

Organ Dose Measurement in Computed Tomography Using Thermoluminescence Dosimeter in Locally Developed Phantoms

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ABSTRACT

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Introduction: Organ dose estimation using thermoluminescence dosimeter (TLD) is known to be a standard, although many other methods, such as simulation software, optically stimulated luminescent dosimeters, and photodiodes are still in use. This study aimed at directly measuring mean organ doses to the selected organs in the head/neck, chest, and abdominal regions from four computed tomography (CT) units in Lagos, southwest of Nigeria.

Material and Methods: This study was conducted on locally constructed inhomogeneous phantoms to measure mean organ doses to the head/neck, chest, and abdominopelvic regions from CT units in the Lagos metropolis, Nigeria. Lithium fluoride doped with magnesium and titanium (LiF: Mg, Ti) TLD was used for the measurement. Statistical analysis was performed by IBM SPSS (version 20).

Results: Validation of the designed phantoms was below $\pm 20\%$ kVp and mAs parameters among the CT units, which was statistically different with regard to the observed dose discrepancies. Generally, a one-way ANOVA showed that there was a statistically significant difference in the investigated mean organ dose ($P = 0.043$). The comparison of the obtained results from this study with those of other studies revealed that there was no statistically significant difference in the TLDs ($P > 0.05$). The maximum relative difference in the dose was $< 200\%$.

Conclusion: The designed phantoms seemed to be useful for CT dose validation and could be used to validate simulation software in areas where readymade phantoms are not available.

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Introduction

Computed Tomography (CT) is one of the most widely used medical imaging modalities in clinical use. Moreover, it is increasingly used because of its sophisticated image quality and projections that technological advancement has brought to it [1, 2]. However, medical imaging from CT examinations has one of the highest patient radiation dose [3, 4, 5]. Therefore, CT dose measurement is becoming increasingly important for the protection and optimization of patients. The most practical way to prospectively determine the radiation dose absorbed by the organs and tissues of the body during a CT examination is either the direct or indirect method of measuring organ doses. In the direct method, radiation is assessed through the measurement of organ dose on physical phantoms by using an ionization chamber or small sized dosimeters, such as thermoluminescence dosimeters (TLDs) and optically stimulated luminescent dosimeters (OSLDs) [6- 9].

However, the second method is a virtual simulation or indirect measurements with the use of special computer software, such as CT-EXPO, CT DOSE, ImpactDose, Virtual Dose, Impact CT dosimetry calculator among others.

Most of the anthropomorphic phantoms constructed by using tissue equivalent materials have been utilized to denote the attenuation features for studies on radiation dosimetry and the physical explanation of the body structure. Anthropomorphic phantoms are popularly used by researchers [10- 12] to measure organ dose as well as determining the effective dose and average organ doses in CT [13, 14]. The use of physical phantoms in measuring organ dose offers more benefits over computational methods because it needs no knowledge of the irradiation geometry or the exact photon energy spectrum. However, one of its disadvantages is that a physical phantom is a representation of an average

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patient size, so organ depth and shape might be different from that of a human [15]. Anthropomorphic phantoms are not readily available in Nigeria, which may be due to their high prices. Therefore, in order to overcome this challenge, an inhomogeneous head and body phantoms were constructed and used for organ dose measurement in the current study.

The aim of this study was to estimate mean organ doses to the selected organs in the head/neck (brain, thyroid, esophagus and eye lens), chest (heart and lungs), and abdominal (stomach, liver, and kidney) regions from four CT units in Lagos metropolis by using TLDs in locally constructed inhomogeneous head and body phantoms. The results of the mean organ doses were analyzed and compared among the four CT units. Additionally, the values of the mean organ doses measured in this study were compared with those reported in the published literature.

Materials and Methods

This study was carried out at four different CT units with four CT scanners in Lagos metropolis. The utilized facilities were one Toshiba CT and three General Electric scanners at the four CT units specified as A-D. Table 1 describes the specification of the CT scanners used in this study. The mean organ dose values were obtained by direct measurement, using thermoluminescent dosimeters (TLDs) in the locally constructed inhomogeneous head and body phantoms as shown in Figure 1 and 2.

