



Review Article

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Contribution of Simulation Method to Estimation of Pediatric Radiation Dose for Abdominal and Pelvic Computed Tomography Procedures: Systematic Review

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To Cite This Article: Khalid M Aloufi*, Contribution of Simulation Method to Estimation of Pediatric Radiation Dose for Abdominal and Pelvic Computed Tomography Procedures: Systematic Review. *Am J Biomed Sci & Res.* 2024 21(3) AJBSR.MS.ID.002836, DOI: [10.34297/AJBSR.2024.21.002836](https://doi.org/10.34297/AJBSR.2024.21.002836)

Received: 📅 January 19, 2024; **Published:** 📅 January 30, 2024

Abstract

Introduction: It is essential to assess accurately the radiation dose from different radiological procedures, especially for pediatric patients. This is because pediatric patients are more radiosensitive than adults and their life expectancy is longer. CT is considered as one of the highest radiation dose sources and is common among medical imaging modalities. Simulation method (SM) is a powerful tool to assess radiation dose for CT procedures and can overcome the limitations of real measurements.

Aim: This paper aims to provide a systematic review of the contribution of SM to estimation of pediatric radiation dose for abdominal and pelvic CT procedures.

Methodology: A wide internet database search was conducted, covering the period from January 1990 to September 2023 to find published papers in SM to estimate pediatric radiation dose for abdominal and pelvic CT procedures. Pediatric age range was assumed to be from birth to 16 years old. The database search was performed via PubMed/Medline and other databases. 31 published papers matched the inclusion criteria of this study, whereas 1,944 papers were excluded.

Results: The highest frequency of publication was during 2015 (39%). Domains of the reviewed studies were classified according to (1) purpose, (2) methodology, and (3) finding. The purposes among the included published papers were distributed approximately equally. Using Simulation codes and voxelized phantoms were dominant methodology with 41.9% and 77.4% respectively. SM estimation of equivalent dose dominated the reviewed studies with 81%. 74.2% of the included studies reported that their results were strongly related to the characteristics of simulated CT scanner or simulated phantom. A few SM studies examined tissue weighting factors and conversion factors.

Conclusions: SM results with the same conditions are comparable. Using CT dose calculators will be the dominant method for assessing CT dose in the near future. Even though Adequate studies were found, conducting studies for specific subjects are recommended. Recommendations: More studies are recommended to investigate SM results when applying different variables, such as tissue weighting factors and conversion factors. Additional studies are recommended to compare the results from different CT dose calculators.

Keywords: Simulation, Computed Tomography, Radiation Dose, Pediatric, Abdomen, Pelvis

Introduction

Pediatric patients are more radiosensitive than adults and their life expectancy is longer. Thus, it is essential to assess radiation dose from different radiological procedures accurately. This is to

optimize radiological procedure, to minimize radiation dose and then, to reduce potential risks associated with ionizing radiation [1-3]. Priority is given to assessing radiation dose in cases of the highest dosage and the most common radiological procedures.



Computed Tomography (CT) is considered as one of the highest radiation dose sources and one of the most common among medical imaging modalities [4]. Simulation Method (SM) is computational method used to predict the results from statistical trails [5]. SM is a powerful tool for assessing radiation doses for CT procedures. This is because SM can be used for radiation dose estimation in complicated human body tissues and organ structures, whereas it is impossible to conduct real experimental procedures [6,7]. In addition, SM can accurately estimate the risks associated with these radiation doses. Factors affecting radiation dose, such as patient size, age, and exposure, can be examined using SM. Radiation dose estimation for CT examinations can be performed using SM based on CT dose calculators or codes.

Using CT dose calculators is a straightforward and simple method of estimating radiation dose. Several CT dose calculators are available: CT-Expo, DoseWatch IMPACT, ImpactDose, NCICT, VirtualDose CT, Radimetrics and WinDose. Some of them are commercials and a few are free. There are some differences between the properties of these CT dose calculators, such as the properties of used computational phantom, tube current modulation modeling and user interface platforms. However, they are comparable in accuracy and results [8-10]. Simulation codes are simulation of radiation physics, geometry and tracking radiation interactions thought the geometry [11]. Examples of these codes are Geometry and Tracking 4 (Geant4) code [12], MC N-Particle (MCNP) code [13], FLUKtuierende KAskade (FLUKA) code [14] and Electron Gamma Shower (EGS) code [15]. These codes can be used (1) to assess radiation dose, (2) to assess image quality, (3) to analyze x-ray tube outputs (4) to optimize x-ray room designs and (5) to simulate pathology images [16-20].

