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Estimation of Absorbed and Effective Doses in Organs through Computed Tomography Examinations Using Automatic Exposure Control and Fixed Tube Current Techniques: A Phantom Case Study

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ABSTRACT

Introduction: The study aimed to assess absorbed and effective doses in organs through computed tomography (CT) examinations using automatic exposure control (AEC) and fixed tube current (FTC) techniques.

Material and Methods: Scanning parameters were obtained for routine adult CT examinations and used to estimate the organ absorbed and effective doses using CT-Expo software. The estimated effective doses were based on International Commission on Radiological Protection publication 103 recommendations.

Results: Regarding the scans performed with AEC, doses to head, chest, abdomen and pelvic organs were within the range of 19.7-41.8, 6.4-17.4, 19.2-20.9, and 10.5-24.9 mGy respectively. Moreover, the effective doses for the mentioned organs were 1.6, 6.1, 6.4 and 5.4 mSv respectively. Considering FTC technique, doses to organs ranged 16.7-75.5, 4.1-52.2, 10.6-33.2 and 5.2-38.7 mGy respectively. Moreover, the mean effective doses of FTC were 2.1, 6.9, 9.4 and 6.1 mSv, respectively. Examinations performed with AEC technique induced a dose reduction of 9% and 34% for head organs, 52, 62 and 25% for chest organs, 16% and 14% for abdomen organs, and 11% and 10% for pelvic organs, compared to the FTC. A dose increase of 3% was observed for testes. The mean effective doses for scans with AEC were 13-46% lower than those obtained by FTC.

Conclusion: According to the obtained results of the current study, the estimated doses for scans with AEC technique were in a lower level compared to FTC technique. Accordingly, it is recommended to utilize this technique for CT examinations to ensure optimal dose reduction to radiosensitive organs.

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Introduction

Over the past recent years, computed tomography (CT) in medical practice has revolutionized diagnostic radiology[1], with its faster data acquisition and reconstruction times, as well as a spiral acquisition mode with multi-slice capability. Its usage has grown considerably over the past few decades leading to an increase in the frequency of CT examinations and widening spectrum of CT applications. The use of CT in providing accurate diagnosis of patients' ailments in the clinical settings cannot be over emphasized. However, radiation doses from CT scans are relatively high, especially to radiosensitive organs. Therefore, it is of utmost importance to consider its potential risks. CT alone constitutes about 20% of the procedures performed in diagnostic radiological examinations worldwide. On the other hand, it accounts for about 70% of the accumulative doses to the general population[2].

It is reported that CT accounts for 17% of the total radiology procedures in the United States and contributes to about 50% of radiological collective dose. This contribution has increased to 10-15% per annum growth due to its usage in the early 90s until mid-2000[3]. The use of ionizing radiation for medical diagnosis has been a global health concern, given the high possibility of causing undesired health effects, such as cancer induction, in patients[4]. The harmful effect of radiation which is a key concern is the development of the superficial radiosensitivity in organs mostly irradiated during a radiological procedure. Absorbed organ dose and its weighted sum of equivalent doses have been widely used to estimate the overall risk radiation exposure to patients[5].

Effective dose is noted to be a useful quantity for the comparison of examinations using different techniques and is currently deemed to be the best widely available dose descriptor for estimating the

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stochastic risks of a given radiological examination as it focuses on the dose to individual organs and tissues [6]. In CT, one of the possible ways to estimate the effective dose is using the effective dose per unit conversion factors for the specific anatomic region based on International Commission on Radiological Protection (ICRP) Publication 103 recommendations [7]. There are many readily available dosimetric tools (e.g., CT-Expo and ImPACT dosimeter calculator,) used for organs and effective doses estimation in CT systems. These tools use a similar method but vary based on the location and the employed type of scanner[8, 9].

The gold standard for assessing organ absorbed doses can be performed in two ways; either by direct measurement in patients using dosimeters such as thermoluminescent dosimeters (TLDs), or on phantoms using either an ionization chamber or TLDs. Organ doses can determined through indirect measurement using measured CT dose indexes (CTDI) and published conventional factors, obtained from Monte Carlo simulation and mathematical phantoms [10, 11]. There is a bulk body of literature on radiation dose and image quality in CT examinations performed with automatic exposure control (AEC) and fixed tube current (FTC) techniques. However, there is a dearth of research addressing the assessment of absorbed and effective doses in organs CT examinations using AEC and FTC techniques. Accordingly, the purpose of the current study was to estimate organ doses and effective doses of adult patients undergoing routine CT scans with CT-Expo dosimetry software using a 16-slice Siemens CT scanner with fixed tube current (FTC) and automatic exposure control (AEC) techniques as a phantom case study. Moreover, the obtained results of the current study were compared with those reported in literature.

