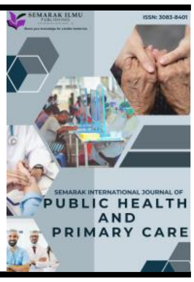
SEMARAK ILMU
PUBLISHING

Semarak International Journal of Public Health and Primary Care

Journal homepage:
https://semarakilmu.online/index.php/sijphpc/index
ISSN: 3083-8401



Radiation Dose Exposure from Routine CT Examination among Paediatric Patients: A Systematic Review

Bishir Umar[1,2], Sulayman Muhammad Kabeer[1], Muhammad Kashfi Shabdin[1], Nor Azura Muhammad[3], Aminu Ismaila[4], Abdu Masanawa Sagir[5], Jamilu Abdullahi[6], Muhammad Khalis Abdul Karim[1,*]

[1] Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia
[2] Department of Environmental Health technology, College of Liberal Studies, Hassan Usman Katsina Polytechnic, 2052, Katsina, Nigeria
[3] College of Health Sciences, University Malaya Medical Centre, 59200, Kuala Lumpur, Malaysia
[4] Department of Physics, Faculty of Science, Ahmadu Bello University, Zaria, 1044, Kaduna, Nigeria
[5] Department of Mathematics, Faculty of Physical Sciences, Federal University, Dutsin-ma, 5001, Dutsin-ma, Katsina, Nigeria
[6] Department of Mathematics and Statistics, College of Science and Technology, Hassan Usman Katsina Polytechnic, 2052, Katsina, Nigeria

ARTICLE INFO

Article history:
Received 27 December 2024
Received in revised form 2 February 2025
Accepted 17 February 2025
Available online 15 March 2025

Keywords:
Radiation dose; computed tomography; CT chest; CT abdomen-pelvis; CT chest-abdomen-pelvis; paediatrics; image quality; radiation exposure

ABSTRACT

The increasing use of computed tomography (CT) in paediatric healthcare has raised concerns about radiation exposure and its potential carcinogenic effects. In this study, we carried out a systematic review to evaluate the radiation dose exposure from routine CT examinations in paediatric patients aged 0-20 years, covering studies published between 2013 and 2024. The review focuses on four types of CT examinations: CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT Chest-Abdomen-Pelvis (CAP). A comprehensive search across four databases, namely ScienceDirect, Google Scholar, PubMed, and Scopus, yielded 37,486 citations, from which 40 eligible studies were selected: 17 on CT Chest, 8 on CT Abdomen, 9 on CT Abdomen-Pelvis, and 6 on CT CAP. Key radiation dose indices, such as volume-weighted CT dose index (CTDIvol), effective dose (E), dose length product (DLP), and size-specific dose estimates (SSDE), were extracted and analysed. The highest mean values of CTDIvol, DLP, and E were observed in CT CAP for patients in the weight-based category >45 kg, with values of 7.80±2.80 mGy, 368.60±107 mGy·cm, and 10.79±3.97 mSv, respectively. The highest mean SSDE was found in CT Abdomen-Pelvis for patients weighing more than 45 kg, with a value of 11.80±4.61 mGy. Regarding image quality metrics, the highest image noise was observed in CT Abdomen for the 0-45 kg weight category, with a value of 21.0±4.5 HU. These findings underscore the importance of implementing body size or weight-based protocols, adjusting CT acquisition parameters, and utilizing advanced reconstruction techniques to achieve significant radiation dose reduction while maintaining diagnostic image quality. This review highlights the need for optimizing CT protocols to ensure radiation safety in paediatric imaging, with an emphasis on tailored strategies based on patient dimensions and cutting-edge technological interventions.

* *Corresponding author.*
E-mail address: mkhalis@upm.edu.my

https://doi.org/10.37934/sijphpc.3.1.3151

1. Introduction

Computed tomography (CT) imaging is an essential diagnostic tool frequently employed in paediatric healthcare because it can deliver precise anatomical information [1]. Since its invention in 1972 by British Engineer Godfrey Hounsfield, CT technology has advanced significantly, providing enhanced resolution and diagnostic accuracy compared to other imaging modalities, which allows for quick and effective diagnosis [2,3]. However, CT scans utilize ionizing radiation, raising concerns, particularly for paediatric patients who are especially vulnerable to radiation-induced effects due to their developing tissues and longer life expectancy [4-6].

Studies indicate that CT accounts for more than half of the effective dose in certain populations, such as in the USA, significantly contributing to overall medical radiation exposure [7]. The radiation burden is a greater concern for paediatric patients. Due to their increased radiosensitivity compared to adults, children face a heightened risk of long-term consequences from radiation exposure, including cancer [8]. A seminal study by Almujally *et al.,* [9] found a significant association between exposure to CT scans in childhood and an increase in cancer incidence, emphasizing the need for careful use of CT imaging in this vulnerable age group.

Several factors influence the radiation doses received by paediatric patients during CT scans, including the anatomical regions being examined, patient demographics, and scanning protocols [10]. Research conducted by authors [11,12] highlights that multi-region scans, such as CT Chest-Abdomen-Pelvis (CAP) and CT Abdomen-Pelvis, can significantly elevate the total radiation doses received by patients. Therefore, optimizing CT acquisition parameters such as tube voltage, pitch, and slice thickness are crucial for minimizing radiation exposure while maintaining diagnostic accuracy [13]. Special attention to dose optimization is necessary in paediatric CT imaging, considering the child's lifetime risk of developing cancer [14].

Given the imperative to reduce radiation exposure without compromising image quality, dose-optimization techniques such as the implementation of advanced reconstruction methods and meticulous selection of acquisition parameters are essential [15]. This systematic review aims to conduct a thorough evaluation of radiation doses in paediatric CT imaging, focusing on the chest, abdomen, abdominopelvic area, and CAP regions. It seeks to explore the relationships between radiation dose, scanning protocols, CT acquisition parameters, and patient characteristics, including body weight, to guide best practices in clinical settings.

While there has been significant research on radiation dose optimization in adult CT imaging, the impact of specific CT acquisition parameters on paediatric populations has not been comprehensively addressed. This review aims to bridge this gap by systematically examining the factors that contribute to radiation exposure in paediatric CT, focusing particularly on multi-region scans like CT Chest-Abdomen-Pelvis (CAP) and how different protocols can be optimized for safer paediatric imaging.

The primary objective of this review is to systematically assess radiation dose exposure in paediatric CT exams. It aims to identify areas needing improvement and to provide evidence-based recommendations that balance patient safety with diagnostic efficacy. By doing so, this review seeks to support ongoing efforts to optimize paediatric CT protocols, ensuring that the benefits of diagnostic imaging outweigh the associated risks of radiation exposure.

2. Methodology

2.1 Study Design

This systematic review aimed to assess radiation dose exposure associated with routine CT examinations (CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT Chest-Abdomen-Pelvis) among paediatric patients aged 0–20 years. The study adhered to established protocols for systematic reviews, ensuring comprehensive and thorough synthesis and analysis of the literature.

2.2 Search Strategy

A detailed search strategy was developed to identify relevant studies published from 2013 to 2024. Four major electronic databases—ScienceDirect, Google Scholar, PubMed, and Scopus—were systematically searched. The search included keywords and Boolean operators: ("radiation dose" OR "radiation exposure" OR "dose exposure" OR "radiation dosage") AND ("CT examination" OR "computed tomography" OR "CT scan") AND ("paediatric patients" OR "children"), alongside Medical Subject Headings (MeSH) terms specific to CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT Chest-Abdomen-Pelvis. Filters were applied to limit the results to studies published in English and within the defined period. The study selection process is illustrated in the flow chart (Figure 1), detailing the number of studies identified, screened, and selected at each stage.