To validate the accuracy of certain SM results, comparisons SM results, real measurements results and results from published studies were performed [9,21,22]. Simulation codes are more complicated compared with CT dose calculators, because of the

complications in CT scanner and computational human body phantom descriptions. This paper aims to provide a systematic review of the contribution of SM to estimation of pediatric radiation dose for abdominal and pelvic CT procedures.

Methodology

Literature Search and Inclusion Criteria

A wide search of internet databases was conducted for the period from January 1990 to September 2023 to find papers published in the “contribution of SM to pediatric radiation dose estimation for abdominal and pelvic CT procedures”. In this systematic review, pediatric age range was assumed to be from birth to 16 years old. The database search was performed via PubMed/Medline and other databases; for example, ScienceDirect, Semantic Scholar and Google Scholar. The keywords used in this database search were “**Simulation, radiation dose, pediatric, and abdominal pelvic computed tomography ([Simulation or Monte Carlo] and [pediatric or pediatrics] and radiation dose AND [computed tomography or CT])**”. In the internet databases search, the method selected for estimating the pediatric radiation dose for abdominal and pelvic CT procedures was the SM using codes and CT dose calculators.

The inclusions were published papers in SM of radiation dose estimation for abdominal and pelvic CT procedures of pediatric patients (i.e., from birth to 16 years old). The exclusions were published papers in SM of other CT procedures, such as brain, chest and extremities, as well as CT procedures for young and adult patients (i.e., over 16 years old). In addition, radiotherapy and other diagnostic procedures rather than CT scan using ionizing or nonionizing methods or radioactive materials were excluded, for instance, general radiography, fluoroscopy, interventional radiology, ultrasound, magnetic resonance and nuclear medicine. The search strategy used to identify the publications for this systematic review is shown in (Figure 1).

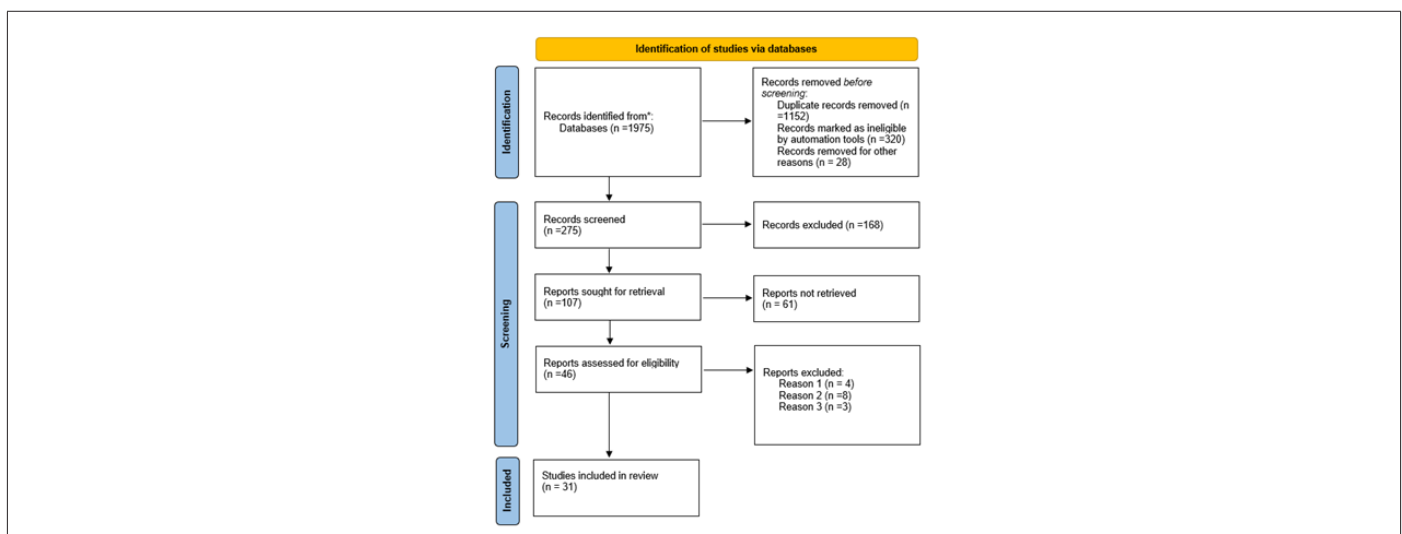


Figure 1: Search strategy used to identify articles for the systemic review regarding PRISMA guidelines. The search was on PubMed/MEDLINE, ScienceDirect, Semantic Scholar, and Google Scholar. Some records were excluded because they were reviews, reports, dissertations, seminar papers, recommendations, and others.