Materials and Methods

The CT scanner

The employed CT scanner in the current study was a multi-detector row CT scanner with 16-slice detector elements (16-slice MDCT; Siemens Somatom Emotion; Siemens Healthcare, Forchheim, Germany) equipped with an up to date automatic exposure control device (CareDose4D) with a focal spot (0.8×0.5 mm) capable of 16×1.2 mm multi-slice. The head (16 cm in diameter) and body (32 cm in diameter) made of Polymethyl methacrylate (PMMA) CT dosimetry phantoms were used to mimic an adult's head and body (representing thorax, abdomen, and pelvis) for dose measurements. The CT examinations in the current study involved four most frequent routine CT examinations, including head, thorax, abdomen, and pelvis. The protocols of examinations corresponded to the default settings by the manufacturer, and scan acquisitions were performed with FTC and AEC techniques.

Table1. Scan parameters used for automatic exposure control technique for routine head and body computed tomography examinations

Parameters	CT Examinations			
	Head	Body		
		Thorax	Abdomen	Pelvis
kVp	130	130	130	130
Effective mAs	160	111	139	142
Rotation Time (s)	1.5	0.6	1.0	0.6
Percentage (%) mAs modulation	-14.3-46.7%	-38.8-49.5%	-73.8-36.8%	-77.5-35.4%
Beam width (mm)	16×1.2	16×1.2	16×1.2	16×1.2
Slice thickness (mm)	4.0	5.0	5.0	5.0
Pitch	0.55	0.8	1.5	0.8
Reconstruction slice thickness (mm)	3.0	3.0	3.0	3.0
Reconstruction Kernel	H31S	B41S	B41S	B41S

KVp: kilo voltage power

Table2. Scan parameters of fixed tube current technique for routine head computed tomographic examinations

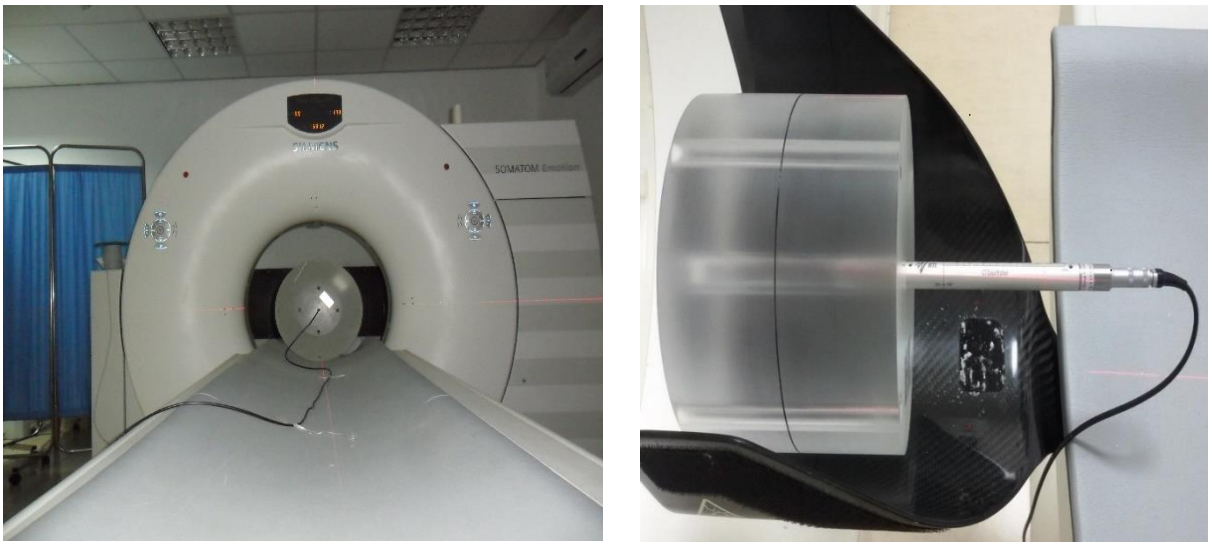
Examination	kVp	mAs	RT (s)	Pitch	ST (mm)	BW (mm)	RS (mm)	Reconstruction kernel
Head	130	140	1.5	0.55	4	16×1.2	3	H31S
Head	130	160	1.5	0.55	4	16×1.2	3	H31S
Head	130	180	1.5	0.55	4	16×1.2	3	H31S
Head	130	200	1.5	0.55	4	16×1.2	3	H31S
Head	130	220	1.5	0.55	4	16×1.2	3	H31S
Head	130	240	1.5	0.55	4	16×1.2	3	H31S
Head	130	260	1.5	0.55	4	16×1.2	3	H31S
Head	130	280	1.5	0.55	4	16×1.2	3	H31S
Head	130	300	1.5	0.55	4	16×1.2	3	H31S

