Radiography 30 (2024) 1–5

Contents lists available at ScienceDirect

Radiography

journal homepage: www.elsevier.com/locate/radi

Evaluation of organ and effective doses using anthropomorphic phantom: A comparison between experimental measurement and a commercial dose calculator

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ARTICLE INFO

Article history:
Received 10 August 2023
Received in revised form
2 October 2023
Accepted 3 October 2023

Keywords:
Computed tomography
Organ dose
Effective dose
TLD
Anthropomorphic phantoms

ABSTRACT

Introduction: The aim of this study was to experimentally measure organ doses for computed tomography (CT) procedures using thermoluminescence dosimeters (TLDs) on a RANDO anthropomorphic phantom and verify the measured doses using CT-Expo software.
Methods: The phantom was irradiated using clinical CT scan protocols routinely used for specific procedures in the radiology department. Fifty TLD chips were used in this study. The scanning parameters (kVp, mA, s) used to scan the phantom were used as input parameters for CT-Expo dose estimations.
Results: The TLD measured organ doses varied between 3.97 mGy for the esophagus and 56.22 mGy for the brain. High doses were recorded in the brain (37.80–56.22 mGy) and the eye lens (29.94–36.16 mGy). Comparing the organ dose measurements between TLD and CT-Expo, the maximum organ dose difference was obtained for the eye lens. A comparison between the two methods for the other organs were all less than 32 %. The effective doses from the TLD measurements for the head, chest, and abdominopelvic CT examinations were 2.78, 6.67, and 17 mSv, respectively and CT-Expo were 2.20, 10.30, and 16.70 mSv, respectively.
Conclusion: The experimental and computational results are comparable, and the reliability of the TLD measurements and CT-Expo dose calculator has been proven.
Implications for study: A reason for the difference in dose measurements between the two methods has been attributed to the dissimilarity in the organ position in the Rando anthropomorphic phantom and the standard mathematical phantom used by CT-Expo. The experimental and computational results have been found to be comparable.

Introduction

Computed tomography (CT) is a noninvasive imaging modality that uses X-ray equipment to generate cross-sectional images of the body. This modality has become an important imaging technique since its introduction into clinical practice in the 1970s.[1] Over the past few years, there has been significant increase in the use of CT scanners around the world.[2,3] In Ghana, where this study was performed, 11 CT scanners were reported by Inkoom et al., in 2011.[2] In 2020, Botwe et al., indicated in their study that 35 CT scanners were authorized to operate in Ghana.[4,5]

The significant concern associated with the proliferation of CT scanners is the increased radiation exposure incurred by patients.[6] Although there is sufficient evidence of the benefits of medical exposure to patients, there is a need for regular review of the principles of justification and optimization.[7] Measuring the energy deposited in a tissue/organ directly within a patient is not possible in clinical settings. However, experimental measurements using dosimeters, anthropomorphic phantoms, and computational approaches are recommended in CT dosimetry.[8]

Three radiation dose estimation approaches, namely biological dosimetry (using biological samples), Monte Carlo computational method, and physical measurements with thermoluminescence dosimeters, have been embraced.[9,10] Each approach has its

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https://doi.org/10.1016/j.radi.2023.10.003
1078-8174/

advantages and disadvantages. Anthropomorphic phantom measurements with dosimeters have been an important and reliable method for organ dose estimation over the past three decades.[9,11] Patient dosimetry is currently considered a vital part of the quality assurance procedure, in addition to radiological audits and optimization. Knowledge of the amount of radiation delivered to patients undergoing CT examination is the first step in dose optimization and has become relevant in quality assurance over the past few decades.[12] Organ doses are usually directly measured by placing TLDs in significant radiosensitive organs in an anthropomorphic phantom, such as the RANDO phantom.[13] The aim of this study was to experimentally measure organ doses using TLDs on a RANDO anthropomorphic phantom and compare the measured dose with the corresponding organ doses obtained using CT-Expo software.