Reason 1: articles were removed from the websites.

Reason 2: articles were not available in English language.

Reason 3: articles were not accessible.

Then, papers published on PubMed/Medline and other database websites on SM of pediatric radiation dose for abdominal and pelvic CT procedures were reviewed. 1,975 papers published between January 1990 and September 2023 were reviewed regarding the keywords, the papers' titles, their abstracts, aims, methodologies and findings. 31 published papers matched the inclusion criteria of this study, whereas 1,944 papers were excluded. The majority of the excluded published papers were for adult patients' dosimetry in diagnostic and radiotherapy fields. In addition, others were concerned with therapeutic beam line simulation, optimization of radiation dose delivery in radiotherapy. Nevertheless, some related published papers might be missing.

Quality Assessment of Selected Published Papers

The criteria of the published papers were selected to be eligible,

and then included in this systematic review. Duplicated published papers were found and then removed. Published papers were selected to include publication information (authors and published year), purpose, methodology and finding.

Ethics Statement

Ethical approval was waived for this study, because there were no human participants, and the study was based on website searching.

Results

The distribution (over 1990 to 2023: 33 years), of the included published papers in this systematic review is illustrated in Figure 2, and the used SM (i.e., CT dose calculators and simulation codes) over 1990-2023 (33 years) is shown in Figure 3.

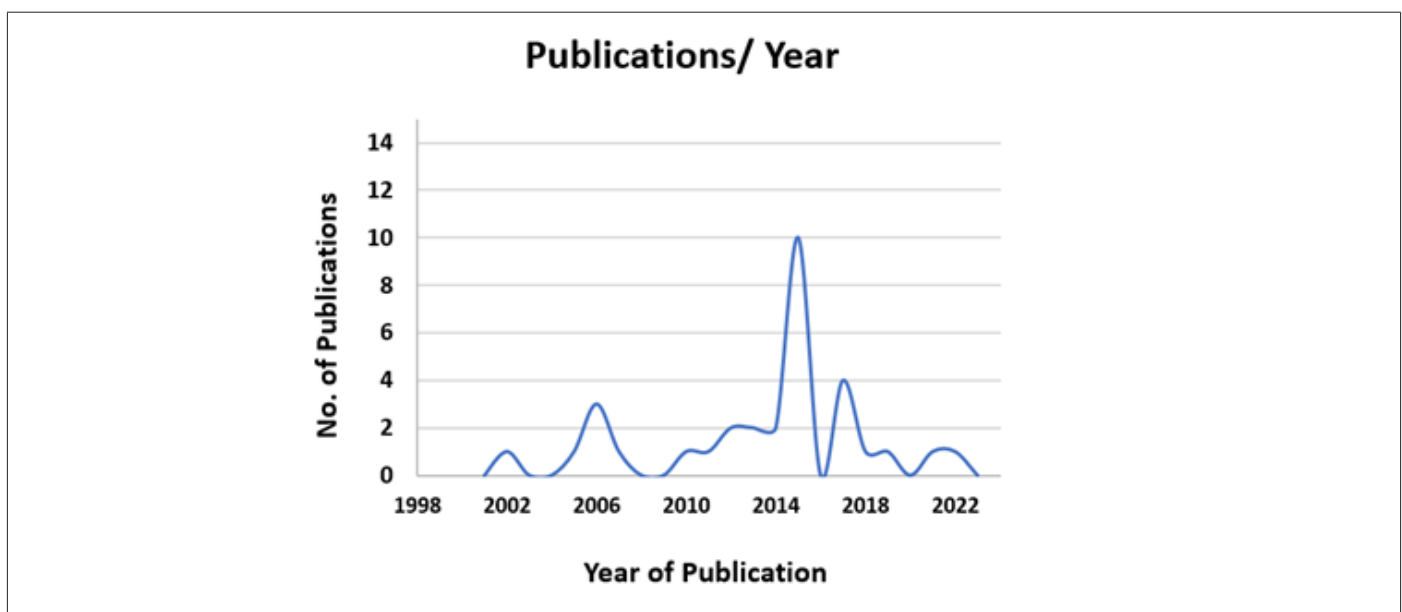


Figure 2: Distribution, over 1990 to 2023 (33 years), of the included published papers in this systematic review.