The phantoms were constructed using a transparent Perspex plastic with a thickness of 3 mm to follow the standard CT dosimetry phantom. The head and body phantoms were cylindrical in shape and were 16 cm and 32cm in diameter, respectively. Each phantom set consisted of had five probe holes; one at the center and the other four around the perimeter, 90° apart and 1 cm from the edge. The probe holes contained tightly compacted bovine tissues, which were used as the organs. Four organs in the head/neck (i.e., brain, eye lens, thyroid, and esophagus), two organs in the chest (i.e., heart and lungs), and three organs in the abdomen (i.e., stomach, liver, and kidney) regions were selected for the measurement. The inhomogeneous phantoms and the probe holes that had no bovine tissues were filled with water as a substitute for soft tissues. Each phantom was tested and verified according to the qualities of the

standard phantom to be qualified for organ dose measurement.

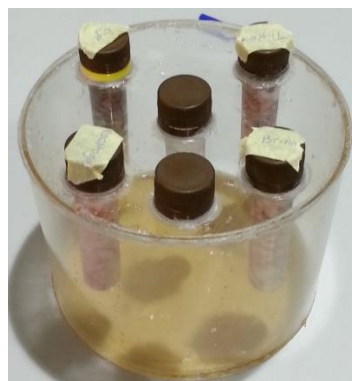


Figure 1. Inhomogeneous head phantom

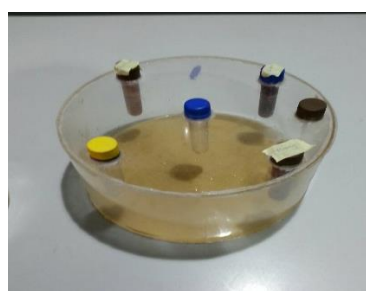


Figure 2. Inhomogeneous body phantom

Lithium fluoride doped with magnesium and titanium (LiF: Mg, Ti) was used in this study. It was manufactured in form of solid pellets, 4.5 mm diameter with a thickness of 0.9 mm. Before exposure, the TLDs were annealed using an automatic reader, Rados RE-2000RT (RadPro Int. Germany) at 400°C for 1hr to remove residual TL, signals at a pre-heating temperature of 100°C for 10 min. The TLD chips were calibrated based on the method described by Akpochafor et al.[16] to preserve the order of identification before irradiation, the TLDs were properly placed in an annealing pan for individual identification and transferred to a plastic holder. The automated RE 2000 reader was used to determine the readout and the response of the TLDs. A dedicated personal computer was linked to the reader to initiate the reading programs as well as the annealing processes.

Table 1. Specification of CT Scanners

Centers	CT scanner model	Manufacturer	Slices	Scan mode/Protocol
A	Aquilion/CXL	Toshiba	128	Helical/ Head, chest, and abdomen
B	Brivo CT 385 series	GE	16	Helical/ Head, chest, and abdomen
C	Brivo CT 385 series	GE	16	Helical/ Head, chest, and abdomen
D	BrightSpeed Edge select	GE	8	Helical/ Head, chest, and abdomen

Table 2. Summary of CT scan parameters

Protocol	CT unit	kV	mA	Slice thickness (mm)	Scan range (mm)	Rotation time (sec)
Head	A	120	220	5	200	0.75
	B	120	197	5	I 106.500-S 73.500	1
	C	120	180	5	I 72.750-S 62.250	1
	D	120	297	10	I 71.750-S 58.250	1
Chest	A	100	290	5	360	0.5
	B	120	179	5	S 102.250-I 62.750	1
	C	120	180	5	S 1.00-I 239.00	1
	D	120	258	10	S 50.00-I 150.00	0.8
Abdomen	A	100	169	5	235	0.5
	B	120	160	5	S 0.250-I 224.750	1
	C	120	160	5	S 105.250-I 62.750	1
	D	120	258	10	S 13.750-I 193.750	1

The response range of the TLDs was determined by the element correction coefficient (ECC) and it was generated as follows:

$$ECC \frac{1}{4} < Q > OQ_i \tag{1}$$

Where,

< Q > is the average charge integral of the TLDs, and Q_i denotes the individual charge integral of the TLDs