Materials and methods

Materials

The materials used for the study included a CT scanner, a RANDO anthropomorphic phantom, TLDs, and CT-Expo software. The RANDO anthropomorphic phantom (Fig. 1) is composed of a natural human skeleton cast inside soft tissue-simulating material.[14] The lungs were constructed to fit inside the contours of the natural ribcage. The male phantom have a total body length of 175 cm and weighed approximately 73.5 kg. It was sliced into 33 axial slices, 1-32−2.5 cm in thickness, and slice 33, which is the last slice beneath the male gonads, was 7.5 cm thick. The head, chest and pelvis length were 26.3, 31.5 and 21.5 cm respectively. This was compared to the Adam mathematical phantom in CT-Expo.

The TLDs used in this study were LiF chips doped with Ti and Mg (LiF: Ti, Mg). The dosimeters are generally used for patient dosimetry in diagnostic radiology because of its physically small nature and sensitivity.[15]

CT-Expo version 2.5 (SASCRAD, Fritz-Reuter-Weg, Buchholz, Germany) was used to estimate radiation doses to patients from CT scans. All essential dose quantities, such as the volume CT dose index ($CTDI_{vol}$), dose length product (DLP), and effective dose (ICRP 60 and ICRP 103), were estimated using CT-Expo.[16] The software provides sex-specific dose calculations for adults and pediatrics and is applicable to almost all scanner models available in recent times.[16] A 64 slice CT 660 Optima scanner (GE Healthcare) was used in this study.

Figure 1. The RANDO anthropomorphic phantom.

Methods

The TLD chips were placed at organ sites within the RANDO anthropomorphic phantom, based on the manufacturer's specified organ location. We evaluated how the TLDs were prepared before they were used for field measurements. TLDs are initially annealed using the Harshaw 6600 plus TLD reader and exposed on a water phantom (torso) to 2 mSv at 1 m using Cs-137 source in SSDL. They are then read to establish their reader calibration factor (RCF) and element correction coefficients ECCs with acceptable limits of ± 30 % deviation.

A minimum of four (4) TLDs were placed in each organ, and the number was determined by organ size and relative radiosensitivity.[8] The phantom was irradiated using clinical CT scan protocols routinely used for specific procedures in the radiology department. The TLDs were stored in a black zip-lock bag and read within 48 h of exposure.

It was impossible to place TLDs for dose measurements in certain organs, such as the thymus, salivary glands, and bone marrow, because of the complexity of the human anatomy and structure of the phantom.[17] The TLDs were read out using a Harshaw Model 6600 TLD reader.

The organs considered for the phantom measurement for each CT examination were:

a. Brain and eye for head CT examination
b. Heart, lungs, breast, and esophagus for chest CT examination
c. Liver, bladder, stomach, and gonads for abdominopelvic CT examination

The tube potentials of the scanner are 80, 100, 120, and 140 kV. Phantom measurements were performed on the CT scanner with the following parameters:192 mAs/140 kV for head CT, 48 mAs/120 kV for chest CT and 120 mAs/120 kV for abdominopelvic CT. The parameters extracted include kV, mA, exposure time, pitch, scan length, and collimation, which were required as input parameters for dose estimation by CT-Expo. Table 1 lists the parameters used to scan the phantom for each CT examination.

The scanning parameters used to scan the phantom were used as input parameters for CT-Expo dose estimations, and CT-Expo software version 2.5 was used for dose estimation. The CT-Expo software uses tables of pre-calculated data derived from Monte Carlo simulation to transport radiation in the computational phantom.[3] It provides an automatic output calculation of organ-equivalent doses to the organs based on the specific scanner model, manufacturer, and scanning parameters as input data.[18]

Table 1
Scanning details for the anthropomorphic CT examination.

Parameter	Head CT	Chest CT	Abdominopelvic CT
Tube voltage (kV)	140	120	120
Tube current (mA)	240	60	150
Tube rotation time (s)	0.8	0.8	0.8
Average effective mAs	192	48	120
$CTDI_{vol}$ (mGy)	48.89	4.20	10.40
DLP (mGy cm)	1466	108	399

Table 2
TLD measured organ doses for the RANDO anthropomorphic phantom.