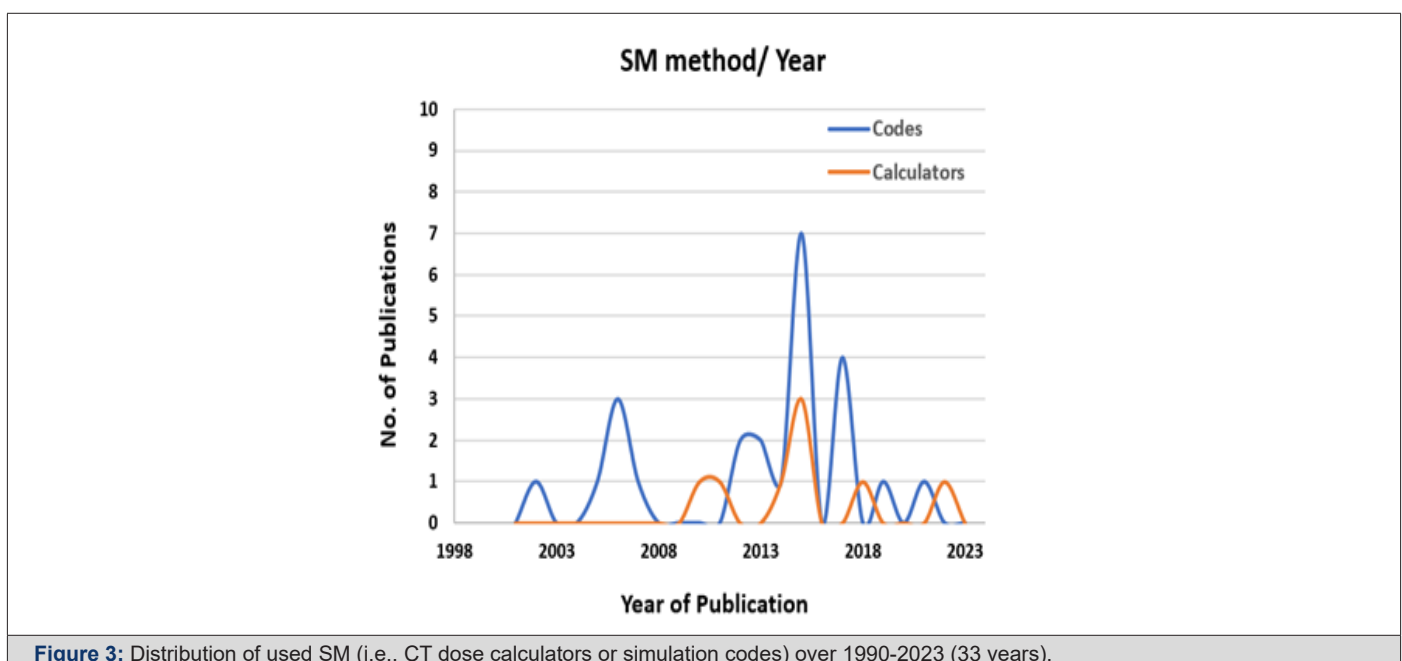


Figure 3: Distribution of used SM (i.e., CT dose calculators or simulation codes) over 1990-2023 (33 years).

In addition, the results comparisons for simulated organ absorbed dose (mGy) and simulated effective dose (mSv) from several studies are shown in Table 1.

Table 1: Comparisons of simulated organ absorbed dose (mGy) and simulated effective dose (mSv) from several studies.

Study	(Palareti et al., 2016)	(Kost et al. 2015)	(Akhlaghi P, et al. 2015)	(Lee et al. 2015)	(Fujii et al. 2015)	(Pan et al., 2014)	(Pan et al., 2014)
Reference	25	26	27	23	24	28	29
Age mAs-kVp	15y 100-120	15y 100-120	11y 100-120	7y 100-120	1y 80-120	1y 80-120	newborn 100-120
Liver	13.6	11.5	8.9	11	11.5	6.84	14.79
Spleen	13.6	10.4	9.4	11.1	..	6.72	14.52
Kidneys	13.9	11.4	8.8	11	..	6.73	14.94
Stomach	14.6	11	8.7	11.6	11.7	6.57	14.55
Pancreas	13.6	10.9	8.8	10.6	..	7.23	14.32
Colon	14.6	12.4	8.8	12.7	11.3	6.39	15.36
Bladder	11.5	10.8	7.8	9.2	10.9	5.88	15.55
Gonads	10.1	11.2	5.2	9.9	3.5	..	14.97
Effective dose	7	..	8.5	..	12.46

