

Patient Dose Audit in Computed Tomography at Cancer Institute of Guyana

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Abstract

Objective: This study is the first investigation on computed tomography (CT) unit in Guyana at the Cancer Institute of Guyana (CIG), aimed at performing an audit on the radiation dose estimated by the GE LightSpeed QXi CT unit for common computed tomography examinations

Method: A RaySafe X2 CT calibration detector were used to obtained measurements for common CT examinations (head, neck, chest, abdomen, pelvis, upper extremity and lower extremity) done in free air as the control (36 data) and also with patients (35 data). Patient's measurement were limited to the head, chest, abdomen and pelvis CT examinations. Exposure/electro-technical parameters and dose metrics (CTDIvol, DLP) were recorded and the k-coefficient conversion factor established by National Radiology Protection Board (NRPB) were used to calculate the effective dose associated with each examination.

Results: The results indicated that the CT unit overestimated the dose for patient measurements and underestimated the dose for measurements taken In-Air with the exception of the head protocol which showed overestimation with the patient measurements. Both over- and underestimation were documented for the neck protocol. Comparison of estimated dose between published data shows that there are variations in techniques and radiation dose across institution for similar examinations and that the protocols reported by CIG documented an overall higher effective dose.

Conclusion: The variation in estimated effective dose reported by CIG, is as a consequence of differences in CT scanner design and examination protocols.

Keywords: Computed tomography; Effective dose; k-Coefficient; Pencil ionization chamber; Dose length product; Overestimation; Underestimation

Introduction

Medical Imaging procedures are becoming the key diagnostic tool for many diseases in Guyana, and is playing a critical role in monitoring treatment and predicting an outcome. In the last ten to fifteen years, the use of these procedures for radiodiagnosis has increased markedly and quite a few imaging modalities are now present in most of the hospitals: Computed tomography (CT) being one of most invaluable since its introduction in Guyana.

The private health sector has capitalized on this innovation, being the main health institutions in Guyana equipped with CT machines. Currently, there are six CT scanners in Guyana; five being centered in its capital Georgetown. The increase in CT units in the country may have led to an increase in the number of patients undergoing these examinations. However, possible existing institutional policy concerning strict referral criteria for patients may not be effectively implemented, thus there is no known documented statistics on the amount of CT examinations being done per patient.

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The technological innovations in CT scanner hardware and software have led to the introduction of many new clinical applications of CT in diagnosis and therapy (CT-guided interventions), however these procedures raises safety and health concerns, as CT technique contribute to the largest cumulative patient doses from radiographic examinations [1-2]. The effective dose (which is the dose that estimates risk) from a single CT scan can range from less than 1.0 mSv to more than 30 mSv (i.e. 1.0 mGy and 30 mGy respectively) although most provide between 2 mSv - 20 mSv (2 mGy and 20 mGy respectively) [3]. This variation in effective dose is a consequence of the different scan protocols in CT employing varying exposure/technical factors and scan parameters for the examination. An abdominal CT examination is expected to produce a higher effective dose when compared to a CT examination of the head. These dose ranges are within safe dose limits (100 mSv per year) for medical examination. Interventional procedures, however, are usually more complex, demanding a larger number of image acquisition and thus delivers a larger amount of radiation doses to both patient and medical staff.

The dose a patient receives during CT examinations, may not be the only isolated dose, that patient is exposed to during his/her lifetime. As such, it is important to be aware of the contributory dose per CT exams. This necessitates the need for monitoring patient dose to evaluate whether patients are getting a higher absorbed dose of radiation, to explore techniques to optimize the radiation dosage delivered to patients and thus maintain regulatory dose limits.

Specification of the amount of radiation in CT examinations is based on two unique dose quantities; $CTDI_{vol}$ and DLP. Computed Tomography Dose Index volume ($CTDI_{vol}$) indicates the intensity of the radiation being directed at that patient and Dose Length Product (DLP) is a quantity that combines both aspects of intensity and extension of patient exposure, thus estimate total patient dose. These dose metrics are equivalent to Dose Area Product (DAP) in projection radiography (fluoroscopy, mammography, conventional radiography) that can be further used to estimate the effective dose received for a particular examination.

Background to problem

Each Radiology Department has guidelines and practical rules for the safe use of ionizing radiation. For occupationally exposed personnel (OEP) the only source of radiation monitoring come through the use of a physical detector called thermoluminescent dosimeters (TLDs). Unfortunately, with respect to patients, there is no physical device that measures the dose they receive whenever a specific examination is performed. The CT unit dose monitoring software, however, produces an estimate of the patient dose for the different CT examination based on preselected parameters. This estimated dose, on the other hand, does not take into consideration variation in patient size nor tissue density and thus produces the same dose estimated for the similar preselected parameter for dissimilar patient.

According to a study by Salerno et al [4], on the evaluation of radiation risks knowledge in pediatric fellows and resident, only

35% of medical staff have sufficient knowledge for radiation risk from common radiological examinations. In addition, even with the availability of continuing education and general information on radiation protection and risk, implementation strategies regarding radiation safety to both OEP and patients may not be sufficiently monitored.

Moreover, with local regulation regarding radiation protection strategies being in its approval stage, accompanied by the lack of sufficient locally trained technical experts in Guyana, radiation protection strategies are not being fully implemented for medically related imaging procedures.

Problem

Radiation exposure and risk from medical imaging examinations is a leading safety issue in radiology. The awareness and protection of occupationally exposed personnel and patient from radiation are crucial obligations that are expected to be enforced and upheld by a radiology department. However, while several of these obligations and methods are observed, few including monitoring patient cumulative dose of ionizing radiation from medical imaging devices may not be fully implemented. This shortcoming exposes the patient to an increased risk of biological stochastic effects due to the higher level of ionizing radiation (125 kVp-150 kVp) produced in computed tomography procedures as compared to conventional radiography (100 kVp-125 kVp). Furthermore, it creates low accountability for radiation protection and ALARA principle by health care providers and results in an inadequate patient monitoring mechanism to protect the public health and maintain safety.