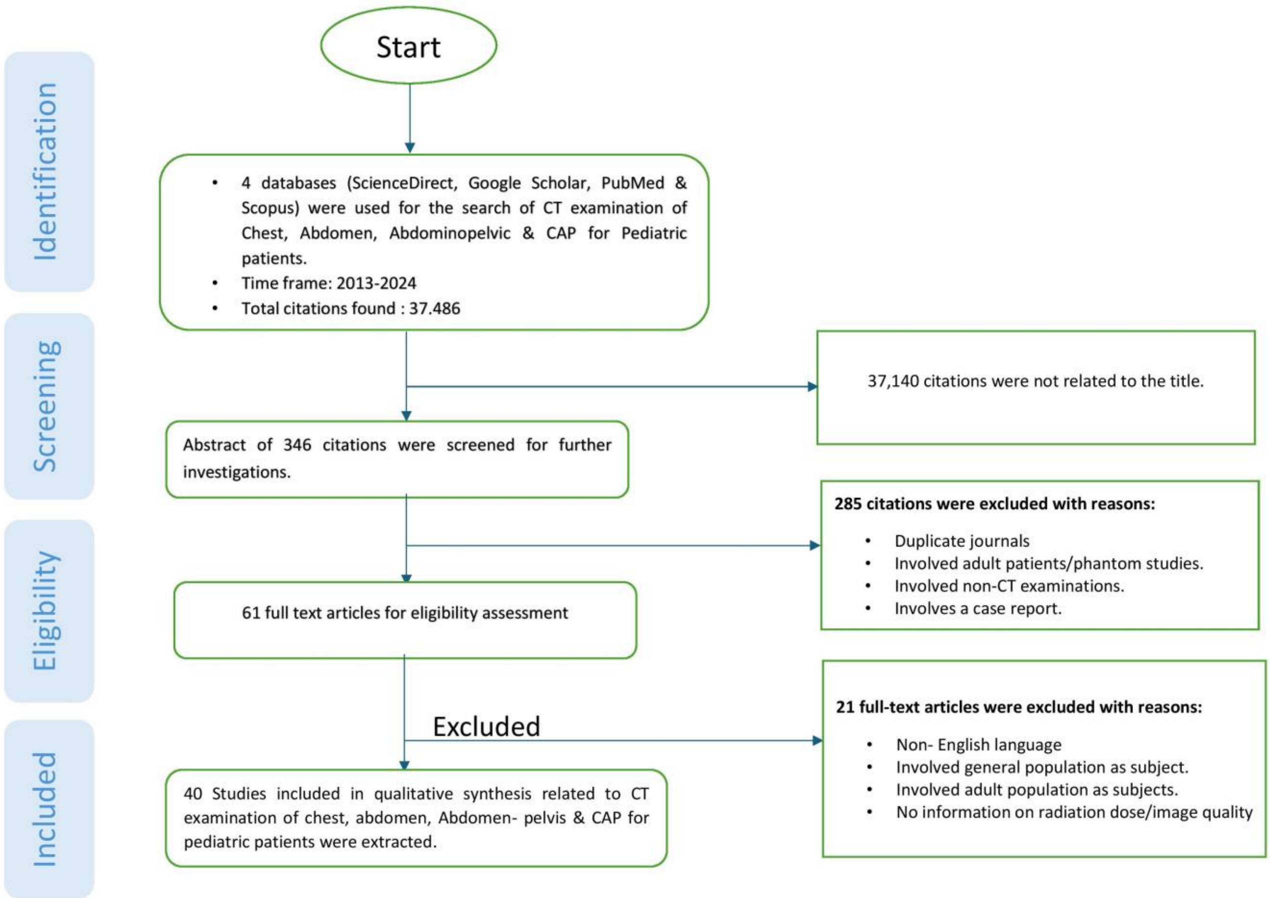


Fig. 1. Flow chart for search strategy employed in the study

2.3 Study Selection Criteria

Eligible studies were selected based on predefined inclusion and exclusion criteria stated below:
Inclusion criteria:

i. Studies involving paediatric patients (0–20 years) who underwent routine CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT Chest-Abdomen-Pelvis (CAP) examinations.

ii. Studies reporting data on radiation dose indices (e.g., CTDIvol, DLP, E, SSDE) and image quality metrics (e.g., image noise).
iii. Original research articles that provided mean and standard deviation of radiation doses.
iv. Studies categorizing patient data by weight (0–45 kg and >45 kg).

Exclusion criteria:

i. Studies lacking demographic information (e.g., age).
ii. Studies focused on multiple unrelated examinations or other imaging modalities.
iii. Studies that did not provide key radiation dose data (e.g., CTDIvol).
iv. Phantom or animal studies, review articles, or meta-analyses.
v. Studies not published in English.

Additionally, the scope of this review was focused on routine CT examinations to ensure standardization across included studies. While other imaging modalities or advanced CT techniques were excluded, this decision was made to provide a concentrated evaluation of radiation exposure and dose optimization in routine paediatric CT imaging.

2.4 Data Extraction

Data extraction was performed independently by two reviewers using a standardized form. The following information was extracted from each study:

i. Study Characteristics: Year of publication, authors, and study design.
ii. Patient Demographics: Age, weight, body width, and sample size.
iii. CT Scanner and Radiation Exposure Parameters: CT scanner model, tube voltage (kVp), tube current (mA), pitch, nominal beam width (NBW), and collimation size.
iv. Radiation Dose Indices: Volume-weighted CT dose index (CTDIvol), dose length product (DLP), effective dose (E), and size-specific dose estimates (SSDE).
v. Basic Image Quality Metrics: Image noise levels and reconstruction techniques.
vi. Discrepancies between reviewers were resolved by consensus, and the accuracy of data extraction was verified by cross-referencing with the original source material.

2.5 Quality Assessment

The quality of the studies included was assessed using the Newcastle-Ottawa Scale (NOS) for cohort studies, focusing on three main domains: selection of study groups, comparability between groups, and accuracy of outcome measurements.

2.6 Data Synthesis and Analysis

A narrative synthesis was conducted to summarize the findings from the included studies. The data on radiation dose indices and image quality parameters were synthesized and presented descriptively, highlighting significant trends, variations, and the effects of different CT acquisition parameters. Subgroup analyses were performed to explore the relationships between radiation dose, image quality, and associated factors, adhering to weight-based protocols (0–45 kg and >45 kg).

2.7 Ethical Considerations and Reporting

As this study involved secondary analysis of data from published studies, ethical approval was not required. All data were obtained while maintaining patient confidentiality and adhering to copyright and intellectual property standards.

This systematic review followed the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines to ensure transparent and comprehensive reporting of the methods and findings.

2.8 Statistical Analysis

The statistical analysis was conducted using IBM SPSS Statistics (Version 20.0, IBM Corporation, Armonk, NY, USA). Descriptive statistics, including mean, standard deviation (SD), minimum, and maximum values, were calculated to summarize radiation dose metrics across different body weight categories and protocols. Inferential tests, including one-way Analysis of Variance (ANOVA) and t-tests, were used to compare variables across protocols. Assumptions such as normality and homogeneity of variances were tested prior to analysis to ensure the validity of the statistical methods. A p-value of < 0.05 was considered statistically significant. Mean differences (MD) for each outcome were reported along with 95% confidence intervals (CI) to provide a measure of precision around the estimates. These techniques were selected to provide robust comparisons and insights into the data, enhancing the credibility of the findings.

3. Results

The literature search retrieved a total of 37,486 citations. After applying inclusion and exclusion criteria, 40 articles were selected for systematic review (see Figure 2). Of these, 17 studies focused on CT Chest, 8 on CT Abdomen, 9 on CT Abdomen-Pelvis, and 6 on CT Chest-Abdomen-Pelvis (CAP). Among the 4,763 paediatric patients included in this study, 1,880 were males and 1,592 were females. The remaining 1,291 patients did not specify gender. Table 1 and Figure 2 summarize the distribution of sample sizes by gender and non-gender categories across CT protocols. The average patient age was 9.09 ± 4.65 years, with an age range from one day to 20 years.

Table 1
Summary of paediatric sample size across ct protocols by gender (male/female) and non-gendered category

Protocol	Sample Size			Total
	M	F	*A	
CT Chest	529	374	881	1784
CT Abdomen	624	543	202	1369
CT Abdomen -pelvis	372	396	103	871
CT CAP	355	279	105	739
Total	1880	1592	1291	4763

M = Male, F = Female
*A= non- gendered category (patients not classified as male or female)

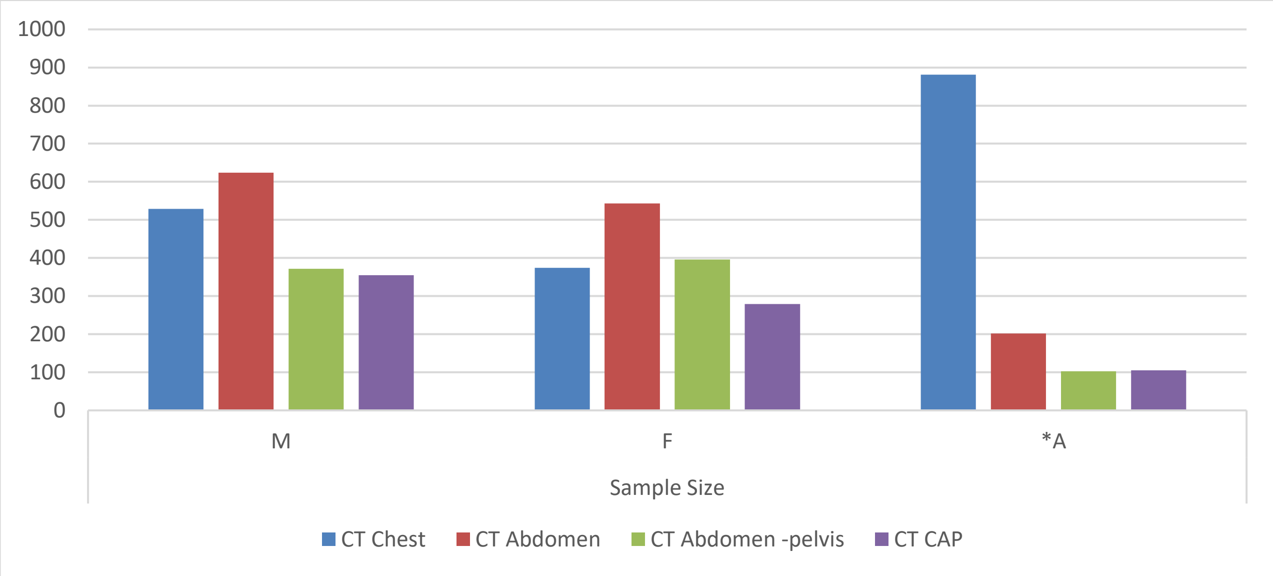


Fig. 2. Distribution of paediatric sample size by CT protocols and gender(M/F) and non-gendered category

Table 2 presents an overview of the various CT scanners used. Siemens Medical Systems was utilized in 19 studies, followed by Philips Medical Systems (11 studies), GE Healthcare (8 studies), and Toshiba Medical Systems (1 study). Figure 3 visualizes the distribution of these scanners across different CT examination protocols.