Domains

Domains of the reviewed studies were classified according to (1) purpose, (2) methodology, and (3) finding. The classification was D.(1) for purposes, D.(2) for methodology and D.(3) for finding. Then, each domain was subdivided into subdomains. Subdomains

classification was D. (1.1), D.(1.2), D.(1.3), ... for purposes, D.(2.1), D.(2.2), D.(2.3), ... for methodology and D.(3.1), D.(3.2), D.(3.3), ... for finding. The subdomains are chosen according to the frequent subjects included in the published papers. Then, the included published papers were distributed and sorted regarding the frequent subjects of the subdomains, as shown in Table 2.

Table 2: The numbers of published studies in frequent subject of the subdomains for purpose, methodology and finding.

Domain	Subdomain	Frequent Subject	No.
D.(1) Purpose	D.(1.1)	to compare real measurement and SM results	4
	D.(1.2)	to build database library for pediatric phantoms of different specifications	4
	D.(1.3)	to validate SM using real measurement	5
	D.(1.4)	to estimate dose and cancer risk using SM (comparison with studies from literature review)	5
	D.(1.5)	to compare SM results using differences variables (e.g., tissue weighting or conversion factors).	6
	D.(1.6)	to develop computational phantoms using SM	5
	D.(1.7)	to compare results from different CT dose calculators	2

D.(2) Methodology	D.(2.1)	Using voxelized phantom to assess radiation dose	Number of studies	13
	D.(2.2)	Using simulation codes to assess radiation dose		24
	D. 2.3)	Using hybrid phantom to assess radiation dose		4
	D.(2.4)	Using cylindrical water phantom to assess radiation dose		1
	D.(2.5)	Using ORNL phantom to assess radiation dose		2
	D.(2.6)	Using mathematical phantom to assess radiation dose		3
	D.(2.7)	Using CT dose calculators to assess radiation dose		7
	D.(2.8)	Using mixed phantom types to assess radiation dose		2
	D.(2.9)	Using stylized phantom to assess radiation dose		1
D.(3) Finding	D.(3.1)	Simulated results were strongly related to simulated CT scanner or simulated phantom characteristics	Number of studies	23
	D.(3.2)	Under the same conditions, there were agreement in results using SM and real measurement		5
	D.(3.3)	Under the same conditions, there were agreement in results using simulation codes and CT dose calculators		2
	D.(3.4)	SM results were related to variables, such as, tissue weighting, conversion factors		3
	D.(3.5)	Under the same conditions, there were variation in results using different CT dose calculators		2

Domian D.(1): D. (1) is the domain of purpose for the included published papers in this systematic review. D.(1) includes seven subdomains. The Subdomains are D. (1.1), D. (1.2), D.(1.3), D.(1.4), D.(1.5), D.(1.6), and D.(1.7). Selection of the subdomains subjects

was regarding frequent purposes among the published papers. Subdomains for “purpose” and their percentages and references are illustrated in Table 3.

Table 3: Subjects, percentages and references for subdomains: D.(1.1), D.(1.2), D.(1.3), D.(1.4), D.(1.5), D.(1.6), and D.(1.7).

Subdomains and Subjects		(%)	References
D.(1.1)	to compare real measurement and SM results	9.7	30, 31, 32, 33
D.(1.2)	to build database library for pediatric phantoms of different specifications	12.9	34, 35, 36, 37
D.(1.3)	to validate SM using real measurement	16.1	27, 38, 26, 24, 39

D.(1.4)	to estimate dose and cancer risk using SM (comparison with studies from literature review)	16.1	22, 40, 41, 42, 43
D.(1.5)	to compare SM results using differences variables (e.g., tissue weighting or conversion factors).	19.4	44, 45, 46, 47, 23, 48
D.(1.6)	to develop computational phantoms using SM	16.1	49, 50, 28, 29, 51
D.(1.7)	to compare results from different CT dose calculators	6.5	9, 10

Domain D. (2): D.(2) is the domain of methodology for the included published papers in this systematic review. D.(2) includes nine subdomains. The subdomains are D.(2.1), D.(2.2), D.(2.3), D.(2.4), D.(2.5), D.(2.6), D.(2.7), D.(2.8) and D.(2.9). Selection of

the subdomains subjects was regarding frequent methodologies among the published papers. Subdomains for “methodology” and their percentages and references are illustrated in Table 4.

