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Radiation Dose Optimization Based on Saudi National Diagnostic Reference Levels and Effective Dose Calculation for Computed Tomography Imaging: A Unicentral Cohort Study

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Abstract: Few studies have reviewed the reduction of doses in Computed tomography (CT), while various diagnostic procedures use ionizing radiation to explore the optimal dose estimate using multiple exposure quantities, including milliampere-seconds, kilovoltage peak, and pitch factors while controlling the CT dose index volume (CTDIvol) and dose length product (DLP). Therefore, we considered optimizing CT protocols to reduce radiation and organ doses during head, chest, abdominal, and pelvic CT examinations. For establishing institutional diagnostic reference levels as a benchmark to correlate with national diagnostic reference levels (NDRLs) in KSA conforming to international guidelines for radiation exposure, 3000 adult-patients underwent imaging of organs. Dose parameters were obtained using Monte Carlo software and adjusted using the Siemens Teamplay™ software. CTDIvol, DLP, and effective dose were 40.67 ± 3.8, 757 ± 63.2, and 1.74 ± 0.19, for head; 14.9 ± 1.38, 547 ± 42.9, and 7.27 ± 0.95 for chest; and 16.84 ± 1.45, 658 ± 53.4, and 10.2 ± 0.66 for abdomen/pelvis, respectively. The NDRL post-optimization comparison showed adequate CT exposure. Head CT parameters required additional optimization to match the NDRL. Therefore, calculations were repeated to assess radiation doses. In conclusion, doses could be substantially minimized by selecting parameters per clinical indication of the study, patient size, and examined body region. Additional dose reduction to superficial organs requires a shielding material.

Keywords: ionizing radiation; organ dose; exposure; computed tomography; achievable dose

1. Introduction

Computed tomography (CT) scans with multi-detectors have become an essential tool in medical practice [1,2]. However, there is an increasing trend in medical radiation exposure caused by CT imaging [3,4]. Ionizing radiation is associated with cancer risk and thus must be subject to strict safety regulations [5]. In diagnostic and interventional medical exposure, the International Atomic Energy Agency (IAEA) refers to "keeping the exposure of patients to the minimum necessary level to achieve the required diagnostic or interventional objectives" [6].

Over the last two decades, researchers have gained interest in developing new approaches to reduce radiation doses. For example, reducing the produced radiation/milliampere-seconds (mAs), tube voltage/kilovoltage peak (kVp), and higher helical pitch will help to optimize patient radiation exposure as well as provide data that can be used for comparison between different CT scanner techniques [7,8]. Other dose parameters that can play a major role in optimizing patient radiation exposure include the computed tomography dose index volume (CTDIvol) and dose-length product (DLP) for complete examination [7,8].

A comparison of CT doses with established diagnostic reference levels (DRLs) ensures CT exposures to be in line with the recommendations of international authorities, such as the IAEA, International Commission on Radiological Protection (ICRP), and European Commission [9]. These organizations encourage international governments to monitor DRL values continuously.

The ICRP also advocates that each country should survey radiology practices, determine national DRLs to be used as exposure indicators, provide guidance for dose optimization, and ensure justification of appropriate doses for a given clinical indication [10,11]. Two essential techniques applied by automatic exposure control are automatic current modulation and automatic current selection, which can be separately enabled or combined [12]. These automatic exposure control techniques are based on mAs modulation to optimize variability in patient attenuation while providing a full scan with maintained image quality [12].

Another essential concept in this era is the implementation of "As Low As Reasonably Achievable" to decrease unnecessary radiation exposure to patients [13]. A recent prospective observational study (2019) [14] demonstrated that the CT dose can be reduced by >50% without affecting image quality. The impact of dose reduction without affecting the quality of diagnostic yields in CT imaging can be observed with comparative strategies between default exposure parameters and a second group scanned with optimized parameters [15].

The initiative to establish DRLs has been undertaken in the Kingdom of Saudi Arabia by the Saudi Food and Drug Authority to establish national diagnostic reference levels (NDRLs) [16]. There are several CT dose reduction techniques; however, few studies have explored optimal dose estimates using multiple exposure quantities.

Additionally, the ICRP 135 report [17] was used as a guide to address contradictions related to the terminology used at that time, for example, the determinants of DRL values, the renewal of those values, and the application of the DRL concept to emerging imaging technologies.