Table 2
Summary of CT Scanner Types Across Examination Protocols

CT Protocols	Sum of Siemens Medical Systems	Sum of Philips Medical Systems	Sum of GE Healthcare Medical Systems	Sum of Toshiba Medical Systems
CT Chest	8	3	5	1
CT Abdomen	4	3	1	0
CT Abdomen – Pelvis	5	2	1	0
CT CAP	2	3	1	0
Grand Total	19	11	8	1

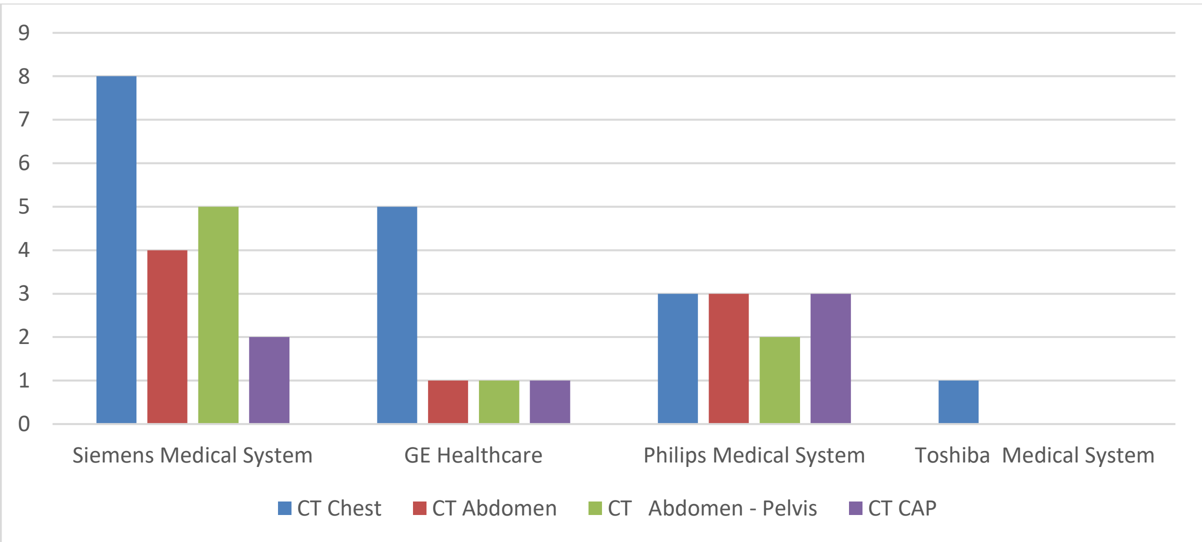


Fig. 3. Distribution of CT scanner types across examination protocols

3.1 CT Protocols and Acquisition Parameters

Key CT protocols and acquisition parameters such as tube voltage (kVp), slice thickness, nominal beam width (NBW), and pitch are summarized in Table 3. These parameters were used across four main protocols: CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT CAP. The tube voltage range used for all protocols was between 80 and 120 kVp.

The widespread use of this tube voltage highlights the need to consider other acquisition parameters, such as pitch, anatomical coverage, body size, and body weight, to understand variations in radiation dose. Larger anatomical regions or patients with greater body weight often require higher radiation exposure to ensure adequate image quality. In conjunction with advanced dose modulation methods like Tube Current Modulation (TCM), these factors influence total radiation exposure in paediatric imaging.

For optimal radiation dose efficiency, most studies reported a pitch factor between 0.6 and 1.4. However, a high pitch value of 3.2 was used by Bodelle *et al.,* [16] for CT Chest (Table 4), reflecting variations in clinical practices and diagnostic needs. Most studies applied TCM as a dose-saving measure to balance radiation exposure with image quality.

Table 3
Summary of CT protocols and acquisition parameters

CT Protocol	No. of detector collimation (mm)	Tube Voltage (kVp)	Tube Current (mA)	Slice Thickness (mm)	Pitch
CT Chest	64 × 0.6 or 64 × 0.625 or 128 × 0.6	80-120	TCM	0.625, 1,2.5,3,5	0.6–3.2
CT Abdomen	64 × 0.6 or 64 × 0.625 or 128 × 0.625	80–120	TCM	0.6,1.2,2.5,5	0.6–1.2
CT Abdomen-pelvic	64 × 0.625 or 128 × 0.6 or 192 × 0.6	80–120	TCM	1,2,3,5	0.5–1.5
CT CAP	64 × 0.6 or 64 × 0.625	80–120	TCM	2,3,5	0.758–1.4

TCM = Tube current modulation

Slice thickness values of 0.6 mm, 3 mm, and 5 mm were commonly used, while the highest range of 1-10 mm was reported by Toossi *et al.,* [17] for both CT Chest and CT Abdomen-Pelvis (Tables 4 and 6). The NBW most frequently used was 64 × 0.6 mm, although Ryu *et al.,* [18] reported a wider NBW of 320 × 0.5 mm for CT Chest (Table 4). This reflects the variability in clinical approaches based on patient demographics and anatomical regions.

Selecting the right pitch factors and slice thicknesses were essential for optimizing radiation dose while maintaining diagnostic image quality. In paediatric imaging, achieving a balance between reducing radiation exposure and ensuring clear images is critical for effective clinical practice.

3.2 Radiation Dose and Image Noise

Among the 40 selected studies, 7 focused on CT Chest, 2 on CT Abdomen, 2 on CT Abdomen-Pelvis, and 1 on CT CAP. None of these articles included patient weight data. Radiation output parameters were compared and distributed between body weight categories (0-45 kg and >45 kg) (Figure 4a-d, Table 8). Across all protocols, paediatric patients in the >45 kg category had higher mean values of CTDIvol, DLP, E, and SSDE values compared to those in the 0-45 kg group, with the exception of CT Abdomen, where higher values were observed in the 0-45 kg group.

Additionally, the results for CTDIvol, DLP, E, and SSDE were generally higher for CT CAP compared to CT Abdomen-Pelvis, CT Abdomen, and CT Chest. Table 4 shows the highest average values of these dose metrics for CT Chest when a weight-based protocol was applied: 9.5±2.1 mGy (CTDIvol), 276±123 mGy·cm (DLP), 6.5±3.5 mSv (E), and 7.6±4.4 mGy (SSDE).

For patients in the >45 kg group, mean CTDIvol, DLP, E, and SSDE values were 4.18±2.23 mGy, 159.53±137.47 mGy·cm, 3.54±1.91 mSv, and 6.36±3.50 mGy, respectively. In comparison, the mean values for the 0-45 kg group were 2.68±1.86 mGy (CTDIvol), 82.81±65.54 mGy·cm (DLP), 2.98±2.83 mSv (E), and 2.84±1.40 mGy (SSDE).

Table 4
Characteristics of selected studies on CT Chest

Study (year of the publication) [Ref.]	No. of patient (M/F)	Mean age ± SD/ median (years)**	Body width (cm)	Body weight (kg)	Radiation dose indices CTDI$_{vol}$ (mGy)	DLP (mGy.cm)	ED (mSv)	SSDE (mGy)	Nominal Beam Width (mm)	Tube voltage (kVp)	Pitch	Image noise (HU)	Reconstruction technique
Weight-based protocol													
[19]	28 (17/11)	10.9±4.8 (3-18)	-	0-45	1.5 ± 0.8	N/R	N/R	1.8 ± 0.9	N/R	100	0.6	N/R	N/R
[20]	46	5.8±4.5 (0-≥12)	-	0-45 >45	2.20±0.52 3.90±0.57	45 (33-76) -	N/R	N/R	N/R	80-120	N/R	17.0±6.3	N/R
[21]	27	N/R (2-15)	-	0-45	9.5±2.1	276±123	6.5±3.5	N/R	N/R	120	1-2 (0.56-2)	N/R	N/R
[18]	59 (39/20)	4.43±4.69	-	0-45	2.69±0.21	49.74± 11.62	N/R	N/R	320×0.5	80-120	1.0	N/R	IR
[22]	13	3.1±1.0 (0-11)	-	0-45 >45	1.6±0.3 2.8±0.7	N/R	N/R	3.6±0.7 5.1±1.3	128×0.6	80-120	1.4	47.8% ± 6.9%	FBP/IR
[23]	514	8 (0-20)	-	>45	5.5 (1.0-15.0)	202.3 (20.9-676.6)	3.85± 1.32	8.7 (2.2-16.4)	N/R	100 or 120	1.26 (0.98-1.38)	N/R	N/R
[24]	72	10±6 (0-19)	-	0-45 >45	2.1 ± 0.5 3.8±2.6	- 125.5 ± 108.0	N/R	- 5.1 ± 3.3	64×0.6, 192×0.6	80-140	0.9 - 1.21	N/R	N/R
[25]	120(79/41)	N/R (0-15)	-	0-45 >45	2.5 ± 1.2 4.9±2.5	59.5 ± 32.9 185.0± 140.8	2.3±1.2 4.2±2.0	5.2 ± 2.4 7.6±4.4	32×0.6, 64×0.6	80-120	0.8-1.4	N/R	N/R
[26]	12	11.5±4.6 (1-18)	-	0-45	1.3±0.5	49.0±26.3	2.2±3.2	2.0±0.6	N/R	70-100	0.992:1	12.6±3.8 - 24.5±6.1	IR, DLR

[27]	345 (190/155)	8 (0-15)	-	0-45 >45	0.77±0.45 4.20±2.48	17.67± 12.06 125.33± 79.43	0.90± 0.36 2.57± 1.24	1.63± 0.67 5.30± 2.21	N/R	70-100	0.6-1.9	N/R	IR
Non-weight-based protocol													
[28]	45 (25/20)	1.8 (0-6)	-	-	0.67 ± 0.17	14.7 ±3.1	0.25 ± 0.05	N/R	N/R	120	1.375	3.0 ± 0.0 – 5.0 ±0.0	FBP, IR
[29]	105	N/R (0-15)	-	-	8.90 ± 3.60	201.75 ±184.75	2.78± 0.24	6.08± 3.59	N/R	<100	N/R	N/R	N/R
[30]	57 (31/26)	14±3.9 (0-20)	-	-	0.51 ± 0.19 (0.20-0.77)	13.14 ± 6.15 (5.65-35.08)	0.31 ±0.14 (0.13-0.57)	0.46 ± 0.17 (0.24-0.76)	64×0.625	80 OR 100	1.375	12.3-47.2	IR
[16]	87 (54/33)	9.1±4.9 (0-18)	17.2± 4.0 - 19.7± 4.3	-	0.58±0.30	16.8 ± 11.2	0.44± 0.20	1.00± 0.43	128×0.6, 2×192×0.6	80	1.2-3.2	110-182	FBP, IR
[31]	10 (10/0)	14.5 (12-18)	-	-	0.20±0.08	7.5±2.9	N/R	0.4±0.1	64×0.625	80	1.375:1	20.0±3.6-26.2±4.9	IR
[17]	152 (84/68)	N/R (1-15)	-	-	5.82±3.25	184.63± 98.39	6.43± 4.46	N/R	N/R	80-130	0.6-1.5	N/R	N/R
[32]	92	6.38±1.16 (0-15)	-	-	5.5 (1-33.8)	131.5 (13.8-375.5)	2.62 ± 0.51	N/R	N/R	80-140	1.3 (0.6-1.6)	N/R	N/R

CTDIvol: Volume CT Dose Index; DLP: Dose-Length Product; E: Effective Dose; SSDE: Size-Specific Dose Estimate; SD: Standard Deviation; N/R: Not Reported; FBP: Filtered Back Projection; IR: Iterative Reconstruction; DLR: Deep Learning Reconstruction; M: Male; F: Female.
** Numbers in Parentheses are Mean/Median age range.