Purpose of research

The purpose of this study was to conduct a patient dose audit in computed tomography (CT), to assess the effective doses of patients, received during common CT examinations and to compare with international studies based on scan protocols.

Significance of the research

The information from this dose audit would permit the institution to establish a set standard for each computed tomography examination performed, thus promoting quality improvement by proposing changes to CT practices where needed in the path of enhancing safe radiation practice. It can also serve as a guiding reference to the institution in conducting reliable self-audits for other imaging modalities or another CT unit that may be installed in the future.

The benefits of the research extend to every facility in Guyana utilizing a CT unit. It can be adapted for different CT units (manufacturer, number of detectors) to determine an estimate of the dose the patient may be receiving and thus identify whether the unit is overestimating or underestimating the patient dose. This can facilitate a quantitative approach to the process of standardization of all computed tomography unit in Guyana to protect the public's health and enable the strict implementation

of legalized policy concerning radiation protection and safety in Guyana.

Moreover, by calculating effective dose for a patient undergoing CT examinations, comparison with international dose limits and of relative patient doses can be made with other imaging modalities.

Hypothesis

Effective dose measurement taken in free air is more than the dose for actual patient measurement.

Research questions

How will the In-Air effective dose measurement vary with that of real-time patient measurement?

What is the % difference between the estimated effective dose and the measured effective dose?

Which CT scan parameter predominantly influences radiation dose?

How would the research aid in optimizing dose delivery to a patient?

Literature review

Introduction

Computed tomography (CT) is now one of the most effective and valuable imaging methods for medical diagnosis and guiding therapeutic procedures especially in Guyana. In fact, in 2001, CT and MRI were cited by physicians as the most significant medical innovations in the previous three decades [5]. While the discussion on the invaluable diagnostic capability of CT seems best, it is necessary to recognize that potential risk relating to radiation exposure exists for CT examinations. From the time of its establishment, and even with further technological advancement, CT is considered as a relatively high-dose imaging technique, graduating to be a major contributor to cumulative medical radiation dose. The effectiveness of CT in medical diagnosis owing to its three-dimensional features, however, is often given precedence over this dose impact leading to a more incautious requisition of CT examinations.

This situation raises concerns relating to the importance of monitoring radiation dose to occupationally exposed personnel and patients, to enhance safe practices and optimize dose delivery. These concerns lay emphasis on patients, as dose to patients is frequently not given much prominence as OEP (OEP experience radiation monitoring from thermoluminescent dosimeter (TLD) and are only exposed to radiation as a result of scattering due to their position behind a closed door, unlike patients who are continuously exposed directly).

Risk-benefit ratio

The risk aspect of the risk-to-benefit ratio in CT must always be considered. The benefit of obtaining a diagnosis of a specific pathology from a CT examination must outweigh the risk of the biological effect occurring due to the high level of ionizing radiation released from the CT producing 125kVp-150kVp from the x-ray tube of the unit. It is part of dose optimization strategies that these potentially high doses be kept to a minimum through careful assessment of protocols, strict referral criteria for patients, use of automatic exposure controls and choice of scan techniques [6].

Radiation dose measurements in CT

Computed tomography uses the same basic technology as conventional radiography, where x-ray photons are produced in a vacuum by bombarding a target anode with high energy (125 keV - 150 keV) electrons. Conversely, unlike conventional projectional radiography where beam exit energy is a fraction of entrance, in CT rotating source encircles the body so that PA and AP entrance dose are nearly identical leading to a more uniform dose distribution and generally higher organ dose. For this reason, the dose quantities used in projection radiography are not applicable to CT.

Computed tomography dose index

Specification of the amount of radiation in CT examinations is based on a unique dose metric known as the Computed Tomography Dose Index (CTDI), which is measured in a cylindrical acrylic phantom placed at the scanner's isocentre [7]. The CTDI method sought to create an "index" to reflect the average dose to a cylindrical phantom by using a 100-mm-long pencil-shaped ionization chamber in one of two phantom sizes (16 cm or 32 cm in diameter). The volume CTDI_{vol} metric represents the average absorbed radiation dose over the x, y, and z directions of the scanner that is dependent on the exposure factors, scan field of view, collimation and pitch factor selections. The CTDI_{vol} is an accurate specification of the radiation dose to the phantom and thus the intensity of radiation output from the scanner. When exam parameters are manually set, the exposure displayed CTDI_{vol} would be the same even if no patient was in the scanner. Thus, the CTDI_{vol} is not an estimate of the actual patient's dose but simply indicates the intensity of the radiation being directed at that patient [7-8]. According to Mc Collough et al. [8], even though CTDI_{vol} cannot be used as a surrogate for patient dose, it provides a very useful way to compare the doses delivered by various scan protocols or to achieve a specific level of image quality for a specific size patient.

Dose length product

An estimate of the total patient exposure in CT is known as the Dose Length Product (DLP). DLP is the equivalent of the dose-area product (DAP) in projection radiography, a quantity that also combines both aspects (intensity and extension) of patient exposure [9]. The DLP is the CTDI_{vol} multiplied by the scan length. So while the CTDI_{vol} remains fixed the dose length

product increases with the number of slices or the length of the irradiated body section. Data obtained from DLP calculation used as an exposure metric permit facilities to compare the amounts of radiation used to perform similar examinations of similar scan length to assess radiation safety practices.

Both CTDI_{vol} and DLP are intended for use as quality improvement and quality control metrics and not for use in deriving estimates of individual patient risk [2] since they are not an estimate of the actual patient’s dose; as the patient’s size and absorption characteristics are not considered. To estimate the relative risk increase for a patient, doses are reported as “effective doses,” [10]. Effective dose is the only dose metric that can represent the risk associated with CT examinations. It permits direct comparison of risk between radiologic examination and other radiation sources (radiation therapy, nuclear medicine, natural background, air travel) and with current regulatory dose limits to occupationally exposed personnel (20 mSv per year) and members of the public (2.0 mSv per year).