kVp: kilo voltage power, mAs: milli-amper seconds, RT: rotation time, ST: slice thickness, RS: reconstruction slice thickness, BW: beam width, s: seconds, mm: millimeters

Table3. Scan parameters of fixed tube current technique for routine body CT examinations

Examination	kVp	mAs	RT (s)	Pitch	ST (mm)	BW (mm)	RS (mm)	Reconstruction Kernel
Body	130	80	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	100	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	120	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	140	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	160	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	180	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	200	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	210	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S
Body	130	220	0.6, 1.0, 0.6	0.8, 1.5, 0.8	5	16×1.2	3	B41S

kVp: kilo voltage power, mAs: milli-amper seconds, RT: rotation time, ST: slice thickness, RS: reconstruction slice thickness, BW: beam width, s: seconds, mm: millimeters



(a) Dose measurement set-up with the body phantom in the gantry of the computed tomography scanner

(b) Set-up indicating the position of the dose profiler probe in the computed tomography body phantom

Figure1.Set-up for dose measurement with computed tomography dose profiler probe in the computed tomography body phantom

The scanned parameters employed for the investigated examinations using the two techniques are shown in tables 1-3. The operating voltage of the CT scanner was 130 kVp in all cases.

The AEC System

The automatic exposure control (AEC) system is a device designed in CT scanners to automatically modulate the tube current either in the x-y plane (angular modulation) or z-axis (longitudinal modulation) scanned direction or both during a CT examination [12].The CT scanner used in this study, uses the CARE Dose 4D as its automatic exposure control feature. The AEC enables automatic adjustment of the tube current depending on the size and attenuation characteristics of the patient together with real-time, online, controlled tube current modulation during each tube rotation [13].Based on a single CT localizer radiograph or topogram, the anterior-posterior or lateral attenuation profile of the patient's long axis (z-axis) can be measured in the direction of the projection and estimated for the perpendicular direction with a mathematical algorithm [14].

The CARE Dose 4D has adequate image noise, which differs depending on the patient's size and shape. The operator can choose the level of tube current using weak, average or strong settings to control the amount of mA according to the patient's size. The CARE Dose 4D modulations can provide a lower tube current to keep image noise consistent regardless of the patient size [15]. The adaptation strengths of the AEC systems are pre-set by the manufacturer which can decrease the radiation dose for slim sections and increase the radiation dose for obese sections.

The CT-EXPO Software

The CT-Expo software (version 2.3, Abt. Experienmentelle radiologie, Carl-Neuberg-Str.1, Hannover, Germany) is a Microsoft Excel application written in Visual Basic for the calculation of patient dose in CT examinations. It offers automatic output calculation of effective and organ absorbed doses based on a scanner model, manufacturer and scanning parameters are entered as input data. It simulates almost all the commercial CT scanners. Doses were calculated using the formalism implemented in the CT-Expo software package [8, 16].

CT Dose Measurements

Patient organ absorbed dose estimation in CT examination requires the measurement of computed tomography dose index (CTDI) and the use of published conventional factors obtained from Monte Carlo simulation and mathematical phantoms [17, 18]. Theoretically, the CTDI represents the dose measured from a single slice irradiation. This defines the integral along a line parallel to the axis of rotation (z) of the dose profiled D (z) divided by the nominal slice thickness, t [17]. In the present study, the CTDI was obtained from the measurement of dose using a CT dose profiler probe (RTI, electronics, Sweden) connected via an extension cable to a barracuda and a computer system with ocean software. With the dose profiler probe, the dose measurements were performed in a single helical scan with the dose profiler probe placed at the central hole of a PMMA head and body CT dosimetry phantoms [19] as shown in Figure 1.