For CT Abdomen, mean CTDIvol, DLP, E, and SSDE values were 10.25±2.87 mGy, 363.5±152.1 mGy·cm, 7.24±1.94 mSv, and 12.0±2.9 mGy, respectively (Table 5). In the 0-45 kg group, the mean CTDIvol and DLP values were 6.59±2.53 mGy and 271.90±163.90 mGy·cm, compared to 4.13±0.71 mGy and 164.80±1.70 mGy·cm for the >45 kg group. E and SSDE could not be compared due to lack of data for the >45 kg group. However, previous study reported higher CTDIvol and DLP values for non-weight-based protocols in the 0-45 kg group [9].

Table 5
Characteristics of selected studies on CT Abdomen

Study (year of the publication) [Ref.]	No. of patient (M/F)	Mean age ± SD/ median (years)**	Body width(cm)	Body weight (kg)	Radiation dose indices				Nominal Beam Width (mm)	Tube voltage (kVp)	Pitch	Image noise (HU)	Reconstruction technique
					$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	ED (mSv)	SSDE (mGy)					
Weight-based protocol													
[33]	939 (499/440)	10 (0-18)	<15-24, 25-≥30	0-45	6.94 ± 3.13	259.08 ± 171.36	7.24 ± 1.94	12.0 ± 2.9	N/R	80-140	N/R	N/R	N/R
[20]	47	5.8±4.5 (0-≥12)	-	0-45 >45	3.25±0.90 5.40±0.71	105 (90-159) -	N/R	N/R	N/R	80-120	N/R	21.0±4.5	N/R
[21]	28	N/R (3-15)	-	0-45	11 (4-22)	554 (163-1652)	9 (2-19)	N/R	N/R	120	1 (0.94-2)	N/R	N/R
[34]	116 (65/51)	N/R (0-12)	-	0-45	10.25 ± 2.87	363.5 ± 152.1	N/R	N/R	N/R	80-120	0.6-1.2	N/R	N/R
[26]	23	11.5±4.6 (1-18)	-	0-45	1.5±0.6	77.9±35.0	2.0±0.7	2.5±0.9	N/R	70-100	0.992:1	11.1±3.6-19.9±3.7	IR, DLR
[35]	112 (60/52)	≤18 (9-18)	-	>45	2.85±0.07	164.8±1.7	N/R	N/R	128 × 0.625, 64 × 0.625	80-120	0.6 - 1.258	2.6 ± 0.8 - 3.5 ± 0.7	IR
Non- weight-based protocol													
[9]	17	N/R (0-10)	-	-	23.93 ± 6.83	651.78 ± 271	N/R	N/R	N/R	130	0.6	N/R	N/R
[36]	87	13±4.5 (2-17)	-	-	9.8 (2.09 - 45.77)	485 (53.59-2012.3)	7.2(3.14-17.68)	N/R	64×0.6	80-140	0.6 ± 0.005 (0.55-0.6)	N/R	N/R

CTDIvol: Volume CT Dose Index, DLP: Dose-Length Product; E: Effective Dose; SSDE: Size-Specific Dose Estimate; SD: Standard Deviation; N/R : Not Reported; FBP: Filtered Back Projection; IR: Iterative Reconstruction; DLR: Deep Learning Reconstruction; M : Male; F: Female.
** Numbers in Parentheses are Mean/Median age range.

For CT Abdomen-Pelvis, the highest mean CTDIvol, DLP, E, and SSDE values were 14.24±0.86 mGy, 301.23±5.40 mGy·cm, 8.50±2.74 mSv, and 15.1±2.5 mGy (Table 6). In the >45 kg group, mean values were 7.60±4.89 mGy (CTDIvol), 334.10±166.0 mGy·cm (DLP), and 11.80±4.61 mGy (SSDE), compared to 6.11±2.06 mGy, 232.12±143.10 mGy·cm, and 7.60±3.56 mGy for the 0-45 kg group. Due to limited data, no comparison was made for E in the 0-45 kg group.

Table 6
Characteristics of selected studies on CT abdomen-pelvis

Study (year of the publication) [Ref.]	No. of patient (M/F)	Mean age ± SD/ median (years)**	Body width(cm)	Body weight (kg)	Radiation dose indices CTDI$_{vol}$ (mGy)	DLP (mGy.cm)	ED (mSv)	SSDE (mGy)	Nominal Beam Width (mm)	Tube voltage (kVp)	Pitch	Image noise (HU)	Reconstruction technique
Weight-based protocol													
[37]	15 (8/7)	10.1±3.1 (6-15)	-	0-45	14.24±0.86	301.23±5.40	N/R	N/R	N/R	80-140	1.375:1	7.06±5.14-15.58±8.40	N/R
[38]	41 (20/21)	10.1±5.3 (2-18)	<18-24 25-≥35	0-45	3.02±0.83	N/R	N/R	4.6±0.4	N/R	80-120	0.758-0.993	12.2±1.3-I5.1±1.7	FBP/IR
[39]	28 (16/12)	10 (0-18)	-	0-45	5.4±2.8	N/R	N/R	N/R	N/R	120	N/R	N/R	N/R
[40]	386 (172/214)	9.4±4.9 (0-18)	<15-24 25-≥30	0-45 >45	5.3±0.7 9.6±2.5	N/R	N/R	11.7±1.4 15.1±2.5	64×0.625	100-120	0.7-1.0	N/R	FBP/IR
[22]	24	8.7±4.8 (1-17)	-	0-45 >45	5.2 ± 2.5 7.4±5.6	N/R	N/R	9.1±3.3 11.1±4.5	128×0.6	80-120	1.4	47.8% ± 6.9%	FBP/IR
[23]	101 (46/55)	8 (0-20)	-	>45	8.4(1.7-21.3)	441.2 (43.5-1218.9)	8.50±2.74	12.7(3.2-28.4)	N/R	100 or 120	1.22 (0.98-1.38	N/R	N/R
[24]	79	12±6 (0-19)	-	0-45 >45	3.5±2.3 5.0±3.2	163.0±143.0 227.0±166.0	N/R	5.0±5.0 8.3±4.0	128×0.6, 192×0.6	80-140	0.9-1.2:1	N/R	IR
Non- weight-based protocol													
[41]	36(27/9)	9.7(1-17)	-	-	3.09 ± 1.66 (0.95-5.36)	134.77 ± 91.88 (31-262)	N/R	N/R	128 × 0.6	80-140	0.6	6.44 ± 0.81-7.21 ± 1.31	N/R
[17]	161 (83/78)	N/R (1-15)	-	-	8.26±4.81	283.17±151.64	9.47±3.57	N/R	N/R	80-130	0.5-1.5	N/R	N/R

CTDIvol: Volume CT Dose Index; DLP: Dose-Length Product; E: Effective Dose; SSDE: Size-Specific Dose Estimate; SD: Standard Deviation; N/R: Not Reported; FBP: Filtered Back Projection; IR: Iterative Reconstruction; M: Male; F: Female.
** Numbers in Parentheses are Mean/Median age range.

For CT CAP, the highest mean CTDIvol, DLP, E, and SSDE values were 6.17±2.53 mGy, 293±107 mGy·cm, 10.79±3.97 mSv, and 5.7±1.6 mGy (Table 7). In the >45 kg group, these values were 7.80±2.80 mGy, 368.6±107.0 mGy·cm, 10.79±3.97 mSv, and 7.25±3.3 mGy, compared to 5.09±3.03 mGy, 217.30±133.09 mGy·cm, 5.23±2.07 mSv, and 5.70±1.60 mGy for the 0-45 kg group.

Table 7
Characteristics of selected studies on CT CAP

Study (year of the publication) [Ref.]	No. of patient (M/F)	Mean age ± SD/ median (years)**	Body width (cm)	Body weight (kg)	Radiation dose indices CTDI$_{vol}$ (mGy)	DLP (mGy.cm)	ED (mSv)	SSDE (mGy)	Nominal Beam Width (mm)	Tube voltage (kVp)	Pitch	Image noise (HU)	Reconstruction technique
Weight-based protocol													
[42]	25 (11/14)	10.8 (1-20)	-	>45	4.4±2.8	N/R	N/R	4.4±3.3	64×0.625	80-120	1.375:1	8.4-19.4	IR
[38]	41 (20/21)	10.1±5.3	<18-24 25-≥35	0-45 >45	4.0±2.0 -	146±60 293±107	N/R	5.7±1.6 -	N/R	80-120	0.758-0.993	12.2±1.3-I5.1±1.7	FBP/IR
[43]	40 (21/19)	7.8±4.7 (0-17)	-	>45	12.6	N/R	N/R	N/R	64×0.625	120	1.0	N/R	N/R
[23]	455 (269/186)	8 (0-20)	-	>45	6.4 (1.4-21.2)	444.2 (45.7-1750.1)	10.79±3.97	10.1 (2.6-24.6	N/R	100 or 120	1.31 (0.98-1.38)	N/R	N/R
[44]	73 (34/39)	N/R (0-12)	-	0-45	6.17 ± 2.27	288.6 ± 118.8	5.23 ± 2.07	N/R	64×0.6	100	1.2	N/R	N/R
Non- weight-based protocol													
[45]	105	8.0±3.87 (0-16)	-	-	8.63 ± 2.53	N/R	N/R	14.72 ± 3.36	64×0.625	80-120	0.891	N/R	N/R