Effective dose/DLP conversion factor

A simplified method of estimating effective dose for CT entails multiplying the DLP value by an appropriate normalized specific k-coefficient (effective dose/DLP conversion factor). The k-coefficient is an effective dose conversion factor established by the National Radiology Protection Board (NRPB) for specific CT examinations which take into account the patient’s age and specific anatomical region being imaged.

The conversion factors have a wide age-based range and do not take into account the patient’s sex or specific scanner used. However, the effective dose/DLP conversion factor has been shown to be substantially the same for different scanners with the same parameters even though different scanners with different designs and beam filtration may produce different numbers for effective dose and DLP [11]. According to Mayo and Thakur [12], body-region specific k factors for head and neck, chest, abdomen and pelvis, and extremities have been determined using Monte Carlo simulation in reference subjects.

Radiation health effects

The biological risk associated with ionizing radiation in medical imaging is a subject of high import. Health effect due to ionizing radiation are classified as either stochastic or deterministic. Stochastic effects refer to the probability of potential long-term cancer or hereditary effects that may occur due to radiation exposure. Radiation-induced cancer and genetic effects are stochastic in nature. Deterministic effects occur when the radiation dose exceed a certain threshold (>2 Gy) resulting in lost or compromised organ functionality [12].

According to Ploussi A et al. [13] a typical head CT scan, which is the most frequent CT examination in adults and children, delivers an effective dose of about 4 mSv whereas the effective doses for the abdomen and coronary angiography CT examinations can reach 25 mSv and 32 mSv, respectively. Thus as far as deterministic effects are a concern, radiation exposure from these procedures are far below the dose threshold. So with

safe radiation practices, these effects are not expected for any patient undergoing a standard diagnostic CT examination.

It has been a matter of great controversy when discussing the magnitude of the stochastic cancer risk attributable to low-dose x-ray radiation exposure. Potential risks are dependent on several variables, including age, gender, region examined (the abdomen is much more radiation-sensitive than the ankle), and genetic susceptibility (Tables 1 and 2).

Table 1: k-coefficient conversion factors for various body region and patient ages. (Mayo. J., Thakur. Y. Pulmonary CT angiography as first-line imaging for PE: Image quality and radiation dose considerations. AJR, 200(3), 522–528. DOI:10.2214/AJR.12.9928).

Region of Body	Effective Dose/DLP Conversion Coefficient				
	0 y old	1 y old	5 y old	10 y old	Adult
Head & Neck	0.013	0.0085	0.0057	0.0042	0.0031
Head	0.011	0.0067	0.004	0.0032	0.0021
Neck	0.017	0.012	0.011	0.0079	0.0059
Chest	0.039	0.026	0.018	0.013	0.014
Abdomen and Pelvis	0.049	0.03	0.02	0.015	0.015
Trunk	0.044	0.028	0.019	0.014	0.015

CT dose optimization strategies

Even with the risk associated with CT examination, it is noteworthy to recognize that CT is an invaluable diagnostic tool and that the benefit from an appropriate CT exam almost always far exceeds the potential risk. It is therefore important to ensure CT practices are carried out in optimized radiation protection conditions. Optimizing technical parameters for exams can help reduce the patient radiation dose, thereby reducing risks.

Several optimization strategies exist to reduce CT dose including adjusting scan parameters (tube current, peak tube voltage and pitch etc.), avoiding overlapping of scan regions, and only scanning the area in question. To optimize the radiation dose delivered to patients, it is recommended that the measured radiation dose is compared against established diagnostic reference levels (DRLs).

Diagnostic reference level

DRLs are defined as dose levels in medical radio-diagnostic practices or, in the case of radiopharmaceuticals, levels of activity, for typical examinations, for groups of standard sized patients or standard phantoms and for broadly defined types of equipment [14]. When these levels are exceeded, an investigation of the appropriateness of the examination protocol is initiated

to set the institution to more appropriate optimize examination quality and safety.

Table 2: Tissue-weighting factors for international commission on radiological protection (icrp) publications 26, 60 and 103.

Tissue/Organ	Publication		
	ICRP 26	ICRP 60	ICRP 103
Gonads	0.25	0.2	0.08
Red Bone Marrow	0.12	0.12	0.12
Lung	0.12	0.12	0.12
Colon	0	0.12	0.12
Stomach	0	0.12	0.12
Breast	0.15	0.05	0.12
Bladder	0	0.05	0.04
Liver	0	0.05	0.04
Esophagus	0	0.05	0.04
Thyroid	0.03	0.05	0.04
Skin	0	0.01	0.01
Bone Surface	0.03	0.01	0.01
Brain	0	0	0.01

Table 3A: Specification of computer tomography scanner at cancer institute of guyana.

Manufacturer	Scanner Model	Maximum Tube Output	Slice Class	Year of Installation
GE Medical System	QXI light speed	140 kVp	4	2009

Table 3B: Specification of the RaySafe × 2 CT Detector.

Raysafe Specification	
Dimensions	14 × 22 × 219 mm
Diameter	12.5 mm
Weight	86 g
Direction of Incident Radiation	± 1800
Operating Temperature	15-35 °C

Controlled in-air measurement

The pencil ionization chamber was placed so as to extend over the end of the scanner couch and moved into the tomographic plane so that the tomographic plane bisects the length of the

Salivary Glands	0	0	0.01
Remainder	0.03	0.05	0.12
Total	1	1	1

Ethical consideration

The procedures used to obtain exposure data required a series of exposure to be made on the CT scanner. As such it was pivotal to observe radiation protection measures and the principle of ALARA during every examination. Also, confidentiality of patient information was a priority. Approval was granted from the Institutional Review Board for patient participants in the research.

Material and Methodology

This study was performed at the Cancer Institute of Guyana conducting the common CT examinations. All CT examinations were performed on a multidetector row CT (MDCT) scanner (LightSpeed QXi; GE Healthcare System) (Table 3A) and the measurement was recorded using the RaySafe X2 Calibration detector (Table 3B) and tabulated in Microsoft Excel.