In order to generate the reader calibration factor (RCF), a set of TLDs within the ECC range were selected to calibrate the reader. The RCF is derived as follows:

$$RCF \frac{1}{4} < Q_c > OQ_D \tag{2}$$

Where, D refers to the absorbed dose delivered to the TLDs, and < Q > signifies the average corrected charge integral. After the irradiation of TLDs, the responses were saved in a database for calibration for calibration purposes. The database was used to generate the ECCs for the calibration dosimeters. The TLDs with zero dose values higher than 30% - 50 % of the mean zero counts were eliminated. After applying the ECCs of calibration dosimeters, the RCF was generated from the database and stored for future use.

For the measurement of organ dose, three TLDs were placed in each of the probe holes of the phantoms in order to improve the counting statistics. Each of the probe holes contained a specific organ for the different scanning protocols. All scans were performed in helical mode. After exposure, scanning parameters, such as the tube voltage, tube current, rotation time, slice thickness, Computed Tomography Dose Index (CTDI), Dose Length Product (DLP) were recorded (Table 2). The chips were later removed and returned to the laboratory for reading. The TLD was read in photon count and converted to doses by subtracting the background count from the actual thermoluminescence counts and then multiplied with a calibration factor of 4.63×10^{-6} .

Statistical analysis

In this study, Microsoft Excel was used for the data analysis while the statistical analysis was carried out with IBM SPSS (version 20) by performing a one-sample t-test, independent student t-test, and one-way ANOVA were used at a 95% level of significance. $P < 0.05$ was considered statistically significant.

Results

Figure 3 shows a sample of the glow curve generated during the TLD calibration. The locally designed inhomogeneous phantoms were validated and tested. The American College of Radiology (ACR) quality control manual was used, which stipulated that CTDI measurement must be within 20% of the values reported by the scanner. The initial performance test was carried out, in which the standard phantom was within the manufacturer’s specification of $\pm 20\%$. The $CTDI_{vol}$ for the head and body of the locally designed phantom was 47.50 mGy and 12.05 mGy, respectively ($P = 0.057$), while the $CTDI_{vol}$ for head and body of the standard phantom was 57.93mGy and 14.39 mGy, respectively ($P = 0.063$).

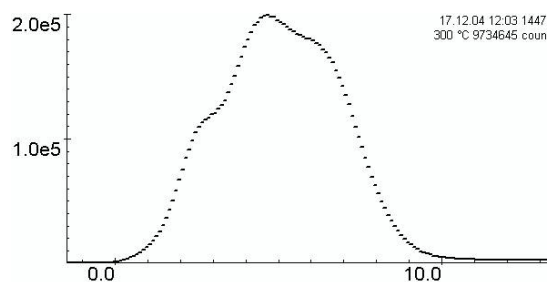


Figure 3. Glow curve obtained from TLD Calibration

The percentage difference between the local and standard phantom was 18% which was within the acceptance range of $\pm 20\%$ as reported by (ACR, 2017 [17]).

The mean doses of organs in the head/neck region for CT units A-D were 34.8, 21.6, 17.2, and 20.5 mGy for brain; 26.9, 40.9, 26.3, and 39.1 mGy for eye lens; 37.3, 40.8, 37.4, and 37.0 mGy for thyroid; and 30.8, 41.7, 34.9, and 26.9 mGy for esophagus, respectively. The obtained results from one-way ANOVA revealed that there was a statistically significant difference between the groups regarding the dose (mGy) to the organs ($F [2, 12] = 3.704; P = 0.043$). On the contrary, the dose to brain and eye lens ($P = 0.190$); brain and esophagus ($P = 0.172$); eye lens and thyroid ($P = 0.711$); eye lens and esophagus ($P = 1.000$); thyroid and esophagus ($P = 0.748$) were not statistically different. The obtained results in Table 3 revealed that the only significant difference was between thyroid and brain.