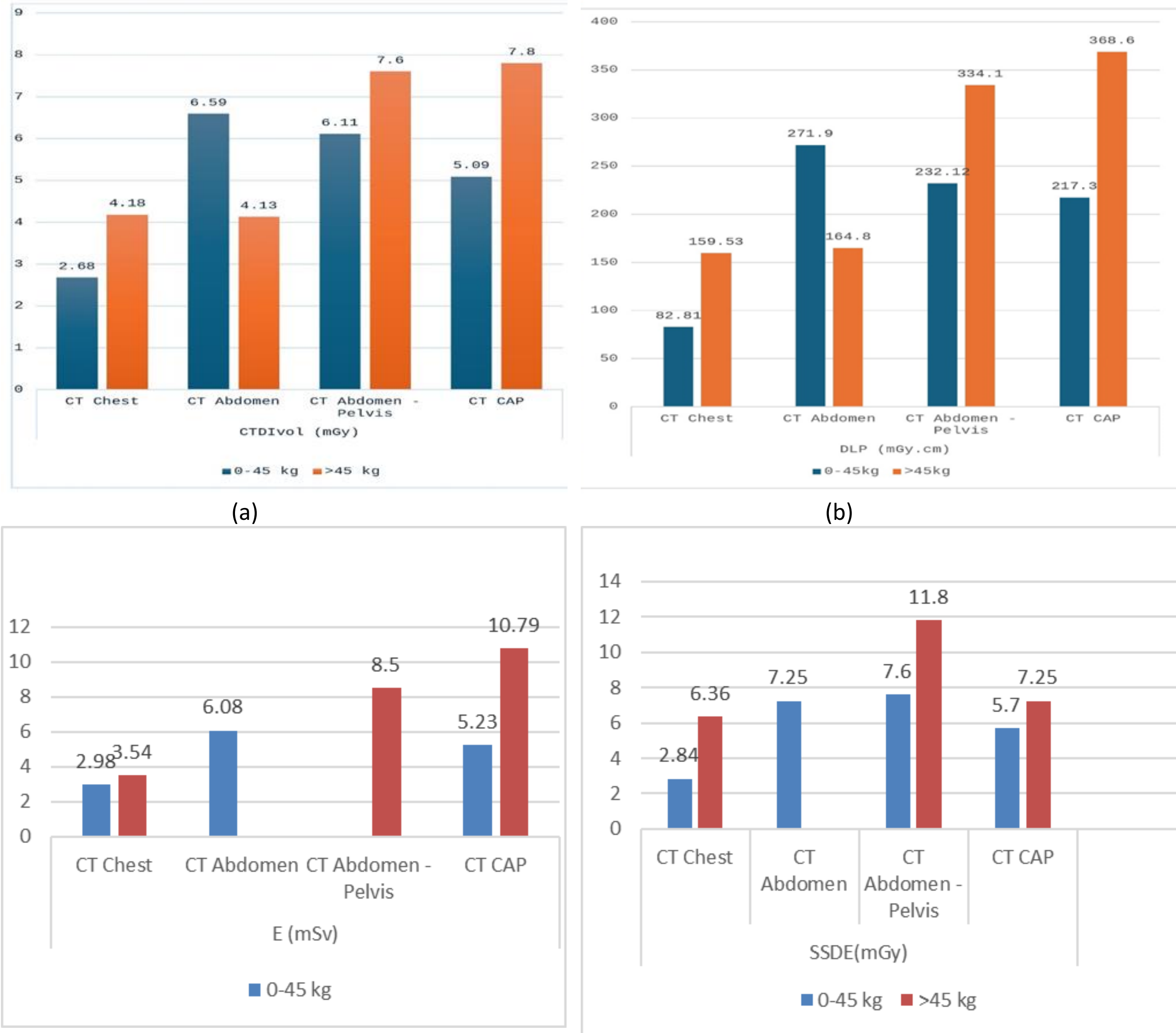
CTDIvol: Volume CT Dose Index, DLP: Dose-Length Product; E: Effective Dose; SSDE: Size-Specific Dose Estimate; SD: Standard Deviation; N/R: Not Reported; FBP: Filtered Back Projection; IR: Iterative Reconstruction; M: Male; F: Female.
** Numbers in Parentheses are Mean/Median age range.

Table 8 and Figure 4 summarize the comparison and distribution of radiation dose parameters across CT protocols according to weight categories.

Table 8
Comparison of radiation dose parameters across CT protocols based on weight categories

Weight Categories (kg)	CT Protocols	Radiation Dose Indices CTDIvol (mGy)	DLP (mGy.cm)	E (mSv)	SSDE (mGy)
0-45	CT Chest	2.68	82.81	2.98	2.84
>45		4.18	159.53	3.54	6.36
0-45	CT Abdomen	6.59	271.90	6.08	7.25
>45		4.13	164.80	N/R	N/R
0-45	CT Abdomen-Pelvis	6.11	232.12	N/R	7.60
>45		7.60	334.10	8.50	11.80
0-45	CT CAP	5.09	217.30	5.23	5.70
>45		7.80	368.60	10.79	7.25

CTDIvol : Volume CT Dose Index; DLP : Dose Length Product; E: Effective Dose; SSDE: Size-Specific Dose Estimate



(a) (b) (c) (d)

Fig. 4 (a-d). Distribution of radiation dose parameters across CT protocols based on weight categories

Tables 5, 6, and 7 also present data on body width for CT Abdomen, CT Abdomen-Pelvis, and CT CAP. Paediatric patients with body widths of 25–≥35 cm had higher DLP values for CT CAP than those with a width of 18–24 cm. Patients with body widths of 25–≥30 cm had higher SSDE values for CT Abdomen-Pelvis than those with widths of <15–24 cm. No comparison of body widths was made for CT Abdomen due to insufficient data.

Among the analysed studies, 16 offered detailed numerical data on image noise, expressed as means and standard deviations (SD) (Tables 4-7). One study used DLR, seven used FBP, and 14 used IR to reduce noise. Qualitative evaluations, based on four-or five-point Likert scales, were applied in 24 studies. These studies consistently reported good to excellent image quality regardless of the protocol used.

Meyer *et al.,* [31] reported the highest image noise range for CT Chest, between 20.0±3.6 HU and 26.2±4.9 HU, although the 0-45 kg group had most image noise values reported across protocols (Table 4). Kritsaneepaiboon *et al.,* [20] found that CT Abdomen had the highest mean image noise value (21.0±4.5 HU) for the 0-45 kg group (Table 5), demonstrating the importance of weight-based protocols and reconstruction methods for controlling image noise and optimizing image quality, particularly in young patients.

Yu *et al.,* [22] reported image noise as a percentage, with a value of 47.8% ±6.9% for weight-based CT Chest and CT Abdomen-Pelvis protocols within the 0-45 kg category (Tables 4 and 6).

Furthermore, for non-weight-based CT Chest protocols, image noise ranges between 110-182 HU were observed, while for weight-based CT CAP protocols, the noise range was reported between 8.4 and 19.4 HU, as highlighted by Bodelle *et al.,* [16] and Smith *et al.,* [42] (Tables 4 and 7). Since this review only considered studies where image noise was presented in terms of means and standard deviations (SD), direct comparisons with these studies were excluded from the analysis.

4. Discussion

Advances in paediatric computed tomography (CT) have greatly enhanced diagnostic accuracy. However, concerns about radiation exposure persist owing to children's increased sensitivity to ionizing radiation. Their rapidly developing tissues and longer lifespans make them particularly vulnerable to radiation-induced effects, such as cancer [46,47] . Given the growing use of CT scans in paediatric care, it is important to optimize imaging protocols to minimize radiation exposure while preserving image quality [10]. This review systematically examined various paediatric CT protocols, including CT Chest, CT Abdomen, CT Abdomen-Pelvis, and CT Chest-Abdomen-Pelvis (CAP), assessing variables including body weight, pitch, slice thickness, and image noise.

These findings reveal that CT CAP registered the highest radiation dose, trailed sequentially by CT Abdomen-Pelvis, CT Abdomen, and CT Chest. This contrasts with Muhammad *et al.,* [48], who attributed higher doses trendy CT Abdomen-Pelvis to the use of higher tube potentials (140 kVp). In the present review, CT CAP exhibited a dose peak at 120 kVp, which suggests that factors like scan length, anatomical coverage, and other factors, in addition to tube potential, play crucial roles in determining radiation dose [49].

This review also chose 0-45 kg and >45 kg weight-based categories instead of the commonly used 0-40 kg and >40 kg categories. The broader range of 0-45 kg and >45 kg was intended to include a wider spectrum of paediatric patients, from infants to adolescents, thereby offering more comprehensive data for radiation dose optimization.

The mean radiation doses for all protocols except CT Abdomen were notably higher in the >45 kg group, aligning with previous findings about the influence of body habitus on dose [22]. Moreover, this review included comparisons of effective doses (E), even though data for E was limited. In-depth comparisons of radiation doses were conducted across all protocols, except for CT Abdomen in the >45 kg group and CT Abdomen-Pelvis in the 0-45 kg group.

Tube Current Modulation (TCM) emerged as an effective strategy in dose reduction without compromising image quality. This is consistent with earlier studies which found that TCM reduced doses by as much as 40% [50-52]. Using higher pitch values, particularly in modern multidetector CT scanners, was also associated with reduced radiation exposure [30,38].

Studies by Yoon *et al.,* [26] and Bos *et al.,* [27] demonstrated that applying 70-100 kVp, especially when paired with advanced reconstruction techniques such as deep learning reconstruction (DLR) or iterative reconstruction (IR), is beneficial for CT Chest protocols. This combination could also be optimal for routine paediatric CT protocols, minimizing radiation while maintaining image quality. For CT Abdomen, particularly in paediatric cases, the use of 100 kVp may balance dose reduction and diagnostic efficacy.

Although the tube potential was consistent at 80-120 kVp across protocols, radiation doses varied significantly. Factors such as body weight, anatomical coverage, and the use of TCM contributed to these differences. The extensive anatomical coverage required by CT CAP, which involves the chest, abdomen, and pelvis, explains its higher radiation doses, as highlighted in previous study [53].