Examination	Organ	No. of TLDs	Organ Dose (mGy)			
			Minimum	Maximum	Median	Mean (±SD)
Head CT	Brain	6	37.80	56.22	45.95	47.48 ± 8.27
	Eye lens	4	29.94	36.16	31.69	32.37 ± 2.94
Chest CT	Heart	6	5.00	8.42	7.29	6.99 ± 1.20
	Breast	4	4.22	6.57	5.61	5.50 ± 1.07
	Lungs	6	5.31	6.46	5.65	5.83 ± 0.43
	Oesophagus	4	3.97	6.58	4.97	5.12 ± 1.11
Abdominopelvic CT	Liver	6	9.81	14.62	11.02	11.61 ± 1.92
	Bladder	6	9.49	16.85	12.30	12.43 ± 2.70
	Stomach	4	14.13	16.69	15.82	15.62 ± 1.23
	Gonads	4	13.03	17.23	15.53	15.33 ± 1.84

Effective doses were assessed on an anthropomorphic phantom for head, chest, and abdominopelvic CT examinations using the effective dose conversion coefficient[3] and CT-Expo.[8]

Results and discussion

Organ doses were directly measured from the RANDO anthropomorphic phantom for the selected radiosensitive organs. TLD dose measurement was necessary to validate the computational algorithm employed in this study.[19] These parameters were consistent with the clinical protocols used for scanning patients in the radiology department. The head CT protocol applied the highest voltage and current of 140 kV and 240 mA, respectively.

Table 2 presents the results from the TLD measurements and the number of TLDs used for measuring the organ doses for each scan. A total of 50 TLD chips were used for each complete scan.

The TLD measured organ doses varied between 3.97 mGy for the esophagus and 56.22 mGy for the brain. High doses were recorded in the brain (37.80–56.22 mGy) and the eye lens (29.94–36.16 mGy). This was due to the high kV and mA parameters used for head CT examinations, as shown in Table 1. Similar observations were obtained by Gharbi et al. (2018) and Breiki et al. (2008) who identified high doses in the brain and eye lens, which ranged between 40.5 and 97.9 mGy.[20] However, Nikupaavo et al. (2015) reported in their study an eye lens dose of 3.1–20.9 mGy, which was less than that measured in this study.[21] Their study recommended the use of supraorbital gantry tilt to reduce eye lens dose up to about 18 %. The TLD-measured doses followed a trend similar to that reported by Chang et al. (2010) and Paul et al. (2012).[22,23] Some of the dose differences could be a result of the varied positioning of the TLDs in the phantom and organ locations.[24]

Measured and simulated organ doses

This section presents and discusses the directly measured organ doses using TLDs and the indirectly estimated organ dose using CT-Expo. Comparisons between the direct (TLDs) and computational (CT-Expo) measurements of the RANDO anthropomorphic phantom are presented in Table 3.

Comparing organ dose measurements between TLD and CT-Expo, the maximum organ dose difference was obtained in the eye lens. The differences between the two methods of dose estimation employed in this study were all less than 32 %, with the smallest difference being observed for the stomach. The mean organ dose for the direct measurement was mostly lower than the simulated dose, except for the brain, heart, bladder, and gonads. One of the reasons for the differences in dose measurements between the two methods include the dissimilarity in the organ position in the RANDO anthropomorphic phantom and the standard mathematical phantom used by CT-Expo.[1] Other than position, other reasons could be the shape and size of the organs. Some organs may be located on the border of the RANDO anthropomorphic phantom, whereas in the mathematical phantom, the organ may be located completely inside the phantom and vice versa.

Table 3
Mean organ doses from the TLD measurements and the CT-Expo.

Examination	Organs	Number of TLDs	Organ Dose (mGy)	
			TLDs	CT-Expo
Head CT	Brain	6	47.48 ± 8.27	36.30
	Eye lens	4	32.37 ± 2.94	42.60
Chest CT	Heart	6	6.99 ± 1.20	5.10
	Breast	4	5.50 ± 1.07	6.80
	Lungs	6	5.83 ± 0.43	6.00
	Oesophagus	4	5.12 ± 1.11	6.50
Abdominopelvic CT	Liver	6	11.61 ± 1.92	15.20
	Bladder	6	12.43 ± 2.70	10.29
	Stomach	4	15.62 ± 1.23	15.50
	Gonads	4	15.33 ± 1.84	12.81
	Total =	50		

Because the anthropomorphic phantom is composed of removable slices, there is a small gap between the adjoining slices of the phantom. Fig. 2 displays a head topogram of the phantom, with small gaps in the head phantom. It was almost impossible to completely eliminate these gaps, which can cause inaccuracies in the TLD dose measurements owing to decreased attenuation.[19]

In addition, there were some inaccuracies in simulating the exact scan length from the TLD measurements to the CT Expo for dose estimation.[25] The slight difference in the scan length between the two methods could have also contributed to the dose variation.