Measurements

Two sets of measurements were taken i.e. In-Air measurement (control measurement) and Patient measurement, according to the following procedures.

sensitive volume of the ion chamber. The scan projection radiograph was performed to ensure the ion chamber was centered vertically and horizontally and the scan protocol was selected along with its specific scan parameters for an adult patient and the exposure was made. The dosimeter measured reading was then recorded and tabulated in Microsoft Excel and the procedure was repeated for the other CT examinations. (Apparatus is depicted in Figure 1).

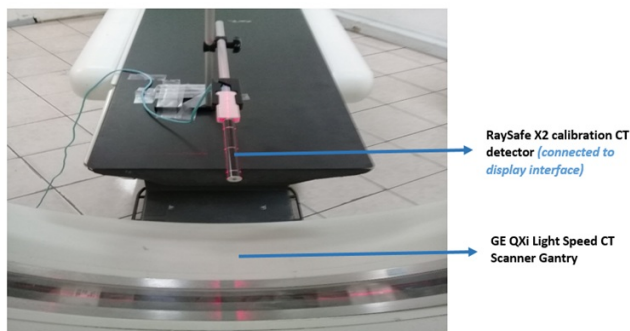


Figure 1: Equipment set-up for measurement of dose in-air using the RaySafe × 2 100 mm ionization chamber.

Patient measurement

The CT technologist positioned the patient on the CT table according to the specific CT scan protocol to be performed. The table was then moved into the tomographic plane so that the tomographic plane bisects the anatomy of the specific body region and the FOV was centered in both vertically and horizontally. The ionization chamber was then placed in the specific area of the patient anatomy and the scan projection radiograph was performed followed by the scan series for the CT examination. The dosimeter measured reading was recorded and tabulated in Microsoft Excel (Tables 4A and 4B).

Table 4A: Age and sample size of patient for the patient measurement.

Scan Protocol	Sample Number	Age
Brain	5	49.8 ± 2.7
Chest	11	50.3 ± 8.5
Abdomen	7	43.7 ± 2.2
Pelvis	12	55.8 ± 1.4

Table 4B: The common CT scan protocols and the variables recorded from the GE QXi CT display unit and the RaySafe unit.

Scan Protocol	GE QXi Unit	RaySafe Unit
Head	KVp	Output CTDIvol
Face/Sinus/Mastoid	mA	Output DLP
Neck	Scan Length	
Chest	Collimation	
Abdomen	Slice Thickness	
Pelvis	Pitch	
Upper Extremity	Input CTDIvol	

Lower Extremity Input DLP

Dose Calculation

From the normalized specified k-coefficient, the effective dose was determined by multiplying it with the dose-length product.

GE QXi estimated effective dose based on scanner inputted parameter

$$\text{Estimated Effective Dose (ED)} = k\text{-coefficient} * \text{Input DPL [Eq 1]}$$

RaySafe measured effective dose based on the GE QXi scanner’s output

$$\text{Measured Effective Dose (ED)} = k\text{-coefficient} * \text{Output DPL [Eq 2]}$$

Results

From the five scan protocol selected, four inclusive of head, chest, abdomen, and pelvis were done for patient measurement and all five protocols were done for In-Air measurement. The patients considered for the head, chest, abdomen and pelvis examination were all adults within the age range of 25-70 yrs. For all the measurements taken, the kVp, mA, and pitch were constant at 120 kVp, 200mA and 0.75 respectively, with automatic exposure control setting off for In-Air measurement and on for patient examinations. These parameter settings reflect the level for optimal penetration, dose delivery and, adequate images details.

Effective dose

In-Air Effective Dose Measurement

Estimated Effective Dose: The estimated effective dose as calculated from the GE QXi input DLP and the respective coefficient for the scan protocol varied between and within examinations. The estimated effective dose differ by a maximum factor of 3, 1.4, 2.6, 1.8 and 2.2 for the head, neck, chest, abdomen, and pelvis In-Air measurement respectively.

The estimated mean (SD) effective dose for these protocols are as follow; for head 1.3 ± 0.5 mGy, for neck 3.72 ± 0.51 mGy, for chest 5.6 ± 2.2 mGy, for abdomen 5.6 ± 1.1 and 4.99 ± 1.4 for Pelvis.

Measured Effective Dose: For In-Air measurement, the measured head CT scans effective dose ranges from 0.09 mGy to 0.23 mGy. The routine neck examination had the widest variation in measured effective dose i.e. from 0.12 mGy to 5.9 mGy. For chest, abdominal and pelvis CT examinations the measured effective dose minimum-maximum value were (6.07- 9.58) mGy, (6.7 - 9.9) mGy and (6.18- 10.1) mGy respectively.

The measured mean (SD) effective dose was 0.15 ± 0.05 mGy for head CT scan, 3.75 ± 2 mGy for the neck, 8.4 ± 1.6 mGy for chest, 8.9 ± 91.4 mGy for abdominal CT scan and 8.3 ± 1.8 mGy for the pelvis.

Head In-Air measurement showed the highest level of consistency in the measured effective dose for the number of measurements taken, with a dose difference of 0.13 mGy.

Consistency measurement was based on the subtraction of the maximum and minimum values in comparison to the standard deviation, given that the number of measurement for the various protocol differ and would produce bias results with standard deviation. CT scans of the neck had the widest variation in measured effective dose with 5.74 dose difference.

Patient effective dose measurement

Estimated Effective Dose: The estimated effective dose as documented for the patient measurement differs by a maximum factor of 2, 2.9, 1.3 and 2.8 for the head, chest, abdomen, and pelvis respectively. The measured mean (SD) effective dose for these protocols are as follow; for head 1.8 ± 0.4 mGy, for chest 9.9 ± 3 mGy, for abdomen 18.9 ± 1.9 and 12.4 ± 3.3 for Pelvis.