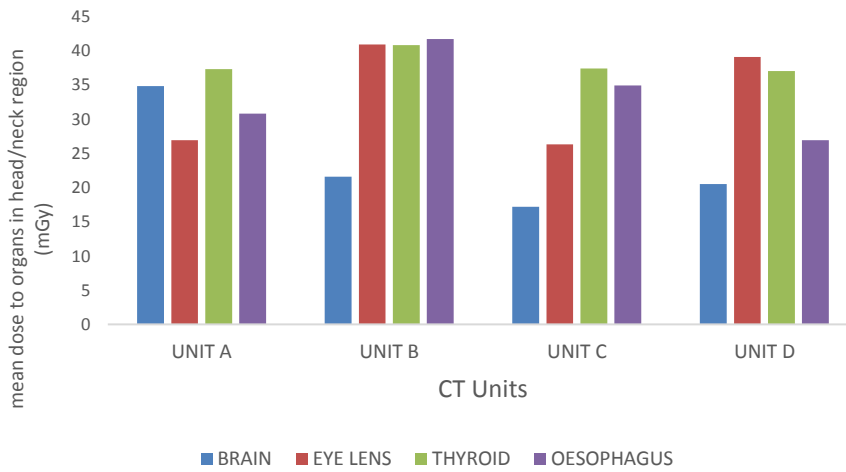


Figure 4. Mean doses to organs in the head/neck region in CT units A-D

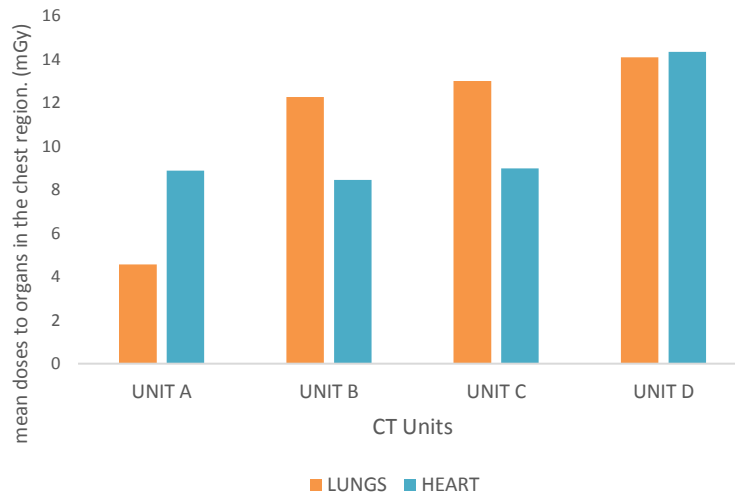


Figure 5. Mean doses to organs in the chest region in CT units A-D

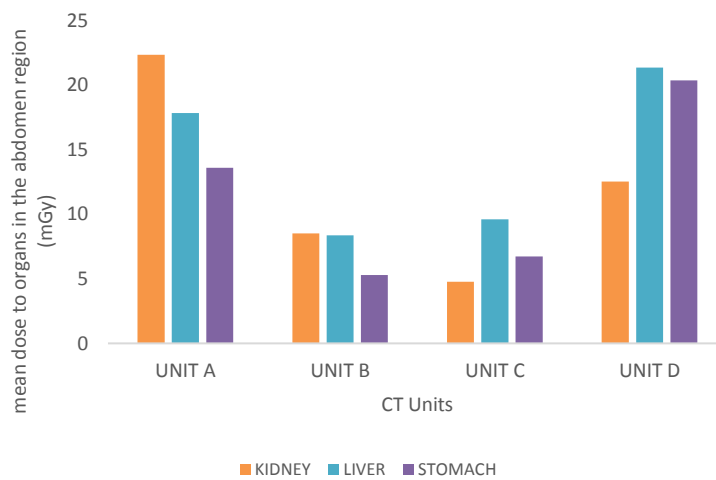


Figure 6. Mean doses to organs in the abdomen region in CT units A-D

The mean doses of organs to the chest region which included heart for the four CT units A-D were 8.87, 8.44, 8.97, and 14.34 mGy; moreover, the means doses for lungs were 4.56, 12.26, 13.00, 14.08 mGy, respectively. However, as it can be seen in Table 4, an independent sample t-test showed that there was no difference in the mean values of heart and lungs ($P=0.762$). With regard to the CT units A-D, the mean doses were 22.36, 8.52, 4.76, and 12.54 mGy to kidney; 17.83, 8.38, 9.61, and 21.35 mGy to liver, and 13.60, 5.29, 6.74, 20.37 mGy to stomach, respectively. The results of a one-way ANOVA showed that there was statistically no difference between dose (mGy) and the above-mentioned organs ($F [2, 9]=0.181$; $P=0.837$). Similarly, the dose to kidney and liver ($P=0.893$); stomach and kidney ($P=0.993$), and liver and stomach ($P=0.840$) were not statistically different (Table 5). Evaluation of CT unit A, B, C, and D for brain, eye lens, thyroid, heart, lungs, kidney, liver, and stomach using one sample t-test showed that organ doses were statistically different when comparing a particular organ ($P<0.05$, figure 4-6).

Table 3. Mean doses for organs in the head/neck region

CT Units	Selected organ	Mean doses (mGy)
A	Brain	34.8±6.1
	Eye lens	26.9±10.2
	Thyroid	37.3±37.3
	Esophagus	30.8±1.8
B	Brain	21.6±4.7
	Eye lens	40.9±4.0
	Thyroid	40.8±8.0
	Esophagus	41.7±1.4
C	Brain	17.2±1.9
	Eye lens	26.3±13.5
	Thyroid	37.4±14.3
	Esophagus	34.9±15.2
D	Brain	20.5±2.5
	Eye lens	39.1±5.0
	Thyroid	37.0±10.0
	Esophagus	26.9±8.5

Table 4. Mean doses for organs in the Chest region

