal to sustain an ongoing optimization process across more and remote sites in Brazil and across the Latin America.

CRediT authorship contribution statement

Mônica Oliveira Bernardo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lina Karout:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Flávio Morgado:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Shadi Ebrahimian:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Alair Sarmet Santos:** . **Clarissa Amorim:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation. **Hilton Muniz Filho:** . **Antonio Moscatelli:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Valdair Francisco Muglia:** Writing – review & editing, Writing – original draft, Resources, Formal analysis, Data curation. **Henrique Schroeder:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Danilo Moulin Sales:** . **Renan Gandolpho Henschel:** . **Bruno Giovanni Valese:** . **Felipe Kiipper:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Publio Cesar Cavalcanti:** . **Ronaldo Lucena:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Tiago Jornada:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Valnir de Paula:** Writing – review & editing, Writing – original draft, Resources, Formal analysis, Data curation. **Marcel Zago:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Ricardo Varella:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Mauricio Anes:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Antonio Márcio Alves Pinheiro:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Luiz Claúdio de Moura Carvalho:** . **Juliana Santana de Melo Tapajos:** . **Fernando Antonio de Almeida:** . **Kimberly Applegate:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Graciano Paulo:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Paulo Roberto Costa:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

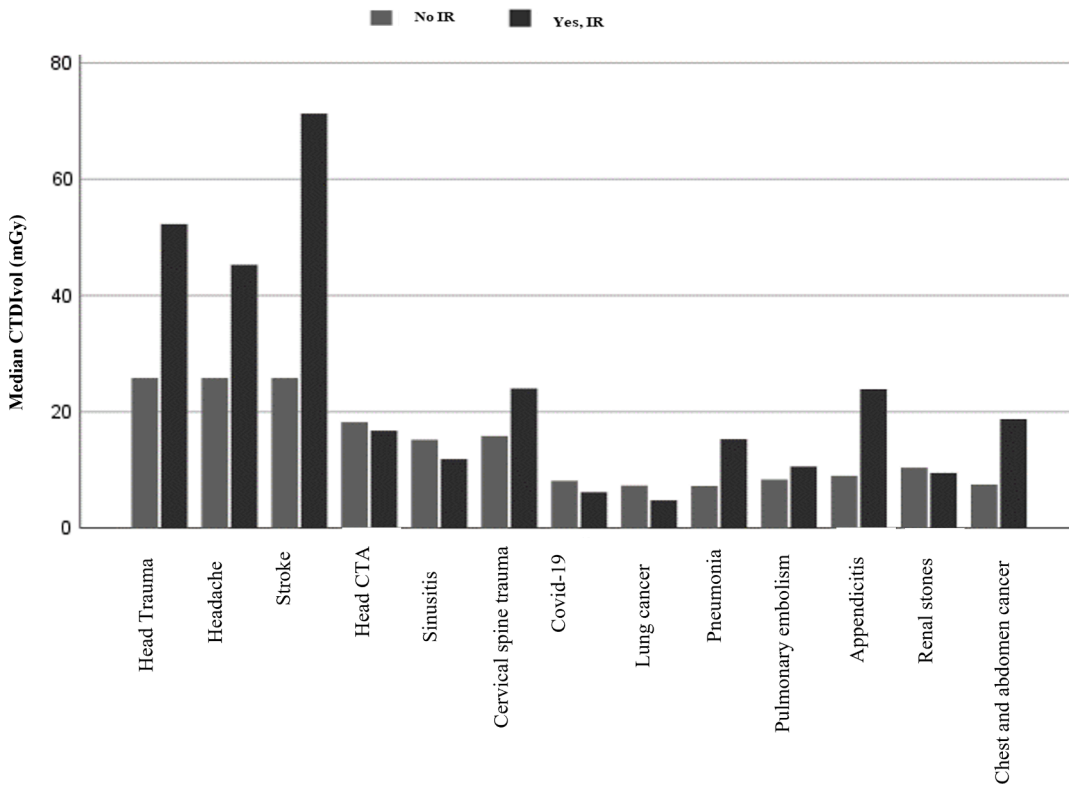

Fig. 5. Clinical indication-based median $CTDI_{vol}$ for CT examinations reconstructed with either iterative (black bars) or filtered back projection (grey bars) reconstruction techniques.

the work reported in this paper.

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