Organ and Effective Dose Estimation

Organ and effective doses were estimated using CT-Expo dosimetry software [16]. The software has been developed for the estimation of organ doses and effective doses of patients undergoing CT examinations. The software calculates the dose for the irradiation of a mathematical phantom representing an adult patient. In the present study, patient's technique parameters were obtained from CT dose descriptors and the head and body phantoms used for the dose measurement of the various routine examinations. These were used as input data into the CT-Expo software for the organ and effective dose estimates. The input parameters included; CT manufacturer, CT model, patient age group, kV, mA, acquisition time, total collimation, and table feed, reconstructed slice thickness, the number of scan series, and scan length. The effective doses which represents the risk-weighted measure of radiation dose to organs on the body associated with an examination(s), were computed according to equation (1) used in the dose calculation of CT-Expo dosimetry software.

$$E_D = DLP \times k \quad (1)$$

Where k is the anatomic region specific conversion factor based on ICRP 103 recommendations [7], the k factor is independent of the type of CT scanner used and is specific to the body area been scanned, whiles DLP is the dose length product.

Results

The results of organ absorbed doses for the conducted examination are presented in Figures 2-5. Estimated doses to organs (eye lens, brain and thyroid) for the head scan with AEC and FTC techniques were within the ranges of 19.7-41.8 mGy and 16.7-75.5 mGy. Doses to radiosensitive organs for chest, abdomen and pelvis with AEC ranged 6.4-17.4, 17.9-20.9 and 10.5-24.9 mGy, respectively. On the other hand, the obtained results of the FTC technique were within the ranges of 4.1-52.2, 10.6-33.2 and 5.2-38.7 mGy. Table 4 shows the effective doses for head, chest, abdomen and pelvis CT examinations. Tables 5 and 6 shows the comparison of organ absorbed and effective doses obtained from the present study and published data in the literature.