The high effective dose (E) observed in CT CAP raised concerns regarding cancer risk. Effective dose, typically expressed in millisieverts (mSv), reflects the risk of stochastic effects, including cancer. Studies such as Bagherzadeh *et al.,* [54] suggest that higher effective doses over large anatomical areas elevate cancer risks. The inability to prevent dose escalation in CT CAP, despite using consistent tube potential, points to the role of acquisition parameters such as pitch in influencing radiation doses and image noise [38].

Weight-based analysis revealed that the >45 kg group consistently exhibited higher radiation doses, except in protocols like CT Abdomen, where the 0-45 kg group recorded higher doses. This complexity is likely due to the increased sensitivity of smaller patients to radiation [20].

CT Chest protocols typically yielded lower radiation doses, because of the high natural contrast between lung tissue and air, as well as the low attenuation of x-rays traveling through the lungs' air [55]. In studies by Yoon *et al.,* [26] and Bos *et al.,* [27], CTDIvol values were as low as 1.3 mGy and 0.77 mGy, respectively. The lower dose in previous studies was attributed to the use of DLR and a 70-100 kVp range [26]. The variation in doses between the two studies likely results from differences in patient demographics, particularly age, with older paediatric patients receiving higher doses [56].

Slice thickness also significantly impacted radiation doses. Thinner slices (1-3 mm), while improving image resolution, increased radiation exposure [57-59]. Adjusting slice thickness based on patient size and clinical requirements, combined with IR techniques, can help balance dose and image quality in paediatric imaging.

DLR and IR methods have proven effective in reducing doses by over 40% compared to conventional Filtered Back Projection (FBP) as reported by authors [26,60,61]. These findings support the use of IR for reducing doses in paediatric CT exams without sacrificing image quality [62,63].

Additional factors contributing to radiation dose variation include operator skill, the imaging protocol used, scanner type and age, and variations in patient anatomy. These variables, alongside body weight and acquisition parameters such as tube voltage and pitch, are critical in determining the overall radiation dose in paediatric populations [64].

Radiologists, radiographers, and technicians play a pivotal role in optimizing radiation doses for paediatric patients. Continuous training, strict adherence to protocols, and professional development are crucial to ensuring minimal radiation exposure while maintaining diagnostic quality.

ICRP [65], Vañó *et al.,* [66] and Siegel *et al.,* [67] highlights essential radiation protection principles, particularly justification and optimization. These principles emphasize that all medical procedures involving ionizing radiation must adhere to justification ensuring that the benefits outweigh the risks and optimization, which focuses on keeping radiation doses as low as reasonably achievable (ALARA). This principle is especially critical in paediatric imaging due to children's increased sensitivity to radiation.

In line with the ALARA principle, radiologists and technicians must tailor radiation doses base on each patient’s specific needs. Regular monitoring of radiological equipment and strict adherence to established protocols ensures compliance with safety standards and helps minimize radiation exposure without compromising diagnostic accuracy. Implementing periodic evaluations of radiological equipment and adjusting scanning parameters according to individual patient requirements plays a crucial role in achieving these objectives.

While the findings are robust, the generalizability of this review may be limited by variations in clinical settings, demographic factors, and equipment performances. Paediatric healthcare practices often differ across institutions, and these differences could impact the applicability of the results. Future research should explore these variables to enhance the transferability of findings to diverse populations.

Moreover, the exclusion criteria, while necessary for standardization, may introduce selection bias by omitting studies lacking detailed demographic or protocol information. Addressing this limitation in future reviews, such as by broadening inclusion criteria, would strengthen the conclusions and provide a more comprehensive understanding of the topic.

This review has certain limitations. Primarily, the study focused exclusively on paediatric populations, excluding adult patients, which may limit the generalizability of the findings. Additionally, variability in scanner types, acquisition parameters, and patient demographics across studies may further constrain the applicability of the results to broader populations. Furthermore, not all studies provided complete data on effective dose (E) and size-specific dose estimates (SSDE), particularly in certain weight categories, which may have affected the comprehensiveness of dose comparisons.

A key limitation is the potential for selection bias introduced by the strict inclusion criteria, which may have excluded relevant studies. This could limit the overall scope and robustness of the findings. Future studies should consider broader inclusion criteria to capture a wider range of data, ensuring more comprehensive and generalizable conclusions across diverse clinical settings.

Future research should consider larger sample sizes for CT CAP examinations to provide more robust and generalized comparisons across paediatric CT protocols. Advancements in dose reduction strategies, including deep learning reconstruction (DLR) and iterative reconstruction (IR), should be further explored to ensure optimal diagnostic outcomes with minimal radiation exposure. Radiologists, radiographers, and technicians must continue to apply the ALARA principle and optimize scanning protocols tailored to paediatric patients to maintain diagnostic quality while minimizing radiation risks.

5. Conclusions

Optimizing radiation doses in paediatric CT imaging is vital due to children's heightened sensitivity to ionizing radiation and their increased risk of long-term cancer. This systematic review highlights significant variations in radiation doses across different paediatric CT protocols, influenced by body weight, CT parameters, and scanning techniques. Implementing weight-adapted protocols and adjusting factors like tube voltage and pitch can significantly reduce radiation exposure while preserving image quality. Moreover, advanced reconstruction techniques like DLR and IR offer promise in enhancing image quality without increasing radiation exposure. Continuous improvements to imaging protocols and adherence to radiation safety principles will ensure that paediatric patients receive the safest and most effective care possible.

Acknowledgement
This research was not funded by any grant.

References

[1] Hussain, Shah, Iqra Mubeen, Niamat Ullah, Syed Shahab Ud Din Shah, Bakhtawar Abduljalil Khan, Muhammad Zahoor, Riaz Ullah, Farhat Ali Khan, and Mujeeb A. Sultan. "Modern diagnostic imaging technique applications and risk factors in the medical field: a review." *BioMed research international* 2022, no. 1 (2022): 5164970. https://doi:10.1155/2022/5164970

[2] Schulz, Raymond A., Jay A. Stein, and Norbert J. Pelc. "How CT happened: the early development of medical computed tomography." *Journal of Medical Imaging* 8, no. 5 (2021): 052110-052110. https://doi:10.1117/1.jmi.8.5.052110

[3] McCollough, Cynthia H., and Prabhakar Shantha Rajiah. "Milestones in CT: past, present, and future." *Radiology* 309, no. 1 (2023): e230803. https://doi:10.1148/radiol.230803

[4] Kutanzi, Kristy R., Annie Lumen, Igor Koturbash, and Isabelle R. Miousse. "Pediatric exposures to ionizing radiation: carcinogenic considerations." *International journal of environmental research and public health* 13, no. 11 (2016): 1057. https://doi:10.3390/ijerph13111057

[5] Marcu, Loredana G., Minh Chau, and Eva Bezak. "How much is too much? Systematic review of cumulative doses from radiological imaging and the risk of cancer in children and young adults." *Critical Reviews in Oncology/Hematology* 160 (2021): 103292. https://doi:10.1016/j.critrevonc.2021.103292

[6] Sayed, Inayatullah Shah, and Muhammad Irfan Mohd Yusof. "Techniques and Strategies to Minimize Radiation Exposure in Pediatric Computed Tomography (CT) Abdominal Examinations: A Review." *Cureus* 16, no. 8 (2024): e67494. https://doi:10.7759/cureus.67494

[7] Jonas, Daniel E., Daniel S. Reuland, Shivani M. Reddy, Max Nagle, Stephen D. Clark, Rachel Palmieri Weber, Chineme Enyioha et al. "Screening for lung cancer with low-dose computed tomography: updated evidence report and systematic review for the US Preventive Services Task Force." *Jama* 325, no. 10 (2021): 971-987. https://doi:10.1001/jama.2021.0377

[8] Little, Mark P., Alina V. Brenner, Eric J. Grant, Hiromi Sugiyama, Dale L. Preston, Ritsu Sakata, John Cologne et al. "Age effects on radiation response: Summary of a recent symposium and future perspectives." *International journal of radiation biology* 98, no. 11 (2022): 1673-1683. https://doi:10.1080/09553002.2022.2063962

[9] Almujally, Abdullah, Nissren Tamam, Abdelmoneim Sulieman, Duong Thanh Tai, Hiba Omer, Nouf Abuhadi, Hassan Salah, Essam Mattar, Mayeen Uddin Khandaker, and David Bradley. "Evaluation of paediatric computed tomography imaging for brain, and abdomen procedures." *Radiation Physics and Chemistry* 200 (2022): 110271. https://doi:10.1016/j.radphyschem.2022.110271

[10] Abdou, Sayed E., Dina H. Salama, Khaled A. Ahmad, Abdelsattar M. Sallam, El-Sayed M. El-Sayed, and M. S. Talaat. "Pediatric computed tomography scan parameters and radiation dose revisited for pediatric imaging team." *Kasr Al Ainy Medical Journal* 27, no. 3 (2022). https://doi:10.4103/kamj.kamj_9_22

[11] Miglioretti, Diana L., Eric Johnson, Andrew Williams, Robert T. Greenlee, Sheila Weinmann, Leif I. Solberg, Heather Spencer Feigelson et al. "The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk." *JAMA pediatrics* 167, no. 8 (2013): 700-707. https://doi:10.1001/jamapediatrics.2013.311

[12] Singh, Ramandeep, Timothy P. Szczykutowicz, Fatemeh Homayounieh, Rachel Vining, Kalpana Kanal, Subba R. Digumarthy, and Mannudeep K. Kalra. "Radiation dose for multiregion CT protocols: challenges and limitations." *American Journal of Roentgenology* 213, no. 5 (2019): 1100-1106. https://doi.org/10.2214/AJR.19.2120

[13] Saidu, A. M., I. Garba, M. Abba, M. A. Yahuza, L. Yusuf, N. M. Tahir, and S. S. Garko. "Evaluation of image quality and radiation dose in computed tomography urography following tube voltage optimisation." *Radiography* 30, no. 1 (2024): 301-307. https://doi:10.1016/j.radi.2023.11.023