CT Units	Selected organ	Mean doses (mGy)
A	Lungs	4.56±1.22
	Heart	8.87±4.67
B	Lungs	12.26± 1.28
	Heart	8.44±3.40
C	Lungs	13.00±1.30
	Heart	8.97±3.05
D	Lungs	14.08±5.12
	Heart	14.34±7.42

Table 5. Mean doses for organs in Abdomen region

CT Units	Selected organ	Mean doses (mGy)
A	Kidney	22.36 ±1.75
	Liver	17.83 ±2.08
	Stomach	13.60 ±3.70
B	Kidney	8.52 ±1.53
	Liver	8.38±3.35
	Stomach	5.29±3.09
C	Kidney	4.76±1.15
	Liver	9.61±3.80
	Stomach	6.74±0.99
D	Kidney	12.54±4.36
	Liver	21.35±5.23
	Stomach	20.37±6.06

Discussion

The obtained results of one-way ANOVA showed that the CT scan parameters were statistically significant differences in kVp against mAs, slice thickness and rotation time, as well as mAs against slice thickness and rotation time among CT unit A-D ($P < 0.05$). However, there were no statistically significant differences in slice thickness and rotation time in CT unit A ($P=0.998$), B ($P=0.949$), C ($P=0.830$), and D ($P=0.761$). Discrepancies in the mean doses to the particular organs among the four CT units were due to the differences in the position of the phantom in the CT gantry, as well as the differences in the placement and orientation of TLDs in the phantom during exposure.

Table 6. Comparison of mean organ doses and percentage differences in the current study with international studies

Organs	This study	Cakmak et al. (Turkey) [19]	RD (%)	Groves et al. (UK) [20]	RD (%)	Nishizawa et al. (Japan) [21]	RD (%)	Akpochafor et al. (Nigeria) [23]	RD (%)	Ngalie et al. (Tanzania) [24]	RD (%)
Brain	23.5	38.00	47	39.1	50	-	-	27.87	17	55.09	80
Eye lens	33.3	47.80	36	-	-	22.40	39	55.00	49	63.90	63
Thyroid	38.1	64.30	51	21.8	-	0.55	194	-	-	2.5	175
Esophagus	33.6	-	-	-	-	-	-	-	-	-	-
Lungs	10.98	48.30	125	19.3	54	19.60	56.30	30.63	94	31.50	97
Heart	10.16	35.70	111	-	-	-	-	-	-	-	-
Kidney	12.05	10.02	18	25.30	73	-	-	-	-	-	-
Liver	14.30	14.10	0.7	25.50	56	64	126	33.06	79	34.1	82
Stomach	11.50	-	-	23.80	70	80	150	34.00	99	35.60	102