Therefore, this study aimed to optimize CT examination protocols to lower patients' organ radiation exposure during head, chest, abdomen, and pelvis CT examinations in our facility and to establish our optimized institutional DRLs as a benchmark that will enable us to correlate with NDRLs in the Kingdom of Saudi Arabia [16] and adhere to international guidelines for radiation exposure.

2. Materials and Methods

All methods were performed in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines and regulations of cohort studies.

2.1. Study Design, Setting, and Patients

This study was conducted at the Radiology Department of King Fahd Hospital of the University (KFHU), Khobar City, which is affiliated with Imam Abdulrahman Bin Faisal University (IABFU) as one of the largest tertiary academic hospitals in the Eastern Province of Saudi Arabia. The Radiology Department began doing research in 1981.

This study comprised a comparative ambispective (i.e., ambidirectional) cohort study conducted from January 2019 to December 2021.

The rationale behind the ambispective design in this study was that the study patients were divided into two equal groups to study the impact of the optimization effect on radiation doses: (A) pre-optimization phase (1500 patients); those imaged on or before 1 June 2021 (1 January 2019, to 30 June 2020 [1.5 y]) and (B) post-optimization phase (1500 patients); and those imaged after 30 June 2020 (1 July to 30 December 2021 [1.5 years]).

Retrospective retrieving and prospective registering of data by utilizing a software program was conducted before and after radiation exposure via CT imaging. Comparative ambispective/ambidirectional design with a fixed interval (e.g., 1.5 years before and 1.5 years after optimization of dose measures) has reasonable scientific merit for studying the impact of dose optimization across time [18,19].

The design adopted for the current study was scientifically apt as it enabled appreciable gains in statistical power for vast cohorts, even in the absence of censoring, and previously served as a control strategy for potential recall bias in cohort studies [18,19].

We included all patients who underwent enhanced and/or non-enhanced head, chest, abdominal, and pelvic CT examinations at the Radiology Department of KFHU.

The enrolled patients ranged in age from 18 to 83 years (1823 Males and 1177 Females).

2.2. Data Collection

Data were extracted from the hospital radiological information systems. Using Monte Carlo calculation software [20], CT exposure parameters (e.g., DRLs) including CTDIvol (mGy), DLP (mGy.cm), and effective dose (ED) in millisieverts (mSv) were obtained and verified using the cloud-based Teamplay™ (Siemens Healthineers, Erlangen, Germany) data management software [21].

Furthermore, the following continuous data were analyzed: mean values of the produced radiation (mAs), exposure voltage (kVp), exposure time (ms), rotation time (ms), scan time in spiral mode (ms), scan length or start and end of scan region centimeter (cm), number of slices, slice thickness millimeter (mm), collimation (helical), and pitch factor. Additionally, we analyzed the following categorical data: CT protocol type, body region scanned, modality type, and calibration type. Lastly, we examined scans of the head, chest, abdomen, and pelvis using CT.

2.3. Dosimetry

Monte Carlo CT-Expo version 2.5 software (Buchholz, Germany) was used for dose calculations. This was applied to contrast-enhanced and blank (i.e., non-contrast-enhanced) studies. Dose estimation was performed based on the averages obtained from all CT examinations on mathematical phantoms for adults (ADAM and EVA) (Figure 1) [22].

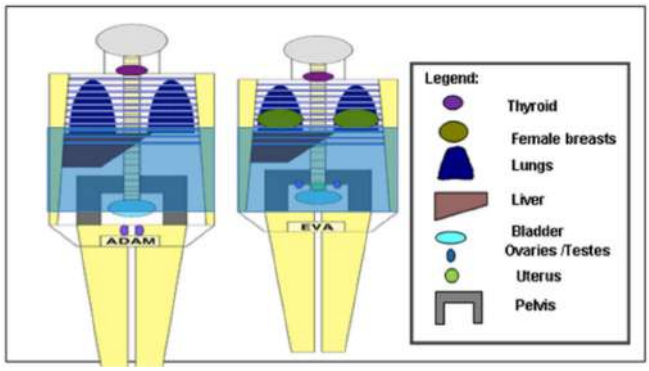

Figure 1. Mathematical phantom for Adam and Eva in Monte Carlo CT-Expo software.

