ORIGINAL ARTICLE

Assessing the Difference between Equilibrium Dose and CTDI in Effective Dose Estimation

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Abstract

Purpose: The dose of Computed Tomography (CT) scan exams consists of a large proportion of all medical imaging modalities' dose burdens. There are different methods to measure and describe radiation in CT. A standardized way is to measure the Computed Tomography Dose Index (CTDI). However, due to the increase in the detector system size along the z-axis in new CT scanner generations, new measurement methods are described in the American Association of Physicists in Medicine-Task Group No.111(AAPM-TG111). This study aims to estimate the equilibrium dose and compare it with the amount displayed in the volume Computed Tomography Dose Index ($CTDI_{vol}$) at the end of each exam. Eventually, the effective dose was calculated for both methods.

Materials and Methods: Using a pencil ionization chamber and standard polymethylmethacrylate (PMMA phantom), the following values were calculated: $CTDI_{100}$, $CTDI_{vol}$, cumulative dose, equilibrium dose, and effective dose.

Results: Six protocols performed in two centers, and the results indicated that the measurements with a standard CT dosimetry phantom, was varied between average equilibrium dose and $CTDI_{vol}$, and the discrepancies ranged between 27% to 33%.

Conclusion: The $CTDI_{Vol}$ is not suitable for evaluating the radiation dose at the end of each scan, and the use of an equilibrium dose for dosimetry of new systems is recommended.

Keywords: Multidetector Computed Tomography; Equilibrium Dose; Computed Tomography Volume Dose Index, American Association of Physicists in Medicine-Task Group No.111; Radiation Dosimetry.

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1. Introduction

Computed Tomography (CT) is an essential imaging modality that utilizes an X-ray beam for diagnostic purposes. The various CT scan generations, from a Single-Detector (one slice) Computed Tomography (SDCT) to present Multidetector Computed Tomography (MDCT), widen the range of clinical applications of CT scans [1, 2]. However, the growing number of exams performed by CT scans and the amount of ionizing beam exposed to patients contribute to a high proportion of the collective effective dose that impacts the population's health [3-9]. There are concerns about the amount of radiation exposure during CT exams, as it is about ten times higher than other diagnostic procedures like radiography. This increased radiation exposure poses a small but significant cancer risk to the general population [4, 7, 10]. Referring physicians should be aware of the potential risks of CT scans and choose this modality only if the potential benefits outweigh the disadvantages [10]. There are various strategies to limit radiation dose by following the ALARA (As Low as Reasonably Achievable) principle, including restricting the examinations to the utmost necessary ones, adjusting CT scan settings based on the indication of the individuals, and limiting the region of exposure.

There are different methods to measure and describe radiation in CT scans. A standardized way is to measure the Computed Tomography Dose Index (CTDI) [8, 11]. $CTDI_{100}$ denotes the incorporated dose along the long axis (z-axis) from a single axial CT scan, and the value was measured with a 100 mm long pencil ionization chamber positioned in the CT head and body phantom [11-13]. However, in the last decade, several severe practical issues regarding CTDI were brought about when the 100-mm pencil CT ionization chamber was utilized to measure CTDI for wide-cone-beams CT and MDCT with a high number of rows [11]. With the new generation of CT scanners, the pencil chamber is too short to measure all the primary radiation, and the increase in length of the detection system along the z-axis makes cone-beam irradiation geometries $CTDI_{100}$ unreliable [2, 14-18]. Furthermore, the measured values of $CTDI_{100}$ are underestimating the accumulated dose at the center of the MDCTs. This is due to the fact that they do not consider the contribution of the dose profile "tail" which is caused by the scattering in the phantom or tissue [2, 14, 15, 17-20]. The AAPM (American Association of Physicists in Medicine) Task Group Report No. 111 describes new methods for measuring radiation using a small ion chamber instead of the usual pencil-shaped chamber. In order to ensure that the chamber accurately measures the absorbed dose, a new position for a phantom is suggested to establish dose equilibrium at the chamber's location [20].