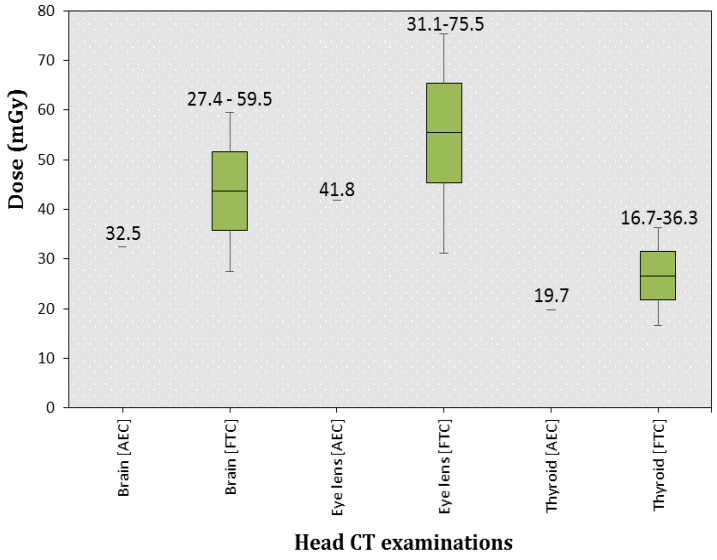


Figure2. Organ doses for head computed tomography examinations

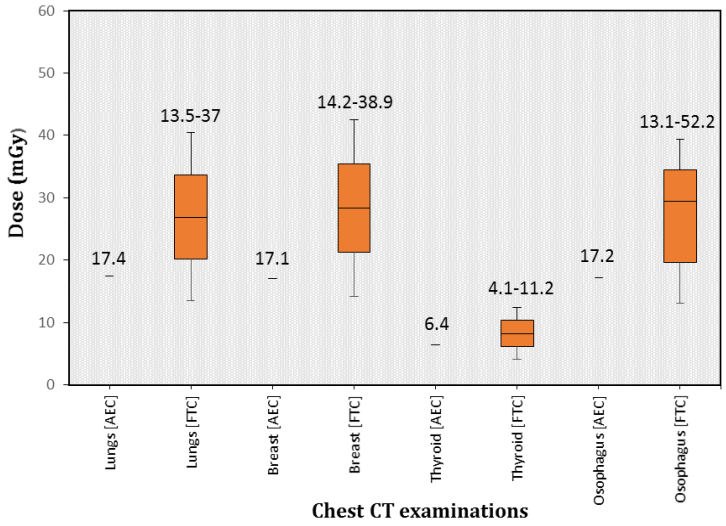


Figure3. Organ doses for chest computed tomography examinations

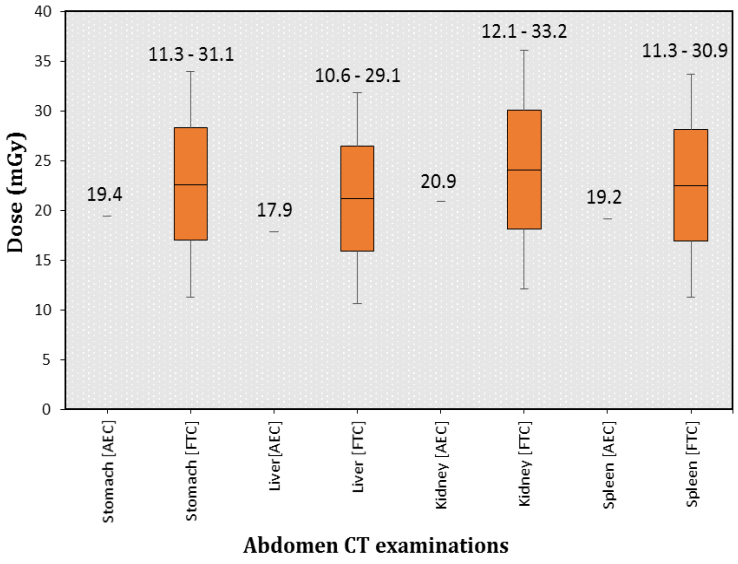


Figure4. Organ doses for Abdomen computed tomography examinations

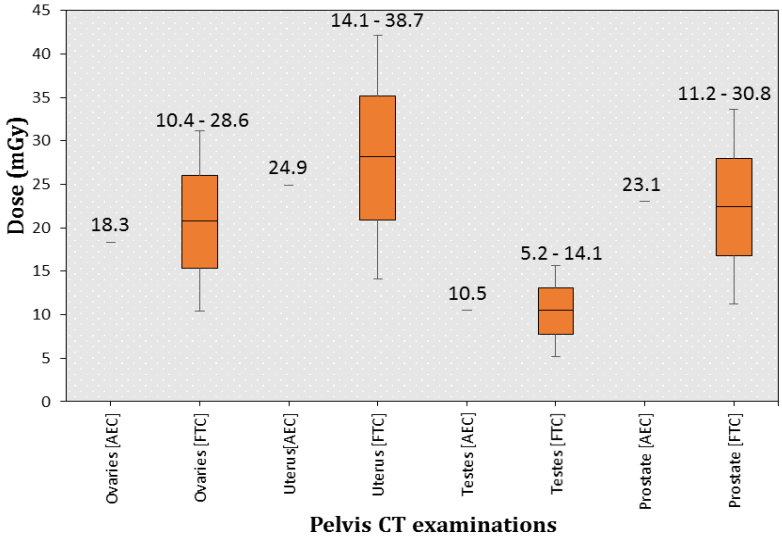


Figure5. Organ doses for pelvis computed tomography examinations

Table4. Estimated effective dose (mSv) values using CT-Expo software for automatic exposure control and fixed tube current techniques

Computed Tomography		Effective Dose (mSv)			
Examination	mAs	Head	Chest	Abdomen	Pelvis
AEC	-	1.6	6.1	6.4	5.4
FTC					
Head	140				
Chest, Abdomen, Pelvis	80	1.4	3.5	4.8	3.1
Head	160				
Chest, Abdomen, Pelvis	100	1.6	4.4	6.0	3.9
Head	180				
Chest, Abdomen, Pelvis	120	1.7	5.3	7.2	4.6
Head	200				
Chest, Abdomen, Pelvis	140	1.9	6.1	8.4	5.4
Head	220				
Chest, Abdomen, Pelvis	160	2.2	7.0	9.6	6.2
Head	240				
Chest, Abdomen, Pelvis	180	2.3	7.9	10.2	7.0
Head	260				
Chest, Abdomen, Pelvis	200	2.4	8.7	12.0	7.7
Head	280				
Chest, Abdomen, Pelvis	210	2.6	9.2	13.0	8.1
Head	300				
Chest, Abdomen, Pelvis	220	2.8	9.7	13.2	8.5