Measured Effective Dose: Consistency and variation in measured effective dose for patient measurements between the different CT examinations and within the same examination were detected over the number of measurement taken. Minimum-maximum measured effective dose observed for the four selected CT scan protocol were (0.01 - 0.2) mGy, (2.5 - 6.34) mGy, (3.3 - 5.1) mGy, (2.0 - 5.1) mGy for head, chest, abdomen, and pelvis respectively. Mean (SD) recorded for these examinations were 0.11 ± 0.09 mGy, 3.3 ± 1.1 mGy, 3.86 ± 0.59 mGy and 3.3 ± 0.7 mGy for head, chest, abdomen, and pelvis respectively.

The head CT examination showed the highest level of consistency for the number of measurements taken, followed by the abdominal CT scan protocol. The dose difference for these examinations is 0.2 mGy and 1.8 mGy. The chest CT examination had the least consistency thus widest variation.

In-Air vs patient effective dose measurement

The mean measured effective dose for CT scans of the head, chest, abdomen, and pelvis varied by a factor of 1.4, 2.6, 2.3 and 2.5 respectively between In-Air and patient measurements. In all situations, a decrease in measured effective dose was documented for the patient with a respective percentage difference of (-2.7%), (-61%), (-57%) and (-60%) for head, chest, abdomen and pelvis with reference to the In-Air measurements.

Discussion

Effective dose is the only dose metric that can represent the risk associated with CT examinations. A major benefit of calculating effective dose for a patient undergoing CT examinations is the ability to directly compare patient relative risk with other imaging modalities involving ionizing radiation, such as radiography, fluoroscopy, or nuclear medicine. Several methods exist for determination of effective dose, inclusive of a software-based Monte Carlo methods such as CT-Expo and a more simplified method using the dose-length product (DLP) and sets of age and body region - specific k-coefficients. The latter approach was used in this study for determination of effective dose. Effective dose values calculated from the NRPB Monte Carlo organ coefficients were compared to DLP values for the corresponding clinical exams to determine the set of k-coefficients, where the values of "k" are dependent only on the

region of the body being scanned (head, neck, chest, abdomen, or pelvis). This method however only produces a rough estimate of effective dose because many parameters that influence effective dose are not taken into account.

The length of the scan for a specific examination has a direct proportionality with the dose length product (DLP) and thus effective dose i.e. as scan length increases the DLP and effective dose are expected to increase. Due to this relationship between the length of scan and effective dose, it was found to be the predominating scan parameter that influences effective dose. This was more noticeable for In-Air measurements than patient measurements, given the additional consideration of variation in patient size for determination of effective dose in patients. For example, (Supplementary file) Graph 1 (A) In-Air head protocol showed an increase in scan length from 8cm - 10cm resulted in a measured effective dose increase of 64 % with every other parameter being kept constant. It is therefore essential for imaging technologists to be cautious so as to decrease unnecessary scan length to decrease the risk of unnecessary radiation exposures to patients.

The DLP is also directly proportional to $CTDI_{vol}$, and an increase of this dose value would result in an increase in DLP thus effective dose, although scan length may remain constant or decrease. In Graph 1 (D), an increase in scan length from 12cm-18cm for In-Air neck protocol result in a drop in the measured effective dose by a factor of 1.2 because of the input $CTDI_{vol}$ decrease by a factor of 1.9.

Moreover, given that the effective dose is marginally dependent on several other parameters apart from the scan length and $CTDI_{vol}$, it was observed that even with an increase of these parameters and subsequently DLP the measured effective dose was decreased.

Effective dose estimation by GE LightSpeed QXi unit

$CTDI_{vol}$ is computed using the radiation output of the CT for a given set of scan parameters using either a small (16 cm diameter) or large (32 cm diameter) PMMA acrylic cylinder. Dose measurements are made at the center and at the periphery, and these values are combined using a weighted average to produce a single estimate of radiation dose to that plastic cylinder. The small phantom is used as the reference for head CT, while the large phantom is used as a reference for adult CT in the torso (chest, abdomen, and pelvis). In an ideal situation, $CTDI_{vol}$ times scan length and the corresponding k-coefficient of the specific scan protocol should estimate the effective dose expected from the examination with no deviation from the measured effective dose from the RaySafe unit calculation.

However, variation was detected between the estimated and measured effective doses resulting in overestimation in some cases and underestimation in the others. The neck protocol in isolation documented both reduction and surge in the effective dose between the GE QXi unit and the RaySafe unit in a random manner.

Dose Overestimation

Dose overestimation was documented with respect to the GE QXi unit for all patient measurements along with the In-Air head protocol measurements. The patient’s dose overestimation can be attributed to variation between phantom and actual patient composition and thus interaction with radiation (Figure 2).

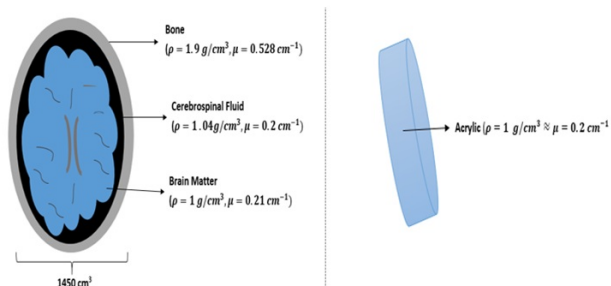


Figure 2: patient and phantom composition with their corresponding density (ρ) and attenuation coefficient (μ).

Phantom composition

Both phantoms used in the determination of $CTDI_{vol}$ to estimate dose are solid cylinders of acrylic material with a uniform density of $1g/cm^3$ and 14 cm thickness.

Patient composition

The anatomy of a patient is such that with each tissue layer, the composition in relation to its type (connective tissue, muscular tissue, nervous tissue, epithelial tissue) varies for their individual functions. Consequently, the density and thus the attenuation properties of these tissues also differ.