A challenge in implementing this methodology to measure the equilibrium dose is the length of the phantom, which should be at least 400 mm [19, 21].

In this study, we calculated the equilibrium dose using standard CT dosimetry phantoms (typically 16 cm in length and 32 cm in diameter) on the MDCT_64 slice [19]. The objective of this study is to determine the equilibrium dose and compare it with the dose displayed in the Computed Tomography Dose Index ($CTDI_{vol}$) by the CT scanner after each scan. In addition, the effective dose was calculated for both methods.

2. Materials and Methods

2.1. Equipment

In this study, we used Philips-MDCT-64 slice and Light Speed VCT-MDCT-64 Slice CT Scanner along with a pencil-shaped ionization chamber (Piranha X-ray Analyzer, RTI Electronics, Sweden) that had an active length of 100 m. The accuracy and uncertainty of the chamber were 5%, and it was calibrated in the Secondary Standard Dosimetry Laboratory. We used a Polymethylmethacrylate (PMMA) phantom with a diameter of 32 cm, a length of 16 cm, a density of 1.13 g/cm3, and an effective atomic number of 6.48 for measurements. The closeness of the effective atomic number of the phantom to tissue makes it very suitable for dosimetry.

To expose the phantom, we applied the most frequently used protocols available in the two centers including radiation conditions to calculate the CTDI values Dose (Table 1).

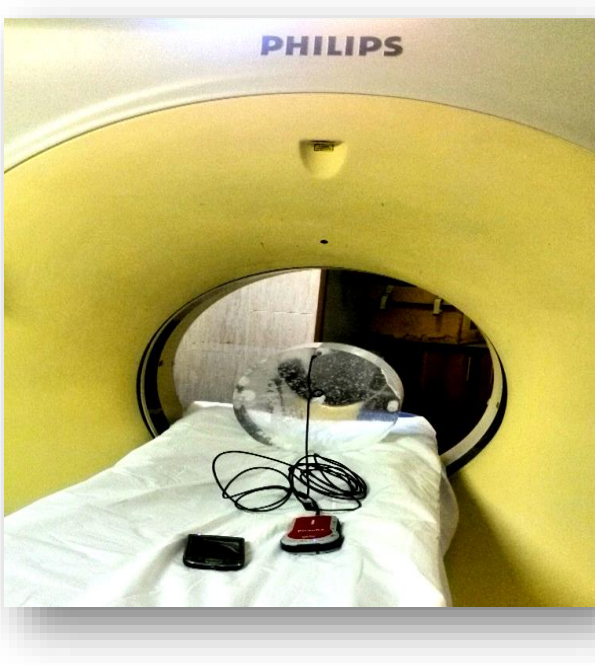

Figure 1. Picture of the measurement setup

2.2. Calculations of the Computed Tomography Dose Index

Figure 1 shows a picture of the measurement setup. The chamber was inserted three times into the central hole and three times into the phantom's peripheral hole, and the corresponding readings of each position were recorded. The Weighted Computed Tomography Index Dose ($CTDI_w$) was then determined based on the following formula (Equation 1):

$$CTDI_w = (\frac{1}{3} CTDI_C) + (\frac{2}{3} CTDI_P) \quad (1)$$

The CTDIc value represents the dose index in the central hole, while the CTDIp value represents the dose index in the peripheral hole of the phantom. Then, we calculated the volume of CTDI and Dose Length Product (DLP) using Equations 2 and 3, respectively.

$$CTDI_{vol} = CTDI_w/pitch \quad (2)$$

$$DLP = CTDI_{vol} \times \text{irradiated length} \quad (3)$$

The final step involved calculating the effective dose using the following formula (Equation 3):

$$\text{Effective dose} = k \times DLP \quad (4)$$

k-factor for the body is 0.015 (mSv. $mGy^{-1}.cm^{-1}$) [22, 23].