[14] Alenazi, Khaled, Essam Alkhybari, Ali Alhailiy, Sultan Alghamdi, Nada Fisal, and Salman Albeshan. "Pediatrics organ dose and lifetime attributable cancer risk estimates in routine computed tomography." *Radiation Physics and Chemistry* 223 (2024): 112021. https://doi:10.1016/j.radphyschem.2024.112021

[15] Dudhe, Sakshi S., Gaurav Mishra, Pratapsingh Parihar, Devyansh Nimodia, and Anjali Kumari. "Radiation dose optimization in radiology: a comprehensive review of safeguarding patients and preserving image fidelity." *Cureus* 16, no. 5 (2024): e60846. https://doi:10.7759/cureus.60846

[16] Bodelle, Boris, Constanze Fischbach, Christian Booz, Ibrahim Yel, Claudia Frellesen, Martin Beeres, Thomas J. Vogl, and Jan-Erik Scholtz. "Free-breathing high-pitch 80 kVp dual-source computed tomography of the pediatric chest: image quality, presence of motion artifacts and radiation dose." *European journal of radiology* 89 (2017): 208-214. https://doi:10.1016/j.ejrad.2017.01.027

[17] Akbari-Zadeh, H., S. S. Seyedi, Z. Ganji, H. Sherkat, A. R. Montazerabadi, and MT Bahreyni Toossi. "Pediatric dose references levels estimation for routine computed tomography examinations in Great Khorasan province, Iran." *International Journal of Radiation Research* 22, no. 1 (2024): 179-184. https://doi:10.52547/ijrr.21.25

[18] Ryu, Young Jin, Woo Sun Kim, Young Hun Choi, Jung-Eun Cheon, So Mi Lee, Hyun-Hae Cho, and In-One Kim. "Pediatric chest CT: wide-volume and helical scan modes in 320-MDCT." *American Journal of Roentgenology* 205, no. 6 (2015): 1315-1321. https://doi:10.2214/AJR.14.13941

[19] Boos, Johannes, Patric Kröpil, Dirk Klee, Philipp Heusch, Lars Schimmöller, Jörg Schaper, Gerald Antoch, and Rotem S. Lanzman. "Evaluation of the impact of organ-specific dose reduction on image quality in pediatric chest computed tomography." *Pediatric radiology* 44 (2014): 1065-1069. https://doi:10.1007/s00247-014-2950-z

[20] Kritsaneepaiboon, S., P. Siriwanarangsun, P. Tanaanantarak, and A. Krisanachinda. "Can a revised paediatric radiation dose reduction CT protocol be applied and still maintain anatomical delineation, diagnostic confidence and overall imaging quality?." *The British Journal of Radiology* 87, no. 1041 (2014): 20140032. https://doi:10.1259/bjr.20140032

[21] Korir, Geoffrey K., Jeska S. Wambani, Ian K. Korir, Mark A. Tries, and Patrick K. Boen. "National diagnostic reference level initiative for computed tomography examinations in Kenya." *Radiation protection dosimetry* 168, no. 2 (2016): 242-252. https://doi.org/10.1093/rpd/ncv020

[22] Yu, Lifeng, Joel G. Fletcher, Maria Shiung, Kristen B. Thomas, Jane M. Matsumoto, Shannon N. Zingula, and Cynthia H. McCollough. "Radiation dose reduction in pediatric body CT using iterative reconstruction and a novel image-based denoising method." *American Journal of Roentgenology* 205, no. 5 (2015): 1026-1037. https://doi:10.2214/AJR.14.14185

[23] Gao, Yiming, Brian Quinn, Usman Mahmood, Daniel Long, Yusuf Erdi, Jean St. Germain, Neeta Pandit-Taskar, X. George Xu, Wesley E. Bolch, and Lawrence T. Dauer. "A comparison of pediatric and adult CT organ dose estimation methods." *BMC medical imaging* 17 (2017): 1-17. https://doi:10.1186/s12880-017-0199-3

[24] Tabari, Azadeh, Michael S. Gee, Ramandeep Singh, Ruth Lim, Katherine Nimkin, Andrew Primak, Bernhard Schmidt, and Mannudeep K. Kalra. "Reducing radiation dose and contrast medium volume with application of dual-energy CT in children and young adults." *American Journal of Roentgenology* 214, no. 6 (2020): 1199-1205. https://doi:10.2214/AJR.19.22231

[25] Karim, M. K. A., H. H. Harun, Z. Kayun, O. B. Aljewaw, S. H. N. Azizan, N. F. N. M. Rafiz, and N. A. Muhammad. "Paediatric radiation dose and cancer risk associated with body effective diameter during CT thorax examination." *Radiation Physics and Chemistry* 188 (2021): 109685. https://doi:10.1016/j.radphyschem.2021.109685

[26] Yoon, Haesung, Jisoo Kim, Hyun Ji Lim, and Mi-Jung Lee. "Image quality assessment of pediatric chest and abdomen CT by deep learning reconstruction." *BMC medical imaging* 21 (2021): 1-11. https://doi:10.1186/s12880-021-00677-2

[27] Bos, Denise, Sebastian Zensen, Marcel K. Opitz, Johannes Haubold, Kai Nassenstein, Sonja Kinner, Bernd Schweiger, Michael Forsting, Axel Wetter, and Nika Guberina. "Diagnostic reference levels for chest computed tomography in children as a function of patient size." *Pediatric Radiology* 52, no. 8 (2022): 1446-1455. https://doi:10.1007/s00247-022-05340-8

[28] Sun, Jihang, Yun Peng, Xiaomin Duan, Tong Yu, Qifeng Zhang, Yong Liu, and Di Hu. "Image quality in children with low-radiation chest CT using adaptive statistical iterative reconstruction and model-based iterative reconstruction." *PLoS One* 9, no. 5 (2014): e96045. https://doi:10.1371/journal.pone.0096045

[29] Hwang, Jae-Yeon, Kyung-Hyun Do, Dong Hyun Yang, Young Ah Cho, Hye-Kyung Yoon, Jin Seong Lee, and Hyun Jung Koo. "A survey of pediatric CT protocols and radiation doses in South Korean hospitals to optimize the radiation dose for pediatric CT scanning." *Medicine* 94, no. 50 (2015): e2146. https://doi:10.1097/MD.0000000000002146

[30] Kim, Hae Jin, So-Young Yoo, Tae Yeon Jeon, and Ji Hye Kim. "Model-based iterative reconstruction in ultra-low-dose pediatric chest CT: comparison with adaptive statistical iterative reconstruction." *Clinical Imaging* 40, no. 5 (2016): 1018-1022. https://doi:10.1016/j.clinimag.2016.06.006

[31] Villanueva-Meyer, Javier E., David M. Naeger, Jesse L. Courtier, Michael D. Hope, Jack W. Lambert, John D. MacKenzie, and Andrew S. Phelps. "Pediatric chest CT at chest radiograph doses: when is the ultralow-dose chest CT clinically appropriate?." *Emergency radiology* 24 (2017): 369-376. https://doi.org/10.1007/s10140-017-1487-5

[32] Alenazi, Khaled, Haitham Alahmad, Sultan Algamdi, Ali Alhailiy, Essam Alkhybari, Ahmad Alhulail, Nada Fisal, and Salman Albeshan. "Assessment of effective dose and cancer risk for pediatric chest and pelvis CT procedures in the central region of Saudi Arabia." *Radiation Physics and Chemistry* 219 (2024): 111690. https://doi:10.1016/j.radphyschem.2024.111690

[33] Goske, Marilyn J., Keith J. Strauss, Laura P. Coombs, Keith E. Mandel, Alexander J. Towbin, David B. Larson, Michael J. Callahan et al. "Diagnostic reference ranges for pediatric abdominal CT." *Radiology* 268, no. 1 (2013): 208-218. https://doi:10.1148/radiol.13120730

[34] Abdulkadir, Muhammad Kabir, Nur Atikah Yusra Mat Rahim, Nur Syazwani Mazlan, Norfataha Mohd Daud, Ibrahim Lutfi Shuaib, and Noor Diyana Osman. "Dose optimisation in paediatric CT examination: Assessment on current scanning protocols associated with radiation dose." *Radiation Physics and Chemistry* 171 (2020): 108740. https://doi:10.1016/j.radphyschem.2020.108740

[35] Kang, Yeseul, Shin Hye Hwang, Kyunghwa Han, and Hyun Joo Shin. "Comparison of image quality, contrast administration, and radiation doses in pediatric abdominal dual-layer detector dual-energy CT using propensity score matching analysis." *European Journal of Radiology* 169 (2023): 111177. https://doi:10.1016/j.ejrad.2023.111177

[36] Sulieman, A., N. Tamam, Abdelrahman Elnour, M. Alkhorayef, E. Babikir, Huda I. Al-Mohammed, N. Abuhadi, Mayeen Uddin Khandaker, and David A. Bradley. "Effective radiation dose and radiogenic cancer risk during contrast enhanced abdominal computed tomography examinations." *Radiation Physics and Chemistry* 200 (2022): 110328. https://doi:10.1016/j.radphyschem.2022.110328

[37] Hu, Di, Tong Yu, Xiaomin Duan, Yun Peng, and Renyou Zhai. "Determination of the optimal energy level in spectral CT imaging for displaying abdominal vessels in pediatric patients." *European journal of radiology* 83, no. 3 (2014): 589-594. https://doi:10.1016/j.ejrad.2013.10.016

[38] Berlin, Sheila C., Dayna M. Weinert, Pauravi S. Vasavada, Claudia Martinez-Rios, Roshni A. Parikh, Michael A. Wien, David W. Jordan, and Ronald D. Novak. "Successful dose reduction using reduced tube voltage with hybrid iterative reconstruction in pediatric abdominal CT." *American Journal of Roentgenology* 205, no. 2 (2015): 392-399. https://doi:10.2214/AJR.14.12698