Table 4: Subjects, percentages and references for subdomains: D. (2.1), D.(2.2), D.(2.3), D.(2.4), D.(2.5), D.(2.6), D.(2.7), D.(2.8) and D.(2.9).

Subdomains and subjects		(%)	References
D.(2.1)	Using voxelized phantom to assess radiation dose	41.9	30, 31, 32, 34, 26, 22, 44, 45, 23, 36, 28, 48, 51
D.(2.2)	Using simulation codes to assess radiation dose	77.4	30, 31, 32, 33, 34, 27, 38, 26, 44, 45, 35, 39, 40, 49, 50, 47, 23, 36, 28, 48, 29, 42, 37, 51
D. 2.3)	Using hybrid phantom to assess radiation dose	12.9	27, 35, 50, 9
D.(2.4)	Using cylindrical water phantom to assess radiation dose	3.2	40
D.(2.5)	Using ORNL phantom to assess radiation dose	6.5	46, 47
D.(2.6)	Using mathematical phantom to assess radiation dose	9.7	39, 41, 42
D.(2.7)	Using CT dose calculators to assess radiation dose	22.6	24, 22, 46, 9, 41, 10, 43
D.(2.8)	Using mixed phantom types to assess radiation dose	6.5	29, 37
D.(2.9)	Using stylized phantom to assess radiation dose	3.2	33

Domain D. (3): D.(3) is the domain of finding for the included published papers in this systematic review. D.(3) includes five subdomains. The subdomains are D.(3.1), D.(3.2), D.(3.3), D.(3.4) and D.(3.5). Selection of the subdomains subjects was regarding

frequent findings among the published papers. Subdomains for “finding” and their percentages and references are illustrated in Table 5.

Table 5: Subjects, percentages and references for subdomains; D.(3.1), D.(3.2), D.(3.3), D.(3.4) and D.(3.5).

Subdomains and Subjects		(%)	References
D.(3.1)	Simulated results were strongly related to simulated CT scanner or simulated phantom characteristics	74.2	9, 10, 22, 26, 27, 24, 29, 31, 33, 34, 35, 36, 37, 39, 40, 41, 42, 43, 45, 48, 49, 50, 51
D.(3.2)	Under the same conditions, there were agreement in results using SM and real measurement	16.1	30, 31, 38, 24, 28
D.(3.3)	Under the same conditions, there were agreement in results using simulation codes and CT dose calculators	6.5	32, 23

D.(3.4)	SM results were related to variables, such as, tissue weighting, conversion factors	9.7	44, 46, 47
D.(3.5)	Under the same conditions, there were variation in results using different CT dose calculators	6.5	9, 10

Discussions

Pediatric patients are more radiosensitive than adults and their life expectancy is longer. Thus, it is essential to assess the radiation dose from different radiological procedures accurately. A wide internet database search was conducted for the period from January 1990 to September 2023 to find published papers in the “contribution of SM to estimation pediatric radiation dose for abdominal and pelvic CT procedures”. In this systematic review, pediatric age range was assumed to be from birth to 16 years old.

It was found that the results with the SM conditions were comparable. For example, the difference in results between *Palareti, et al.* [25] and *Kost, et al.* [26] was less than 20%. However, the difference in results between *Fujii, et al.* [24] and *Pan, et al.* [28] was significant (approximately 45%). This is because of different specifications of the simulated CT scanners and phantoms. High organ doses reported by *Pan, et al.* [28] was because of youngest age used phantom and consequently there were small organs sizes and high organ doses. Thus, it is clear that simulated phantom and scanner characteristics strongly affect the SM results.

The subjects for purpose among the included papers were distributed approximately equally. For example, among the included papers, the purposes of subjects of D.(1.3) “to validate SM using real measurement” [27,38,26], D.(1.4) “to estimate dose and cancer risk using SM” [22,40,41], and D.(1.6) “to develop computational phantoms using SM” [49,50,28]. were 16.1% for each one of them. However, D. (1.7), which was “to compare results from different CT dose calculators” [9,10,] had the lowest percentage (7%). Therefore, more studies are required to be conducted, to compare results from different CT dose calculators. This is to find the differences in accuracy of these CT dose calculators and to contribute to their development.