2.3. Equations for Calculating the Equilibrium Dose

Equilibrium dose (D_{eq}) was calculated from $CTDI_{100}$ and $\epsilon(CTDI_{100})$ ($CTDI_{100}$ efficiency), and cumulative dose ($DL(0)$) was calculated from D_{eq} and the approach to equilibrium function ($H(L)$)[17, 20]

The calculations are based on $CTDI_{100}$ efficiency [15, 24] (Equation 5).

$$\epsilon(CTDI_{100}) = CTDI_{100}/CTDI_{\infty} \quad (5)$$

$CTDI_{\infty}$ is an infinite integration length, sometimes called the ideal CTDI [25].

The dose at the midpoint of the scan range in CT scanning can be computed by (Equation 6):

$$D_L(0) = H(L) \times D_{eq} \quad (6)$$

Both Equations 5 and 6 are valid on the central and peripheral phantom axes.

The Equilibrium function is related by (Equation 7) [26]:

$$H(L{=}100\text{ mm}) = \epsilon\ (CTDI_{100}) \times (1 + \delta) \quad (7)$$

where δ characterizes the difference between two phantom lengths (15 cm and infinity) and $\delta \approx 0.08$ (32-cm phantom center) or ≤0.02 (32-cm phantom periphery) [17, 24].

The equilibrium dose product is given by [21] (Equations 8, 9).

$$D_{eq,C} = (3R_{100}/(2 + R_{100}))\times (CTDI_{Vol}/\epsilon(CTDI_{100,C}))\times \text{pitch} \quad (8)$$

$$D_{eq,P} = (3/(2 + R_{100}))\times (CTDI_{Vol}/\epsilon(\ (CTDI_{100,P}))\times \text{pitch} \quad (9)$$

Where *C* is the center, and *P* is the periphery.

R_{100} is also useful for predicting the central to peripheral D_{eq} ratio (Equation 10):

$$R_{100} = CTDI_{100,C}/CTDI_{100,P} \quad (10)$$

The planar average equilibrium dose was calculated by [20] (Equation 11)

$$D_{eq} = \frac{1}{2}D_{eq,C} + \frac{1}{2}D_{eq,P} \quad (11)$$

A patient's radiation risk can be predicted using the effective dose obtained by multiplying the planar average equilibrium dose with the scanning length and a conversion coefficient ("k").

2.4. Statistical Analysis

Statistical data analysis was performed using IBM SPSS (IBM SPSS Statistics for Windows, version 16.0., IBM Corp., NY, USA). The findings were calculated using mean value. As the normality test was not rejected, a pair T-test was used to compare the differences between the two groups. Statistical significance was defined at a level of 5%.

3. Results

Table 2 provides the values of $CTDI_{Vol}$ and the effective dose for six protocols. These were obtained using a 64-slice MDCT scanner at A and B centers.

The values for the cumulative dose, equilibrium dose, and the effective dose calculated with them in the two centers are expressed in Table 3.

For a better comparison, Table 4 shows the results of equilibrium dose, $CTDI_{vol}$, and differences between them for all protocols.

4. Discussion

In our study, we compared two methods for estimating the effective dose for a CT examination: first, the simpler mathematical approach determined by the volume of CTDI and $CTDI_{vol}$ to the DLP and a DLP to an effective dose, and second, the planar average equilibrium dose. We then utilized the PMMA standard phantom and pencil ionization chamber and calculated the values of $CTDI_{100}$, $\epsilon(CTD_{100})$, $CTDI_{vol}$, cumulative dose, equilibrium dose, and effective using the $CTDI_w$ equations, which measure the dose profile in the center and peripheral section of the ionizing chamber [27]. Based on our findings, differences between the average equilibrium dose and $CTDI_{vol}$ ranged between 27 - 33% in 6 protocols performed with a standard CT dosimetry phantom in two centers. This may be because the $CTDI_{vol}$ cannot include the dose profile "tail" contribution caused by scattering in the phantom.