Using this software, the following measures were calculated:

- CTDI, CTDIvol, and the average absorbed dose in the scanned region. CTDIvol does not provide an actual dose measurement for the patient; it is a standardized measure that helps users compare different scanners and scan protocols [23,24];

- DLP, integrated absorbed dose along a line parallel to the axis of rotation for complete CT examination. DLP is directly related to patient risk from the absorbed dose received; hence, it was used as a reference value for routine CT investigations in this study [25];
- ED: A method for comparing patient doses from different diagnostic procedures. The organ dose and ED were per the recommendations of the ICRP [11];
- These measured quantities were utilized for dose optimization strategies in this work;
- The optimized protocols in this study were defined by the resultant post-optimization protocols in relation to NDRLs with significantly reduced radiation doses to patients and their organs, which were implemented in our department;
- This study primarily focused on deriving DRL as a typical value according to the terminology definition from the ICRP 135 report [17] and was applied in our unicentral facility for local use, requiring further optimization.

2.4. Eligibility Criteria

All CT examinations were performed using two commercially available CT devices (SOMATOM Definition AS 64-slice kV 120 and SOMATOM Definition flash dual-source 128-slice kV 140, Siemens™, Munich, Germany). Patients of various nationalities, sexes, and adult age groups were included in the study. Initially, 3280 patients were enrolled. We excluded examinations in which CT-related dose estimation parameters were missing (n = 280 patients). A total of 3000 patients were included in this study.

2.5. Statistical Analysis

Statistical analysis was performed using R v 3.6.3 Counts and Minitab version 17.0 (Penn State University). Categorical and continuous variables are expressed as percentages and mean ± standard deviation, respectively. Unpaired t-tests and chi-squared tests of independence were used to compare continuous and categorical variables, respectively. An unpaired t-test was used when the data were abnormally distributed. Hypothesis testing was performed at a significance level of 5%. The data used to establish the DRL at our hospital were based on the rounded third quartile and compared with the initial NDRL report [16] as well as available international reports [26–32].

2.6. Ethical Approval

This study was performed in accordance with the 1975 Declaration of Helsinki (revised in 1983). The Institutional Review Board of IABFU granted ethical approval for this study on 23 January 2022, to be conducted at the KFHU (IRB-PGS-2021-11-249). Informed consent was obtained from each patient before imaging. The collected data were anonymized, analyzed, and reported solely in an aggregate form. No identifiable participant information (such as patient images, faces, or names) was disclosed in the study.

3. Results

This study included 3000 adult patients aged 18–83 years (1823 males and 1177 females).

3.1. Main Findings before Optimizing Radiation Doses Based on National NDRLs

The dose parameters for all patients were set at an average KV of 120 for all scanned organs. The highest mAs were for head imaging (210), whereas the lowest were for imaging of the abdomen/pelvis (140). With regard to pitch, head imaging had the lowest pitch (0.88) while chest imaging had the highest (1.33).

The scan length varied from the shortest head (18.0) to the longest abdomen/pelvis (46.0) imaging. CTDIvol and DLP were highest for head imaging (averaged at 40.67 and 757, respectively) in comparison to chest imaging (14.9 and 547, respectively). The ED was the lowest for head imaging (1.74) and highest for abdomen/pelvic imaging (10.2) (Table 1).

Table 1. Mean dose parameters ± Standard deviation before and after optimization.

	Pre-Optimization							Post-Optimization *						
	KV	**mAs**	**Pitch**	**Scan length (ms)**	**CTDIvol (mGy)**	**DLP (mGy.cm)**	**ED (mSv)**	**KV**	**mAs**	**Pitch**	**Scan Length (ms)**	**CTDIvol (mGy)**	**DLP (mGy.cm)**	**ED (mSv)**
Head	120	210	0.88	18.0	40.67 ± 3.8	757 ± 63.2	1.74 ± 0.19	120	190	0.9	17.5	45.61 ± 3.11	788 ± 61.2	1.83 ± 0.13
Chest	120	160	1.33	38.0	14.9 ± 1.38	547 ± 42.9	7.27 ± 0.95	120	130	1.38	37.0	10.40 ± 1.01	393 ± 33.6	4.19 ± 0.77
Abdomen/Pelvis	120	140	1.25	46.0	16.84 ± 1.45	658 ± 53.4	10.2 ± 0.66	120	120	1.3	43.0	12.20 ± 1.09	583 ± 21.4	8.72 ± 0.66