Given the homogenous nature of the phantom density, the attenuation are limited to tissues with similar density to the phantom only and exclude those tissues with higher density that would interact differently with radiation. Higher density tissues would attenuate radiation to a greater extent as compared to a phantom, resulting in a lower measured dose reading. The estimated dose would be reasonable if the patients were comprised of acrylic and if the patient had similar dimensions as the cylinder phantoms.

The In-Air measurement taken for the head protocol also showed overestimation and this is attributed to the interaction and scattering process of the phantom used in establishing estimated dose value in comparison to the interaction of radiation in free-air with negligible scatter (Figure 3).

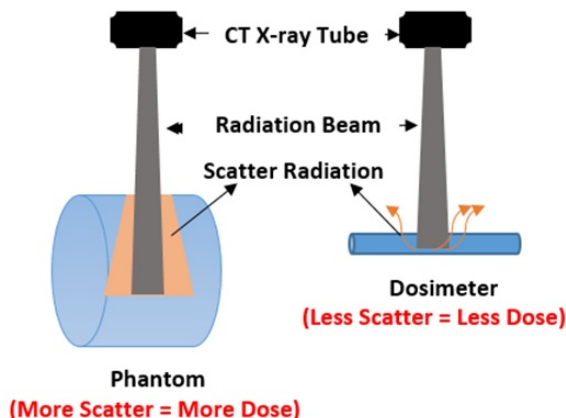


Figure 3: Radiation scattering process in phantom vs ionization chamber.

The overestimation of the dose by the CT unit is however beneficial to a patient. Although a dose overestimation as much as 78.6 %, differences (as was observed in patient chest measurement) may be documented; in reality, the patient is receiving a lower dose from that estimated by the unit. This allows for compensation for more radiation protection measures than is needed by the patient.

Dose underestimation

Unlike an overestimation of the effective dose that is beneficial to the patient, under-estimation is unfavorable. An underestimation implies that a patient would be receiving more dose than what was attributed by the CT unit. With the exception of the In-Air head protocol, all the measurements taken In-Air reported an underestimation of effective dose with reference to the GE QXi unit. This is attributed to the addition of remnant radiation from previous scans from the scanner’s x-ray tube contrary to what was programmed by the unit.

The data for In-Air measurements were acquired consecutively to each other with a limited time lapse (<20 Sec) as follows; Head-Face/Sinus/Mastoid-Neck-Chest-Abdomen-Pelvis-Upper Extremity-Lower Extremity. The Face/Sinus/Mastoid, Upper Extremity, and Lower Extremity protocol were omitted from the research after data collection due to the lack of established k-coefficient for these protocols to facilitate conversion to their respective effective dose. This consecutive series of exposure from the scanner may result in the production of additional radiation from the x-ray tube.

In the production of x-ray, the cathode filament is heated to produce electron to be accelerated to the anode to produce x-ray. Following an examination, the current to the filament is removed and the remnant electron charge cloud loses energy and is dissipated in preparation for another examination with varying current. Given the repeated exposure and short time span (<20 Sec) between the In-Air measurements taken the remnant electrons in the space charge cloud as such does not lose all their energy and dissipate but is added to the subsequent measurement producing a higher output dose when accelerated to the anode. So the In-Air measurement for chest, abdomen and pelvis protocol following the head, face/sinus/mastoid, and

neck protocol reflect the dose output of accelerated electron due to remnant space charge cloud as well as those from the new current applied to the filament for the specific examination. This event explains why the In-Air head protocol (the only In-Air measurement) that showed overestimation being the first of the sets of measurement taken. This event emphasizes the risk of radiation exposure when enough time is not apportioned between computed tomography examinations.

The results obtained for the In-Air neck protocol fall between overestimation which is attributed to the scattering process of the phantom in comparison to in air and dose underestimation which is attributed to the additional radiation outputted from the scanner. This over- and underestimation occurring in the same protocol may be attributed to the complete dissipation of the electron charge cloud due to interruption of In-Air measurement for emergency patients.

During this time period and in preparation for the next In-Air measurement data the electron charge cloud was permitted ample time of about 10 minutes to dissipate, thus resulting in an overestimation by the CT unit.

Effective Dose

Patient effective dose measurements

The Patient’s measured effective dose behave differently from the In-Air measured effective dose as will be explained in 6.2.2. The variation in measured effective dose for these protocols take additional parameter into consideration besides inputted parameters such as scan length and $CTDI_{vol}$. As mentioned in 6. the determination of effective dose using the k-coefficient approach only produce a rough estimate of effective dose because many parameters that influence effective doses such as specific body size and the exact location of the scanned area (Figure 2) in relation to the dose sensitive organs are not taken into account.

The head protocol showed the least variation between examinations as scan length increases, due to tissues composition consistency of the head anatomy between patients compared to the other reference anatomy. The anatomy of the head is shaped as such that the high-density cranium is encircling the entire brain soft tissues compared to being enclosed by soft tissues in the other body’s anatomy as seen in (Figure 2). The x-ray radiation, therefore, needs to interact with the bony structure in its passages into and out of the head anatomy, thus suffering greater attenuation. Consequently, the head protocol also possesses the least measured effective dose measurement.

The patient chest examination had the least consistency thus widest variation. This is attributed to the variation in tissue composition in the thoracic cavity along with the body habitus and gender characteristic of the patient. The tissue-air ratio of the patient relating to the lung field and the surrounding tissue can considerably alter the X-ray beam interaction process and thus the dose reading. Variation in patient’s body habitus from hyposthenic to hypersthenic with varying tissue-air ratio (volume) of the thoracic cavity, considerably influences the

radiation scattering and transmission process. This variation thus produces different dose reading. Breast tissues is also a contributory factor in attenuating a portion of the beam before interaction with the remaining underlying anatomy of the chest. A dense breast would attenuate more radiation in comparison to lesser dense breast and an absence of the breast altogether would possibly permit more transmission and thus greater dose reading.

Additional variation in effective dose due to similar patient factors was also evident in the abdomen and pelvis protocol. With the increased size of a patient, more absorption of radiation occurs resulting in a lower effective dose reading, in comparison to a smaller patient allowing more transmission and thus higher dose reading (Figure 4). The effect was less profound in the pelvis protocol, due to the consistent composition of the pelvis.