Table 1. Details about the parameters used for routine scans in two different centers

Centers	CT scan type	Protocols	kVp	mAs	Slice thickness (mm)	Pitch
A	Light speed VCT -MDCT_64 slice	1	120	250	2.5	1
		2	120	350	0.6	1
		3	120	300	0.6	1
B	Philips MDCT_64 slice	4	120	400	1.25	1
		5	120	500	1.25	1
		6	100	200	2.5	1

CT – Computed Tomography; MDCT – Multidetector CT; VCT – Volume Computed Tomography

Table 2. Dose parameters in daily scans in centers A and B

Protocols	$CTDI_{100,C}$ (mGy)	$CTDI_{100,P}$ (mGy)	$CTDI_W$ (mGy)	$CTDI_{Vol}$ (mGy)	DLP (mGy.cm)	Effective dose with calculated $CTDI_{Vol}$ (mSv)
1	30.35	40.14	36.87	36.87	590.02	8.85
2	40.21	40.84	40.63	40.63	650.08	9.75
3	30.86	40.28	37.14	37.14	594.24	8.91
4	40.49	40.58	40.55	40.55	648.80	9.73
5	40.94	50.19	47.11	47.11	753.71	11.31
6	30.08	30.53	30.62	30.62	489.92	7.34

$CTDI_{100,C}$ – Computed tomography dose index Central; $CTDI_{100,P}$ – Computed tomography dose index Peripheral ; $CTDI_W$ – Weighted computed tomography dose index; $CTDI_{Vol}$ – Computed tomography volume dose index. DLP- Dose length product

Table 3. Cumulative dose, Equilibrium dose, and Effective dose with calculated D_{eq}

Protocols	$D_L(0)_c$ (mGy)	$D_L(0)_p$ (mGy)	$D_{eq,c}$ (mGy)	$D_{eq,p}$ (mGy)	D_{eq} (mGy)	Effective dose with calculated D_{eq} (mSv)
1	32.78	40.94	53.11	48.97	51.04	12.24
2	43.42	41.65	70.36	49.82	60.09	14.42
3	33.32	41.08	54.01	49.14	51.57	12.37
4	43.72	41.39	70.85	49.51	60.18	14.44
5	44.21	51.19	71.64	61.23	66.43	15.94
6	33.26	31.14	53.90	37.35	45.57	10.93

Table 4. Comparison of Equilibrium dose and the $CTDI_{vol}$

Protocols	$CTDI_{Vol}$ (mGy)	D_{eq} (mGy)	Variation %
1	36.87	51.04	27.75
2	40.63	60.09	32.39
3	37.14	51.57	27.98
4	40.55	60.18	32.62
5	47.11	66.43	29.09
6	30.62	45.57	32.81

However, one of the remaining challenges for direct measurement of average equilibrium dose or cumulative dose on CT scanners is the need for a 400-mm long phantom [12, 17, 20, 26, 28]. The CTDI dosimetry technique for evaluating CT dose proves inaccurate since it downplays scatter radiation outside the length of the 100 mm pencil ionization chamber and hence undervalues the accumulated dose at the phantom central plane. In 2010, AAPM task group 111 proposed an alternative measuring methodology for CBCT acquisitions to address challenges faced by modern CT technologies and solve dosage underestimation caused by the CTDI method. With enhanced CT equipment, numerous research has tackled the limits of the traditional CTDI measurement. The AAPM approach is one of these new methods which, despite being time-consuming and difficult to implement in a medical setting, it yields reliable information. However, the AAPM approach is limited in two ways. Firstly, the exam takes at least four-dose metrics to estimate Dose $_{eq}$ and Length $_{eq}$; and, secondly, assembling the experimental setup and performing measurements is time-consuming, and it takes roughly 2 hours on average to complete each phantom. Having said that, the CTDI method takes only 1 hour to complete for all three phantoms. To solve the AAPM method's problem, we propose an alternative approach that takes considerably less time and resembles the AAPM outcome close enough [29].