AEC: Automatic Exposure Control, FTC: Fixed Tube Current

Table5. Comparison of organ doses in this study and other studies

Computed Tomography	Selected	Present Study		UK [18]	Japan [20]	Germany [10]	Tanzania [21]
Examination	Organs	AEC (mGy)	FTC (mGy)	(mGy)	(mGy)	(mGy)	(mGy)
Head	Eye lens	41.8	45.4 (±15.2)	N/A	22.4	24.8	63.9 (± 32.6)
	Thyroid	19.7	26.3 (± 6.8)	1.9	0.6	N/A	2.5 (± 1.3)
Chest	Lungs	17.4	26.4 (± 8.4)	22.4	19.6	20.5	31.5 (± 10.6)
	Breast	17.1	27.7 (± 8.8)	21.4	15.9	22.6	26.1 (± 10.8)
	Thyroid	6.4	8.0 (± 2.6)	2.3	1.9	N/A	12.3 (± 8.5)
Abdomen	Liver	17.9	20.8 (± 7.1)	20.4	27.8	15	34.1 (± 10.7)
	Stomach	19.4	22.1 (± 6.6)	22.2	26.9	15.4	35.6 (± 10.3)
Pelvis	Ovaries	18.3	20.3 (± 6.5)	22.7	15.1	14.9	24.0 (± 17.1)
	Uterus	24.9	27.5 (± 8.8)	25.5	N/A	14.6	26.5 (± 18.6)
	Testes	10.5	10.2 (± 3.2)	1.7	1.0	N/A	12.5 (± 19.9)

AEC: Automatic Exposure Control, FTC: Fixed Tube Current. Note: (N/A) means no available data, and values in parenthesis represent the standard deviation of the mean organ doses.

Table6. Comparison of effective dose (mSv) values of the current study and those reported in the literature (Mean values in brackets)

Study	CT Examinations			
	Head	Chest	Abdomen	Pelvis
Shrimpton et al., (1991) [18]	0.46-4.94 (1.78)	1.05-22.5 (7.8)	1.58-22.6 (7.58)	1.13-24.8 (7.12)
Breiki et al., (2008) [22]	1.14-2.74 (1.76)	4.65-24.45 (14.56)	3.86-32.53 (14.56)	4.08-18.10 (11.21)
Goddard & Alfarsi, (1999)[23]	0.3-8.2 (2.4)	0.3-10.8 (3.4)	1.4-31.2 (9.5)	N/A
Inkoom et al., (2014) [24]	1.1-1.6	2.7-9.3	5.3-13.2	5.5-9.1
UNSCEAR, (2008) [25]	1.6	9.7	12	9.8
Clarke et al., (2000) [26]	0.98-2.11 (1.9)	3.84-14.58 (8.9)	3.8-13.35 (10.6)	1.86-12.60 (8.4)
Present Study				
AEC	1.6	6.1	6.4	5.4
FTC	1.4-2.8 (2.1)	3.5-9.7 (6.9)	4.8-13.2 (9.4)	3.1-8.5 (6.1)

AEC: Automatic Exposure Control, FTC: Fixed Tube Current. Note: Values in brackets represents mean effective dose values for various computed tomography examinations and (N/A) indicates no available data

Discussion

The present study was conducted to determine absorbed and effective doses to the selected organs (i.e., head, chest, abdomen and pelvis) through CT examinations using AEC and FTC techniques. The obtained results for the two scan techniques of the present study in terms of the organ doses were compared with the reported values of the United Kingdom [18], Japan [20], Germany [10] and Tanzania [21] Table 5. The results were similar to those obtained from studies conducted in United Kingdom [18], Japan [20] and Germany [10] except for Tanzania. The results of the Tanzania study when compared to the present study gave a variation factor of up to 1.9 for AEC and 1.6 for FTC techniques of the estimated organ doses. In the Tanzania study [21], the authors used the ImPACT CT dosimeter calculator based on National Radiological Protection Board (NRPB) conversion factors of different CT scanners across different institutions. It is important to note that the observed variation in these doses may be attributed to the difference in employed methods in the dose measurements, investigated subjects, CT scanners, CT scanned protocols, and the equipments used.