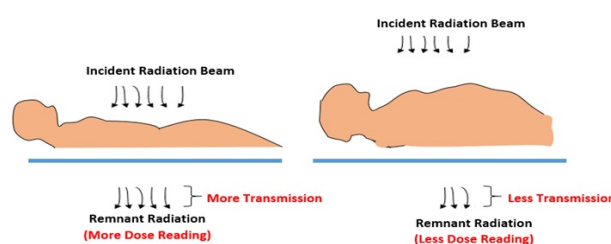


Figure 4: Influence of patient’s body characteristics on radiation attenuation.

In-air effective dose measurements

Effective dose is not ideally calculated for radiation interaction with air, given that it is used to estimate risks of ionizing radiation to the patient. This procedure was done as a control for the actual patient measurements. Radiation interaction with air particle is negligible, thus the ionization chamber is receiving the full intensity of the radiation over the scan length for the specific scan protocol. The resultant effective dose is therefore expected to be high. Variation in measured effective dose for these protocols is attributed to the length of scan and $CTDI_{vol}$ of the examination, with a direct proportionality in both cases.

Pitch

Irregularity in the measured effective doses with the scan parameter for all protocols is attributed to the pitch factor of the examination. Based on a research done simultaneously at CIG on the CT unit by Nirvanie Sukdeo and Petal Surujpaul title “Determination of Calibration Cycle for Computed Tomography at Cancer Institute of Guyana, it was found that as a consequence of the age of the scanner the pitch factor varied from the preset pitch on the unit. The input pitch according to the GE QXi display unit was constant at 0.75, but when calculated was found to be different along with the output pitch.

Therefore, the inverse proportionality relationship of the pitch with effective dose, resulting in a decrease in effective dose measurement even with an increase in scan length and $CTDI_{vol}$. For example, (Graph 1 (A)) In-Air head protocol showed an increase in scan length from 10cm – 11cm result in a drop in measured effective dose by a factor of 1.6. Both the input pitch

and output pitch was calculated to be 4 and 5.4 respectively; a 1.4 factor differences.

In-air vs patient effective dose measurement

The measured effective doses documented for the In-Air measurements were higher than that of the patient measurements (Table 5). The In-Air measurement used as a control for the patient measurement was set to mimic an actual clinical patient measurement completely or as much as possible with minimal variations in few scan lengths and the AEC control being on for patient measurement and off for In-Air measurement.

Table 5: Summary of mean measured effective doses of in-air measurement vs patient measurement with percentages difference with reference to in-air measurement in the bracket.

Protocol	In-Air	Patient	P-Value
Head	0.15	0.11 (-27 %)	0.1
Chest	8.37	3.28 (-61 %)	<0.05
Abdomen	8.96	3.87 (-57 %)	<0.05
Pelvis	8.29	3.32 (-60 %)	<0.05

The AEC systems use attenuation calculations based on the scout images of a patient to prescribe changes to the scanner output tailored for the specific region of interest on the patient, to meet the desired image quality. It generally increases CTDI_{vol} for large patients and decreases it for small patients. The scout images of the plain dosimeter for In-Air measurements, eliminated the area that would have corresponded to a patient anatomy and the AEC system, therefore, adjust accordingly to its minute size. The resultant displayed CTDI_{vol} and DLP were thus negligible in relation to a patient. For this reason, the system was set on manual to reproduce the input CTDI_{vol} and DLP of an actual patient anatomy and hence mimic patient measurements.

In itself, it can be argued that variations in effective doses between In-Air and patient measurements may be attributed to the exposure control settings. The dosimeter is directly exposed to the radiation with no alteration from AEC to compensate for it smaller volume and the excessive beam interacting with the detector surface to form a detailed image.

In as much as the In-Air measurement may have mimic the patient measurement, one variation that unquestionably contributed to the difference between the measured effective doses for these measurements, is the influence of the patient tissue on radiation. In patient, before X-ray is incident on dosimeter, it has to interact with several different layers of tissues that reduces the radiation based on the attenuation through each tissue layer Fig 2 (skin, muscle, fat, bone etc.). Thus the remnant radiation incident on the dosimeter is less in comparison to the In-Air measurement where x-ray interaction only occurs in the air before being incident on the dosimeter.

Patient estimated effective dose vs reference dose

The reference studies were performed at five hospitals conducting CT procedures located in Johor, Malaysia. A total of 460 patients with various CT examinations which includes the brain (head), thorax (Chest) and abdomen were obtained in this study corresponding to 32, 30 and 30 samples for each CT examination procedure, respectively (Table 6). Radiation doses from the patients were calculated using the format implemented in the program CT-EXPO (Version 2.3.1, Germany) a software that offers automatic output calculation of effective dose to the organs based on the specific scanner model, manufacturer and scanning parameters as input data [15].

Table 6: Scan protocol selected CT parameters and resultant DLP.

Hospital/ Examination	kVp	Effective mAs	Scan Range (cm)	DLP (mGy.cm)
CIG				
Head	120	200 (mA)	13.6 ± 3.8	834.1 ± 202.5
Chest	120	200 (mA)	28 ± 8.5	713.9 ± 217.1
Abdomen	120	200 (mA)	48.6 ± 4.5	1262.7 ± 125.3
H1				
Head	120	420	14.5 ± 1.8	838.3 ± 87.4
Chest	120	142.3 ± 15.3	45.6 ± 8.3	374.8 ± 133.6
Abdomen	120	241.1 ± 147.9	36.9 ± 18.4	558.1 ± 166.5
H2				
Head	130	260	12.2 ± 1.9	756 ± 62.2
Chest	110	90	39.8 ± 13.9	165.8 ± 40.9
Abdomen	130	80	39.6 ± 12.1	263.5 ± 104.5
H3				
Head	130	270	14.9 ± 2.4	943.3 ± 202.3
Chest	130	121.8 ± 71.3	40.3 ± 9.8	535.9 ± 304.1
Abdomen	130	72.6 ± 20.4	31.3 ± 8.3	300.2 ± 135.4
H4				