In a study by Albngali *et al.*, the equilibrium dose in two protocols, namely, thoracic and abdominopelvic, was used to approximate the dose and then compare it to CTDI values. The findings of their study demonstrate that the dose equilibrium measures of those protocols were 29% and 30% greater than those informed by the CT scanner, respectively. As a result, when contrasted to the D_{eq} procedure, the $CTDI_{vol}$ process effectively undervalued the absorbed dose for all our populations [30]. In measurements with a 450mm CT phantom, there were significant differences between the Planar Average Equilibrium Dose ($D_{eq,p}$) and $CTDI_{vol}$, ranging from 30-37%. $CTDI_{vol}$ cannot account for the "tail" contribution of dose profiles caused by phantom scattering, especially for broader beam widths. Therefore, while $CTDI_{vol}$ is a valuable indicator for quality assurance purposes across patients, protocols, and scanners, it does not accurately represent the actual patient dose [4]. In another study conducted by Albngali *et al.*, 25 to 35% less estimation was obtained for measurement by the CTDI method compared to equilibrium doses [31].

Deschamps *et al.* conducted a study to measure the dose received during a CT scan using the AAPM TG 111 methodology. They found that the $CTDI_{Vol}$ provided by the CT scanners for all protocols was lower than the equilibrium doses by 32% to 35% [6]. Therefore, the $CTDI_{Vol}$ is unsuitable for accurately defining the delivered dose while the exam is performed [32]. A comparison of the Li study, which utilized formulas, and Descamp's study, which used a direct approach, showed a significant agreement between the two methods (difference: 0.7% median and 5.3% maximum) [21]. Additionally, the discrepancies between the results of $CTDI_{Vol}$ and the

Monte Carlo Boone *et al.* equilibrium dose indicated an underestimation of the systematic volume of CTDI [14].

In calculating the effective dose, we use scanning length and a conversion coefficient, which are the same in both methods and there is a difference of 27-33% between the equilibrium dose and $CTDI_{vol}$, which also affects the effective dose. The mean value of the effective dose calculated by $CTDI_{Vol}$ and equilibrium dose was 9.32 ± 1.37 and 13.39 ± 2.14 mSv, respectively. This means that in our study, the effective dose calculated by the equilibrium dose method is up to 5 millisieverts larger than the $CTDI_{Vol}$ method.

Albngali *et al.* conducted a study to estimate the effective dose of the patient. Their results are consistent with our study. In their study, first, the equilibrium dose and CTDI values were obtained, and then the effective dose was calculated using them, which showed that the effective dose calculated by the CTDI method is about 26 to 31% less than the effective dose calculated using the equilibrium dose. Also, the effective dose was up to 6 millisieverts larger than the previous values [33].

Brix *et al.* measured the effective dose of four 64-slice CT centers. The effective dose was reported to be 10.5 mSv. [34] Hausleiter *et al.* estimated the effective dose and obtained a value of 11 mSv for a 64-slice unit [35].

In the study by John *et al.*, the effective dose range was reported to be 5 mSv –14 mSv [1]. In this study, the mean value of the effective dose calculated by $CTDI_{Vol}$ was 9.32 ± 1.37 mSv.

Comparing our values to those obtained in other studies, it can be illustrated that the average effective dose in this study is significantly lower than that of the other studies. Finally, the important point is that the average effective dose calculated by the equilibrium dose is higher than the values of other studies.

$CTDI_{Vol}$ has been used prevalently in the literature [36] to calculate the effective dose. However, due to the at least 30% differences obtained in $CTDI_{Vol}$ and equilibrium dose, the calculated effective dose profiles are not suitable for comparison with international references. Thus, more valid approaches are needed to calculate the risk of cancer.

5. Conclusion

The difference between CTD_{vol} and equilibrium dose values was consistent with the previous studies. To evaluate the radiation dose at the end of each scan, the $CTDI_{Vol}$ is not suitable, and the use of an equilibrium dose for dosimetry of new systems is recommended for quality control and quality assurance. If the CT scan device is calibrated and ensures the accuracy of the $CTDI_{Vol}$ informed by the CT scanner, the equilibrium dose can be obtained without direct measurement.

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