Dose quantities	**KV**	**mAs**	**Pitch**	**Scan length (ms)**	**CTDIvol (mGy)**	**DLP (mGy.cm)**	**ED (mSv)**
***p* value**¯	0.087	0.07	0.87	0.048	0.034	0.047	0.01

Notes: Mean dose parameters ± Standard deviation (SD) were determined for all patients before and after optimization by applying National Diagnostic Reference Levels. * The dose quantities after optimization reflect the achievable doses (ADs) in our department. ¯ Statistical tests were conducted at a significance level of 0.05. Comparison of the pre-optimization phase with the post-optimization phase using an unpaired t-test of independence. **Abbreviations:** SD, standard deviation; DLP, dose-length product (mGy.cm); CTDIvol, volume computed tomography dose index; ED, effective dose (mSv); mAs, mean values of the produced radiation; kV exposure volume; and ms (millisecond).

3.2. Main Findings after Optimizing Radiation Doses Based on National NDRLs

The average KV remained unchanged in all scanned body organs, with an average of 120 (p = 0.87). In the pre-optimization phase, the highest mAs were for head imaging, which was lowered to 190, whereas the lowest was for imaging of the abdomen/pelvis, which was lowered to 120 (p = 0.07). Likewise, in the pre-optimization phase, head imaging had the lowest pitch (0.9) while chest imaging had the highest (1.38; p = 0.87).

Nonetheless, the scan length was the shortest in head imaging, which was lowered to 17.5; the longest abdomen/pelvis imaging was lowered to 43.0 (0.048). CTDIvol and DLP were the highest for head imaging, which increased to 45.61 and 788, respectively, compared to chest imaging, which decreased to 10.40 and 393, respectively (p = 0.034 and 0.047, respectively). ED was the lowest for head imaging, which increased post-optimization to 1.74, and the highest for abdomen/pelvis imaging, which decreased to 8.72 (p = 0.01) (Table 1; Figure 2).

Table 2 displays the current study NDRLs in comparison with those in other organizations, whereas Table 3 compares the mean organ dose between this study and similar international studies from the literature.

Table 2. Comparison between the current study results, National Diagnostic Reference Levels, and international studies.

Exam	Current Study KFHU (2022)		NDRL Saudi Arabia 2021 [16]	Nigeria 2018 [26]	ICRP 2007 [11]	US A 2016 [27]	Japan 2015 [28]	EU 2014 [29]	Greece 2014 [30]	Egypt 2016 [31]	UK 2011 [32]	Italy 2020 [33]
	Before *	After **										
CTDIvol (mGy)												
Head	47	50	55	61	60	56	85	60	67	30	60	70
Abdomen /Pelvic	19	15	15	20	35	16	20	25	16	31	15	18
Chest	17	12	12	17	30	12	15	10	14	22	12	15
DLP (mGy.cm)												
Head	845	903	1077	1310	1050	962	1390	970	1055	1360	970	1300
Abdomen /Pelvic	773	685	886	1486	780	781	1000	745	760	1325	745	550
Chest	624	461	468	735	650	443	550	610	480	420	350	570

Notes: * Before applying the National Diagnostic Reference Level (i.e., pre-optimization with default parameters). ** After applying National Diagnostic Reference Level (i.e., post optimization with optimized parameters). The dose quantities after optimization reflect the achievable doses (ADs) in our department. **Abbreviations:** DLP, dose-length product (mGy.cm); CTDIvol, volume computed tomography dose index (mGy).

Table 3. Comparison between the mean organ dose in the current study and similar international studies.

Organ	Current Study 2022	Tanzania 2006 [34]	UK 2011 [32]	ICRP 2007 [11]
Eye lens	42.0	63.9	-	50
Breast	24.6	26.1	21.4	112
Lung	23.9	31.5	22.4	114
Liver	16.4	34.1	20.4	30
Bladder	18.6	28.8	23.2	43
Uterus	22.4	26.5	25.0	26.0
Ovaries	16.7	24.0	22.7	11