Head	120	375	16.2 ± 2.9	1174.2 79.9	±
Chest	120	166.5 ± 77.0	38.9 ± 18.3	1077.9 479.7	±
Abdomen	120	81.6 ± 11.4	36.5 ± 8.9	547.1 252.4	±
H5					
Head	130	270	15.6 ± 0.7	975.7 262.6	±
Chest	130	97.0 ± 19.8	38.2 ± 3.8	479 ± 187.5	
Abdomen	130	98.9 ± 28.1	44.5 ± 11.5	499.5 235.9	±

effective dose from Cancer Institute of Guyana (CIG) scanners with Malaysia hospitals (H1-H5) data reveals small variation for CT scans of the head with the exception of H4 that showed a 128 % increase. An increase in effective dose was observed for these hospitals excluding H2 that uses a Siemens Emotion Duo scanner; a 2-slice unit. This decrease was expected considering design differences and the fact that, with 4-slice, the scanning of a volume of the body is carried out using a smaller slice width than that of a 2-slice, thus increasing accumulated dose. This event covers the possible reasons for the lower dose observed in H2 for all scan protocol in comparison to CIG. The opposite occurrence explains the increase in mean effective doses in the other hospitals.

Comparison of patient’s estimated dose with other referenced studies is detailed in Table 7. Comparing the mean estimated

Table 7: Details of the Scanners Specifications and Summary of Mean effective doses at Cancer Institute of Guyana (CIG) versus other reference studies with percentages difference from CIG in the bracket.

Criteria	CIG*	Malaysia Hospital						
		H1	H2	H3	H4	H5		
Manufacturer	General Electric	Siemens	Siemens	Siemens		Toshiba	Siemens	
Brand	LightSpeed Qxi	Definition AS	Somatom Emotion 16	Somatom Duo	Emotion	Activion 16	Somatom 16 Emotion	
No. of Detector	4	64	2	16		16	16	
Installation years	2009	2010	2004	2010		2010	2014	
Scan Protocol	Effective Dose (mGy)							
Head	1.75	1.9 (+8.6%)	1.5 (-14%)	2.1 (+20%)		4 (+128%)	2.4 (+37%)	
Chest	9.99	6.9 (-31%)	3.1 (-68.9%)	10.1 (+1.1%)		4.6 (-54%)	6.4 (-35%)	
Abdomen	18.94	8.9 (-53%)	4.4 (-76.7%)	4.8 (-74%)		11.7 (-38%)	(-63%)	

All mean effective dose documented for Malaysia hospitals were lower than the mean effective dose for the chest CT scan protocol apart from H3. The effective dose for these hospitals was less by a factor of 1.4, 3.2, 2.2 and 1.6 for H1, H2, H4 and H5, respectively. H3 showed a dose difference of 0.11 with a 1.1% increase with reference to CIG. Abdominal CT scan for CIG recorded a larger effective dose in comparison to the five Malaysian hospitals.

Possible explanations for the difference in the mean effective dose for the similar types of CT examination may be attributed to both site-specific methods of choosing different technical parameters to answer the same clinical question and different scanner technology. Although the clinical problem in question is identical, the imaging procedure employed at two different imaging centers may be completely different. This explains why H3 and H5 having similar scanners relating to manufacturer, brand and detector rows, documented a dose difference of as much as 37% for the similar scan protocols (chest). Some

physicians may increase field of view by increasing the scan length which may result in higher radiation exposure.

It was observed that there was variation in the measured scan parameters in the five hospitals and CIG which attributed to the difference in the size of the patients, scanned area and scan mode. For example, CIG using a scan range of 48.6 ± 4.5 cm for an abdominal CT examination and H3 using 31.3 ± 8.3 cm result in a higher effective dose observed in CIG (18.94 mGy) compared to H3 (4.8mGy). In addition, the resultant DLP which is a product of the CTDIvol and scan length varies between manufacturer and directly influence the effective dose. At CIG, with the exception of the head protocol, a larger DLP was documented for the scan protocols in comparison to majority of the Malaysian hospitals, thus resulting in a higher effective dose.

Furthermore, scanners with a varying number of detector rows as highlighted in table 7, and different brand have specific manufacturer detector configuration and dose compensation mechanism that respond to exposure contrarily from each other and thus produce dissimilar doses. GE, Siemens, and Toshiba uses Smart mA & Auto mA, Care dose 4D and Sure Exposure Dose management software respectively.

Variation in the patient dose for a specific body part within and between institutions is not necessarily a bad thing. A positive spin on variation is that it may indicate that scans are being tailored to patient body types and clinical indication [16].

Limitation

Percentage errors of equipment and human

Patient availability to perform specified computed tomography examination to obtain data.

Placement of detector as it shows up on the image and thus limiting the researcher in placing it directly under the patient.

Calibration record of machines (if not adequately done may produce inaccurate results)

Conclusion

In this study, the effective doses of common CT examinations were calculated and compared to its estimated value by the CT unit and with an international study. This study showed that the GE QXi LightSpeed CT unit is overestimating the dose the patient is receiving that proved to be advantageous since they would be receiving less exposure to radiation. The Cancer Institute of Guyana can, therefore, remain committed to their institutional standard for patient examinations.

The effective doses from diagnostic CT examinations at Cancer Institute of Guyana are comparable with results from the published study. The study shows that there are variations in technique and radiation dose across institution for similar examinations and that the protocols reported by CIG produce an overall higher effective dose than that documented in the reference study. This variation is, however a consequence of differences in CT scanner design and examination protocols.

Recommendation

The research was conducted using a 4-slice computed tomography unit and can be performed for other computed tomography unit with different slices (e.g. 16 slices) to evaluate correlation with these measurements. Also, it can be extended to include other modalities to assess the risk to patient relating to radiation exposure between different imaging modality (e.g. mammography).

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