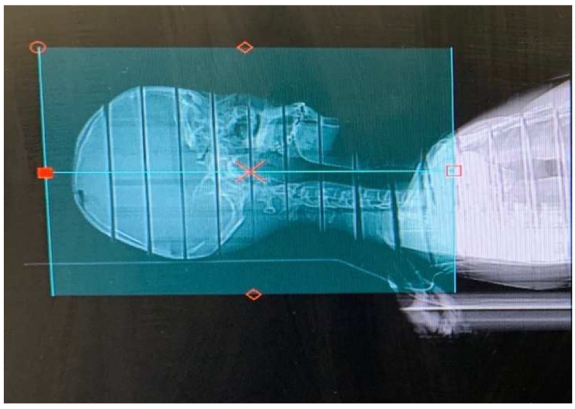

Figure 2. Topogram of the head of the RANDO anthropomorphic phantom.

Table 4
Effective dose from conversion coefficient and CT-Expo.

Examination	Effective dose (mSv)	
	DLP-E (k)	CT-Expo
Head CT	2.78	2.20
Chest CT	6.67	8.30
Abdominopelvic CT	17.39	16.70

Effective dose from the RANDO anthropomorphic phantom

Although it is well documented that the effective dose from head CT is generally lower than that from chest and abdominopelvic CT, the radiosensitive organs in the head (brain and eye lens) received a higher dose than the other organs under consideration. Jaffe et al., in their study, indicated that a typical effective dose for the head CT ranged between 1.22 and 1.86 mSv.[26,27] Furthermore, AAPM (2017) reported that the approximate effective dose to the head was 1.6 mSv, whereas the effective doses to the chest and abdominopelvic were 6.1 and 7.7 mSv, respectively.[28] Table 4 shows the effective dose obtained from the RANDO anthropomorphic phantom. The DLP data from the TLD measurements were used to estimate the effective doses in the case of the conversion coefficient method, whereas the scan parameters were used to estimate the effective doses in the case of CT-Expo. The effective doses from TLD measurements were 2.78, 6.67, and 17.39 mSv for the head, chest, and abdominopelvic CT examinations, respectively. The corresponding effective doses for CT-Expo were 2.20, 10.30, and 16.70 mSv.

The estimated effective doses by conversion coefficient and CT-Expo methods for all three examinations considered were quite comparable (<25 %), and each was within the ±40 % tolerance, as reported by Brady et al.[8] The highest difference was observed in chest CT and smallest in abdominopelvic CT. CT-Expo's estimated effective doses for the head and abdominopelvic regions were lower than the corresponding estimates in the conversation coefficient method, in agreement with the observation reported by Brady et al.[8] that CT-Expo produces lower dose estimates due to underestimation.[8] This underestimation may occur due to over-ranging effects that are not integrated into CT-Expo.[8]

Groves et al. also reported that the effective dose from TLD was 18 % higher than that from the computational method,[29] and this was attributed to the differences between the RANDO anthropomorphic and mathematical phantoms.

Conclusion

An experimental technique using TLDs and a computational technique using CT Expo were employed in this study to evaluate organ doses in an anthropomorphic phantom for three different CT examinations. The experimental and computational results are comparable, and the reliability of the TLD measurements and CT-Expo dose calculator has been proven. In summary, dose estimations from TLD measurements within an anthropomorphic phantom and CT-Expo dose calculations are both effective methods for estimating doses for patients undergoing CT examinations.

Funding

No direct funding was received for this work.

Availability of data and material

The data that was used to prepare the manuscript is available upon request.

Ethical approval

This study received ethical approval from the Ethics Review Committee of the Ghana Health Service under protocol number GHS-ERC 012/05/19.

Code availability

Not applicable.

Authors' contributions

All the authors contributed to the various stages of the study and the manuscript preparation.

Conflict of interest statement

None.

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