As can be seen in Table 6, the effective doses of the present study were compared with those data published by Shrimpton et al., (1991), Breiki et al, (2008), Goddard and Alfarsi (1999), Inkoom et al, (2014), UNSCEAR (2008), and Clark et al, (2000) [18, 22, 23, 24, 25, 26]. It is important to state that the effective doses reported by Breiki et al.,(2008) Shrimpton et al.,(1991) Clark et al.,(2000) and UNSCEAR(2008) were phantom based studies while those reported by Goddard and Alfarsi as well as Inkoom et al., (2014) were clinical based studies. The effective doses for the head scan with AEC were similar to the reported values for UNSCEAR (2008) [25]. However, the obtained results were in a lower level compared to those reported by Breiki et al., (2008), Goddard and Alfarsi (1999), Clark et al., (2000) and Shrimpton et al., (1991) [22, 23, 26, 18] for all the conducted CT examinations except for the chest CT examination (6.1 mSv) which exceeded the mean value of a study conducted by Goddard and Alfarsi (1999) [23] and gave a variation factor of 1.8.

The mean effective dose values for all the CT examinations, using FTC technique were consistent with the mean values reported by Goddard and Alfarsi (1999) [23]. Moreover, this similarity was also observed regarding the obtained results of head CT scans and values reported by UNSCEAR (2008) [25]. However, it was observed that the mean effective dose values were lower than published data and international diagnostic reference levels of UNSCEAR (2008) [25] for abdomen and pelvis CT examinations. On the other hand, the head and chest CT mean effective dose values exceeded those of the published data, except for the chest CT examination that was lower than the reported value by Breiki et al., (2008) [22], and gave a variation factor of 1.5. The variations seen in the effective doses of the present study and the published data may be attributed to differences in imaging protocols, type of equipment used, and the utilized method used for the effective dose estimations.

The effective dose values reported in the literature were estimated using the CT dosimetry software, except for the estimated values by Inkoom et al., (2014) [24] which used the DLP and anatomic region specific conversion factors. It is also important to state that the findings from the present study were based on standard-sized mathematical dosimetry phantoms. This accounted for the dose discrepancies observed in this study and the published data.

According to the results of the present study, there was a dose reduction using the AEC technique for the head, chest, abdomen and pelvic organs (9 and 34% for eye lens and thyroid; 52, 62, and 25% for lungs, breast and thyroid; 16 and 14% for liver and stomach; 11 and 10% for ovaries and uterus and a 3% increase for testes), and 13-46% reduction in mean effective doses compared with FTC scan technique. The use of ionizing radiation for medical imaging and diagnoses need to be investigated constantly in order to reduce the possible deleterious effects of radiation dose, especially exposure to highly radiosensitive organs. The estimation of effective dose values allows for the comparison of different regional radiation exposures and comparison of doses from different imaging techniques. Moreover, it reflects the difference in the biological sensitivity of the exposed tissues or organs. Effective dose reduction in CT examinations can be achieved by reducing scan duration as much as possible, while not missing any vital anatomical regions of interest.

Dose reduction in CT, especially to radiosensitive organs, has been a major concern with several optimization strategies formulated to outweigh the benefit to risk ratio, and modulation of exposure factors during scanning as one of the best ways of reducing patient dose. Patient radiation exposure in CT examinations can be reduced considerably using tube current modulated AEC which provides a constant level of image noise based on patient size, attenuation profile and scanned parameters. Additionally, the justification of each individual CT examination, reduction of the scanned volume, and use of optimized scan technique factors (i.e., kV, mA, rotation time, slice width and pitch (for helical scans) or couch increment (axial scans) are other alternative means of maintaining the patients exposure dose as low as possible.

Study Limitation

Calculated doses in the current study were performed with a 16-slice scanner at a single institution. Regardless of the scanner type, it should be kept in mind that patient scan parameters vary among institutions for a given examination. With this background in mind, it is essential to conduct additional research in a large number of institutions using different CT scanners.

Conclusion

The obtained results of the current study regarding absorbed and effective doses in organs through AEC

and FTC techniques were in line with published data and international diagnostic reference levels. However, the thyroid and liver organ doses from Tanzania gave a variation factor by up to 1.9 and 1.6 for AEC and FTC respectively. Furthermore, the implementation of AEC resulted in 10-62% and 13-46% decrease in absorbed and effective doses to organs compared with the FTC technique. Accordingly, the use of AEC could significantly reduce the radiation exposure to the patient. Therefore, it is recommended to utilize this technique during CT examination to ensure optimal dose reduction to radiosensitive organs.

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