RD = Relative Difference

Many studies have reported the effect of kVp, mAs, and slice thickness as part of parameters that could affect dose at any given point in a medium. Ekpo et al [18] reported a significant difference in the kVp and

pitch between the two CT scanners which were used to determine CT dose index, DLP, organ, and effective dose, which have contributed to the observed dose discrepancies.

With regard to TLDs, the comparison of the current study and the one carried out by Cakmak et al [19] revealed that there was no statistically significant difference in mean organ doses obtained in the brain, eye lens, thyroid, lungs, heart, kidney, and liver ($P=0.075$), although the range of the relative differences was between 0.7-125%. Similarly, the comparison of mean organ doses (brain, thyroid, lungs, kidney, and liver) between the current study and the study conducted by Groves et al [20] (16-CT slices with TLDs) showed no statistically significant difference ($P=0.326$) and the maximum relative difference between the current study and the one by Groves et al was 73%. Moreover, the comparison of the current study and a study performed by Nishizawa et al [21] revealed that the mean dose to the eye lens, thyroid, lungs, liver, and stomach were not statistically different ($P=0.355$), the maximum relative difference between these two studies was 194%, which was twice more than the results obtained in the study by Groves. Nishizawa et al made use of BeO TLD and the CaSo₄ TLD which were more sensitive than the LiF: Mg, Ti. This difference in detectors can contribute to dose variations, as well.

The overall mean relative difference in dose between the chest and head/neck was 100%. Similarly, the relative difference between the chest and abdomen was 34.5% and that of the head/neck and abdomen was 87%.

Regarding mean organ dose (10.98 mGy) and dose range (4.56-14.08 mGy) to the lungs, liver, and stomach, the comparison of the results between the current study and a study conducted by Sinclair [22] showed the difference of 43.6, 38.9, and 64%, respectively. In the study by Sinclair, there was a use of eight cadaver subjects with OSLDs with a mean dose of 17 mGy and dose range of 11.4-21.9 mGy to the lungs. Mean organ dose was also compared between this study and the current one for lungs, liver, and stomach, and the findings revealed that there was a statistically significant difference in dose ($P=0.013$). In spite of the reduced relative dose differences, there was still a difference in the mean dose.

With regard to the tools of the study, the findings revealed there was a significant difference between the current study and the studies conducted by Akpochafor et al. [23] and Ekpo et al., in which the imPACT dosimetric calculator and CT-Expo software were employed ($P=0.027$; $P=0.021$, respectively). However, there was no difference between the current study and the one conducted by Ngaile et al., [24] although the imPACT dosimetric calculator was used ($P=0.158$). The maximum relative difference among the current study, Akpochafor et al., Ngaile et al., and Ekpo et al. were 99,175 and 105.2%, respectively. In a study by Poletti et al. [25], the dose difference of 200% or 300% was at peak dose by using a cylindrical phantom. Relative differences in organ doses between the current study and other studies were seen in Table 6 to be below 200%. This study has shown that a comparison of organ dose using TLDs was more accurate. Invariably, studies that

used similar CT with multiple methods to determine dose had lower relative differences.

Conclusion

The mean organ dose among the four CT units in Lagos, southwestern Nigeria was determined by using an inhomogeneous phantom with TL dosimeter (LiF: Mg, Ti). This study has shown that relative difference in dose could be associated with the individual CT parameters, which were mainly observed in kVp, mAs, slice thickness, and rotation time. Generally, there were differences in dose among the four CT units. The comparison of this study with other similar ones, where TLDs were used, revealed no significant difference. Differences in mean dose were observed with simulation software. Relative dose differences were generally below 200%. This study would be highly useful in validating simulation software in the southwest of Nigeria since TLD measurement in this study and other studies are statistically not different.

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