[39] Baker, Mark E., Wadih Karim, Jennifer A. Bullen, Andrew N. Primak, Frank F. Dong, and Brian R. Herts. "Estimated patient dose indexes in adult and pediatric MDCT: comparison of automatic tube voltage selection with fixed tube current, fixed tube voltage, and weight-based protocols." *American Journal of Roentgenology* 205, no. 3 (2015): 592-598. https://doi:10.2214/AJR.14.13242

[40] Didier, Ryne A., Petra L. Vajtai, and Katharine L. Hopkins. "Iterative reconstruction technique with reduced volume CT dose index: diagnostic accuracy in pediatric acute appendicitis." *Pediatric radiology* 45 (2015): 181-187. https://doi.org/10.1007/s00247-014-3109-7

[41] Kim, Taek Min, Young Hun Choi, Jung-Eun Cheon, Woo Sun Kim, In-One Kim, Ji Eun Park, Su-mi Shin, Seong Yong Pak, and Bernhard Krauss. "Optimal kiloelectron volt for noise-optimized virtual monoenergetic images of dual-energy pediatric abdominopelvic computed tomography: preliminary results." *Korean Journal of Radiology* 20, no. 2 (2019): 283-294. https://doi:10.3348/kjr.2017.0507

[42] Smith, Ethan A., Jonathan R. Dillman, Mitchell M. Goodsitt, Emmanuel G. Christodoulou, Nahid Keshavarzi, and Peter J. Strouse. "Model-based iterative reconstruction: effect on patient radiation dose and image quality in pediatric body CT." *Radiology* 270, no. 2 (2014): 526-534. https://doi:10.1148/radiol.13130362

[43] Kost, Susan D., Nicholas D. Fraser, Diana E. Carver, David R. Pickens, Ronald R. Price, Marta Hernanz-Schulman, and Michael G. Stabin. "Patient-specific dose calculations for pediatric CT of the chest, abdomen and pelvis." *Pediatric radiology* 45 (2015): 1771-1780. https://doi.org/10.1007/s00247-015-3400-2

[44] Muhammad, N. A., Muhammad Khalis Abdul Karim, Hasyma Abu Hassan, Mazliana Ahmad Kamarudin, Jeannie Hsiu Ding Wong, and Mohammad Johari Ibahim. "Estimation of effective dose and organ cancer risk from paediatric computed tomography thorax–abdomen-Pelvis examinations." *Radiation Physics and Chemistry* 165 (2019): 108438. https://doi:10.1016/j.radphyschem.2019.108438

[45] Özsoykal, İsmail, Ayşegül Yurt, and Kadir Akgüngör. "Size-specific dose estimates in chest, abdomen, and pelvis CT examinations of pediatric patients." *Diagnostic and Interventional Radiology* 24, no. 4 (2018): 243. https://doi:10.5152/dir.2018.17450

[46] Toma, Paolo, Alessandra Bartoloni, Sergio Salerno, Claudio Granata, Vittorio Cannata, Andrea Magistrelli, and Owen J. Arthurs. "Protecting sensitive patient groups from imaging using ionizing radiation: effects during pregnancy, in fetal life and childhood." *La radiologia medica* 124 (2019): 736-744. https://doi:10.1007/s11547-019-01034-8

[47] Kiani, M., and A. Chaparian. "Evaluation of image quality, organ doses, effective dose, and cancer risk from pediatric brain CT scans." *European Journal of Radiology* 158 (2023): 110657. https://doi:10.1016/j.ejrad.2022.110657

[48] Muhammad, N. A., A. Sabarudin, N. Ismail, and M. K. A. Karim. "A systematic review and meta-analysis of radiation dose exposure from computed tomography examination of thorax-abdomen-pelvic regions among paediatric population." *Radiation Physics and Chemistry* 179 (2021): 109148. https://doi:10.1016/j.radphyschem.2020.109148

[49] Yang, Ching-Ching. "Evaluation of impact of factors affecting CT radiation dose for optimizing patient dose levels." *Diagnostics* 10, no. 10 (2020): 787. https://doi:10.3390/diagnostics10100787

[50] Matsubara, Kosuke, Tadanori Takata, Masanao Kobayashi, Satoshi Kobayashi, Kichiro Koshida, and Toshifumi Gabata. "Tube current modulation between single-and dual-energy CT with a second-generation dual-source scanner: radiation dose and image quality." *American Journal of Roentgenology* 207, no. 2 (2016): 354-361. https://doi:10.2214/AJR.15.15404

[51] Huck, Sascha Manuel, George SK Fung, Katia Parodi, and Karl Stierstorfer. "A method for optimizing the x-ray tube current in ROI imaging using a simulation framework for radiation dose and image quality calculation for arbitrary fluence distributions." In *Medical Imaging 2021: Physics of Medical Imaging*, vol. 11595, pp. 11-21. SPIE, 2021. https://doi:10.1117/12.2580828

[52] Lell, Michael, and Marc Kachelrieß. "Computed tomography 2.0: new detector technology, AI, and other developments." *Investigative Radiology* 58, no. 8 (2023): 587-601. https://doi:10.1097/RLI.0000000000000995

[53] Muhammad, Nor Azura, Zunaide Kayun, Hasyma Abu Hassan, Jeannie Hsiu Ding Wong, Kwan Hoong Ng, and Muhammad Khalis Abdul Karim. "Evaluation of organ dose and image quality metrics of pediatric CT chest-abdomen-pelvis (CAP) examination: an anthropomorphic phantom study." *Applied Sciences* 11, no. 5 (2021): 2047. https://doi:10.3390/app11052047

[54] Bagherzadeh, Saeed, Afsaneh MirDerikvand, and Ali MohammadSharifi. "Evaluation of radiation dose and radiation-induced cancer risk associated with routine CT scan examinations." *Radiation Physics and Chemistry* 217 (2024): 111521. https://doi:10.1016/j.radphyschem.2024.111521

[55] Willemink, Martin J., and Peter B. Noël. "The evolution of image reconstruction for CT—from filtered back projection to artificial intelligence." *European radiology* 29 (2019): 2185-2195. https://doi:10.1007/s00330-018-5810-7

[56] Tan, Xi Min, Mohammad Taufik Bin Mohamed Shah, Shu-Ling Chong, Yong-Kwang Gene Ong, Peck Har Ang, Nur Diana Bte Zakaria, Khai Pin Lee, and Jen Heng Pek. "Differences in radiation dose for computed tomography of the brain among pediatric patients at the emergency departments: an observational study." *BMC Emergency Medicine* 21 (2021): 1-9. https://doi:10.1186/s12873-021-00502-7

[57] Huang, Kai, Dong Joo Rhee, Rachel Ger, Rick Layman, Jinzhong Yang, Carlos E. Cardenas, and Laurence E. Court. "Impact of slice thickness, pixel size, and CT dose on the performance of automatic contouring algorithms." *Journal of applied clinical medical physics* 22, no. 5 (2021): 168-174. https://doi:10.1002/acm2.13207

[58] Albeshan, Salman, Sultan Algamdi, Essam Alkhybari, Ali Alhailiy, Nada Fisal, Mohammed Alsufyan, Sultan Aldosari, and Abdullah Abuhaimed. "Radiation exposure and cancer risk of pediatric head CT scans: Impact of age and scanning parameters." *Radiation Physics and Chemistry* 216 (2024): 111459. https://doi:10.1016/j.radphyschem.2023.111459

[59] Kataria, Bharti, Mischa Woisetschläger, J. Nilsson Althén, Michael Sandborg, and Örjan Smedby. "Image quality assessments in abdominal CT: Relative importance of dose, iterative reconstruction strength and slice thickness." *Radiography* 30, no. 6 (2024): 1563-1571. https://doi:10.1016/j.radi.2024.09.060

[60] Szczykutowicz, Timothy P., Giuseppe V. Toia, Amar Dhanantwari, and Brian Nett. "A review of deep learning CT reconstruction: concepts, limitations, and promise in clinical practice." *Current Radiology Reports* 10, no. 9 (2022): 101-115. https://doi:10.1007/s40134-022-00399-5

[61] Chen, Hongchi, Qiuxia Li, Lazhen Zhou, and Fangzuo Li. "Deep learning-based algorithms for low-dose CT imaging: A review." *European Journal of Radiology* (2024): 111355. https://doi:10.1016/j.ejrad.2024.111355

[62] Joyce, Stella, Owen J. O'Connor, Michael M. Maher, and Mark F. McEntee. "Strategies for dose reduction with specific clinical indications during computed tomography." *Radiography* 26 (2020): S62-S68. https://doi:10.1016/j.radi.2020.06.012

[63] Godt, Johannes Clemens, Cathrine K. Johansen, Anne Catrine T. Martinsen, Anselm Schulz, Helga M. Brøgger, Kristin Jensen, Arne Stray-Pedersen, and Johann Baptist Dormagen. "Iterative reconstruction improves image quality and reduces radiation dose in trauma protocols; A human cadaver study." *Acta Radiologica Open* 10, no. 10 (2021): 20584601211055389. https://doi:10.1177/20584601211055389

[64] Tsapaki, Virginia. "Radiation dose optimization in diagnostic and interventional radiology: Current issues and future perspectives." *Physica Medica* 79 (2020): 16-21. https://doi:10.1016/j.ejmp.2020.09.015

[65] ICRP, "ICRP PUBLICATION 103 The 2007 Recommendations of the International Commission on Radiological Protection," Radiat. Phys. Chem., vol. 188, no. 24, pp. 1–337, 2007.

[66] Vañó, E., D. L. Miller, C. J. Martin, M. M. Rehani, K. Kang, M. Rosenstein, P. Ortiz-López, S. Mattsson, R. Padovani, and A. Rogers. "ICRP publication 135: diagnostic reference levels in medical imaging." *Annals of the ICRP* 46, no. 1 (2017): 1-144. https://doi:10.1177/0146645317717209

[67] Siegel, Jeffry A., Bill Sacks, and Bennett S. Greenspan. "Justification and Optimization: ICRP's 2 Fundamental Principles of Radiation Protection are Unsuitable Companions for Medical Imaging." (2019): 18N-18N. https://doi.org/10.2967/jnumed.119.226845