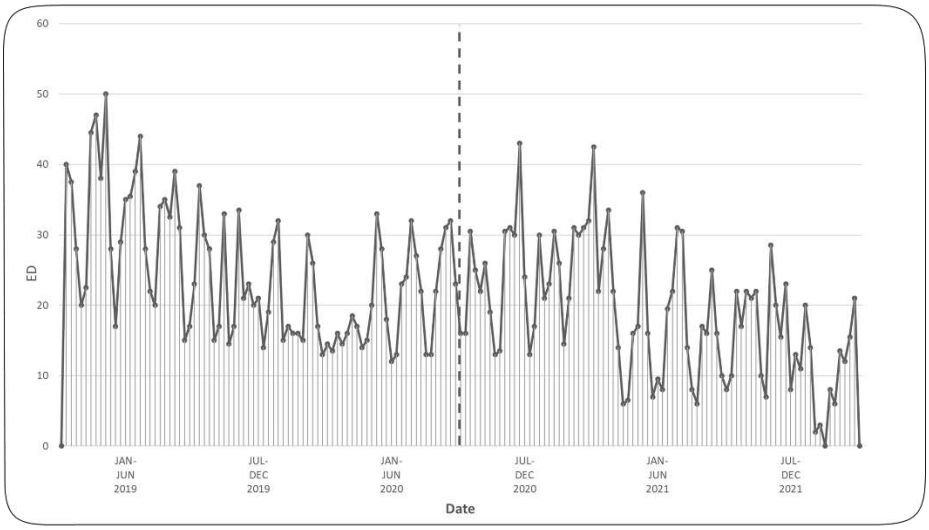

Figure 2. Distribution of effective dose across the study period. Linear histogram showing the distribution of effective dose across the study period (Midline: to separate pre- and post- optimization phases).

4. Discussion

Although numerous studies have been conducted to reduce radiation exposure in CT imaging procedures, concerns among medical professionals still exist when the delivered doses are evaluated in CT scanning. These diagnostic parameters were observed critically between two periods: pre-optimization and post-optimization of the exposed radiation.

In this single-center cohort study, the authors evaluated ED and organ radiation doses to create an institutional benchmark and compared it with NDRLs [16] at a tertiary academic hospital in Saudi Arabia (Table 1).

Dose parameters determine the average absorbed dose in the scanned region CTDIvol and the integrated absorbed dose along a line parallel to the axis of rotation for the complete CT examination. Nonetheless, DLP can provide a method for comparing patient radiation doses from different diagnostic procedures. Establishing DRLs would minimize the overall dosage in clinical practice. [35,36]

In our sample, the CTDIvol values were 75% lower after applying NDRLs [16], except for the head examinations, where the CTDIvol values were higher after applying NDRLs [16]. However, when comparing our results to NDRLs, the CTDIvol values for head examinations were lower than those for NDRLs [16]. Nevertheless, the chest, abdomen, and pelvic examination values were consistent with the NDRLs [16] (Table 2).

When comparing our study results with those of previous studies in Nigeria [26], ICRP [11], the United States of America (USA) [27], Japan [28], the EU [29], Greece [30], Italy [33], Egypt [31], and the United Kingdom (UK) [32], the CTDIvol values in head examinations were lower than those in all other studies, with the exception of those in Egypt [31]. The CTDIvol values in abdomen/pelvic exams were lower than those reported in studies from Nigeria [26], ICRP [11], USA [27], Japan [28], EU [29], Italy [33], and Greece [30]. However, these values were consistent with NDRLs in the UK [28]. Regarding chest examinations, the CTDIvol values were equivalent to NDRLs, higher than those in the study from Egypt [31], and lower than those in other studies [26–32].

DLP reflects the total energy absorbed (and thus the potential biological effect) attributable to complete scan acquisition. In the current study, after the application of NDRLs [16], the DLP was lower than that before applying NDRLs, except in head examinations. The DLP values in the head and abdominal examinations were lower than those reported in previous studies.

The values in chest examinations were higher in the current study than those in studies from the USA [27], Egypt [31], Italy [33], and the UK [32], but lower than NDRLs and values

reported in studies from Nigeria [24], ICRP [11], Japan [28], the EU [29], Italy [33], and Greece [30]. It is important to recognize that the potential biological effects of radiation depend not only on the radiation dose received by a tissue or organ but also on the biological sensitivity of the irradiated tissue or organ.