The subjects for methodology among the included papers varied significantly. For example, using “voxelized phantoms” was 41.9% [22,26,44,45] whereas using “stylized phantoms” was 3.2% [33]. In addition, the percentage of using simulation codes (e.g., MCNP and Geant4) was 77.4% [22,23,26,44,45] whereas using CT dose calculators was 22.6% [9,10]. However, development of CT dose calculators started significantly in 2008, whereas using simulation codes started approximately two decades earlier. Nevertheless, regarding the complexity of using simulation codes, significant progress and easiest use of CT dose calculator software, it is expected that using CT dose calculators will be dominant for assessing CT dose in the near future.

The assessed radiation dose types among the included papers were effective and equivalent or absorbed doses. SM estimation of equivalent and absorbed doses dominated with 81%, whereas estimation of effective dose was 19%. However, it is easy to obtain

the effective dose, if the equivalent or absorbed dose is known, whereas the opposite cannot be performed. This is because effective dose is a summation of all equivalent doses, as well as equivalent dose is absorbed dose multiplies by tissue weighting factor for each tissue or organ [52]. Thus, it is recommended to obtain simulated organ radiation dose (i.e. equivalent or absorbed), rather than effective radiation dose.

In this systemic review, 74.2% of the SM studies reported that simulated results were strongly related to simulated CT scanner or phantom characteristics [9,10,22,24,26,27]. Also, it was reported that under the same conditions, there were agreement in results using simulated and real measurement methods [24,28,38]. In addition, it was reported that under the same conditions, there were agreement in results using simulation code and CT dose calculator [23,32]. Thus, different simulation codes, CT dose calculators and real measurements are comparable in their results for the same applied conditions. Nevertheless, few studies reported that there was variation in results using different CT dose calculator types [9,10]. Therefore, more studies are required to be conducted to compare results from different CT dose calculators.

A few studies examined the difference in results for different variables that were applied in simulation codes or CT dose calculators, such as, tissue weighting factors, conversion factors (e.g., DLP to effective dose conversion factors). For example, it was reported that the dose to pelvis was found to be 6.5% higher if using ICRP publication 103 recommendations rather than using ICRP publication 60 recommendations, whereas it was lower for all other examinations [44]. Another study found that conversion factors were lower by 33% and 32% than the published data for ICRP publication 60 and ICRP publication 103, respectively [46]. Only one SM study was found in radiation dose estimation of blood circulation and cancer risk estimation [22]. Thus, it is recommended to conduct more SM studies (1) to assess using different conversion and tissue weighting factors and (2) to estimate cancer risk from pediatric abdominal and pelvic CT procedures.

Finally, some studies highlighted their limitations, for example estimation of radiation dose was performed for certain pediatric age or CT scanner type. However, estimation of radiation dose independent on CT scanner type are broadly used in many CT dose calculators [8,53]. Another study highlighted that SM was performed with fixed exposure factor (i.e., mAs) [26,30,34]. To overcome this limitation and to avoid imprecise radiation dose estimation, tube current modulation (TCM) is recommend rather fixed tube current or exposure factors [54]. On the other hand, some studies highlighted their advantages of wide variation in pediatric phantom models, recommendation for development of conversion factors and recommendation for using certain phantom type (e.g., voxelised phantom) [31,46,49].

Conclusions

It can be concluded that SM results with the same conditions are comparable, and the efficiency of different SM were approximately the same (i.e., codes and CT dose calculators). However, it is expected that using CT dose calculators will be dominant method for assessing CT dose in the near future. This is because of the significant progress achieved in these CT dose calculators and the ease of use, compared to simulation codes. Even though Adequate studies were found, conducting studies for specific subjects are recommended.

Recommendations

It is recommended to obtain simulated organ doses rather than simulated effective, as it is easy to drive the effective dose, if the equivalent or absorbed dose is obtained, whereas the opposite cannot be performed. More studies are recommended to investigate the results of SM with applying different variables, such as tissue weighting factors and conversion factors. Additional studies are recommended to compare the results from different CT dose calculators. This is to find the accurate difference in their results and to contribute significantly to the development of SM. Also, it is useful to conduct studies in estimation of radiation dose for blood circulation and cancer risks.

Financial Support and Sponsorship

None.

Conflict of Interests

There is no conflict of interest in this study.

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