ED is a dose descriptor that reflects differences in biological sensitivity. It is a single-dose parameter that represents the risk of non-uniform exposure in relation to an equivalent whole-body exposure. Therefore, an ED can be used to estimate the risk factors. In this study, the ED after applying NDRLs [16] was lower than it had been before applying NDRLs, except in the case of head examinations.

Applying NDRLs remarkably reduced the patient dose in most CT examinations. The mean organ dose compared to similar studies from other countries (e.g., Tanzania [34], UK [32], and ICRP [11]) showed that the organ dose was lower in chest, abdomen/pelvic, and head examinations than in examinations from all other countries [28].

4.1. Research Limitations

This research was based on diagnostic imaging data acquired from the KFHU, and the results were limited to the radiographic examinations of a single department (i.e., one facility with two scanners). To achieve more accurate results, this research requires extension to other hospitals in the Kingdom of Saudi Arabia so that a large-scale analysis can be conducted, and any probability of error in recorded dosimetry can be eradicated through the examination of a larger sample of recorded DRLs and ADs for both mammography and radiography procedures.

Second, the cohort was limited by the fact that the data monitoring system only recorded the patient's body mass index, and the exact weight of a patient was missing. Patient weight (kg) is a key indicator of the size of a patient in medical imaging and it affects the DRL values of the research. Moreover, the estimations made in this study are subject to a considerable level of uncertainty and may affect the principal results of the research. This research was confined to the use of two radiography scanners and one mammography scanner, which contributed to the lack of sufficient systems to monitor the data acquired from diagnostic medical imaging. Finally, this study did not assess image quality, which was beyond the scope of our study.

4.2. Future Scope of the Research

There is a need for a systematic process and assessment of diagnostic referencing in medical imaging and for more training and specialized programs so that radiologists and technologists can become more efficient in the field of medical imaging. Radiologists must be skilled and aware of this collective responsibility to support and actively participate in dose regulation efforts by adapting to data management software, which will facilitate the key proposition of radiology departments regarding low achievable doses and reduced radiation exposure [37]. Al-Sharydah et al. recently (2022) explored the role of data management software in the establishment of DRLs and how it reduces ADs despite the ergonomic complexities of COVID-19 [38].

5. Conclusions

Optimized radiation exposure can be achieved by close monitoring and compliance with the NDRLs. This can result in the establishment of optimized CT protocols and institutional local DRL expressed as typical values. Most ED and organ dose values were lower than those reported in similar studies conducted in other countries. The role of the medical industry is to offer more radiation dose optimization tools and provide training, not only on basic operation and equipment, but also on the application of preset exam protocols. The optimization process should include the joint efforts of key professionals and incorporate activities focused on equipment performance, examination protocol customization, and staff behavior.

Author Contributions: A.Y.A.-O., A.M.A.-S., E.I.A., R.M., A.B.D., T.M.H., A.A.T., S.S.A., F.M.A.-M. and S.A. have contributed substantially to the study conception, design, analysis and manuscript writing. Data collection was done by A.Y.A.-O. and A.M.A.-S. The first draft of the manuscript was written equally by A.Y.A.-O.and A.M.A.-S. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was performed in accordance with the Helsinki Declaration of 1975 (revised in 1983). The Imam Abdulrahman Bin Faisal University Institutional Review Board considered the descriptive and observational nature of this study and granted approval for the study to be conducted at KFHU (IRB-PGS-2021-11-249). Anonymized data were collected, analyzed, and reported only in aggregate form, and no identifiable participant information was revealed in the study.

Informed Consent Statement: Given the purely descriptive and observational nature of the study, and in compliance with the Helsinki declaration, informed consent was waived. No identifiable information (image, face, name etc.) of participant is revealed in the submission. Data were collected in anonymously, and analyzed and reported only in aggregate form. In addition, ethical approval was granted by the local Institutional Review Board of Imam Abdulrahman Bin Faisal University (IRB-PGS-2021-11-249).

Data Availability Statement: The principal investigator is responsible for sharing the study-related data publicly upon reasonable request from the publishing journal.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

COVID-19	Coronavirus disease 2019
AD	Achievable dose
CT	Computed Tomography
DRLs	diagnostic reference levels
KFHU	King Fahd Hospital of the University
DLP	dose-length product
CTDI	CT dose index
CTDIvol	volume CT dose index
SFDA	Saudi Food and Drug Authority
WED	water-equivalent dose

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