UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

DEVELOPMENT OF NATIONAL INDICATION-BASED DIAGNOSTIC REFERENCE LEVELS AND OPTIMISATION METHODS FOR COMPUTED TOMOGRAPHY EXAMINATIONS IN GHANA

BENARD BOTWE

DEPARTMENT OF NUCLEAR SAFETY AND SECURITY

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BY

BENARD BOTWE

(10600444)

A DISSERTATION SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE AWARD OF DEGREE OF DOCTOR OF PHILOSOPHY IN RADIATION PROTECTION

DEPARTMENT OF NUCLEAR SAFETY AND SECURITY

JULY, 2020

DECLARATION

I hereby, declare that this dissertation is the result of original research work undertaken by Benard Botwe in the School of Nuclear and Allied Sciences (SNAS), University of Ghana (UG), under the supervision of Professor Cyril Schandorf (SNAS UG-Legon), Dr. Stephen Inkoom (SNAS UG-Legon) and Professor Augustine Faanu (SNAS UG-Legon). This work has not been previously accepted in substance for any degree, and neither is it being concurrently submitted in candidature for any degree.

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ABSTRACT

Background: Diagnostic reference levels (DRLs) and dose optimisation methods are crucial for effective radiation dose management. Countries utilising ionising radiation for medical purposes are required to develop and implement them, taking into consideration their clinical situations, infrastructure, population characteristics as well as social, technical and economic factors. However, in Ghana, there is no established national indication-based DRL.

Main Objective: The main objective of this study was to develop national indication-based DRL values for common and prioritised indications of the adult human body for clinical application in Ghana. It was also to assess the risk of undertaking each indication-based CT examination, and also propose some steps for dose optimisation.

Materials and Methods: The methodological approach recommended by the International Commission for Radiological Protection (ICRP), publication 135, for the development of DRLs, was employed. Studies on CT infrastructure and common indications as well as quality management systems (QMS) were conducted. Quality control (QC) tests were undertaken using a CT dose profiler, barracuda set, uniform water phantom and an ImageQC software v.1.43. Radiologists were mainly requested to define the basic diagnostic requirement of each indication. Dose descriptors such as volume weighted CT dose index ($CTDI_{vol}$) and dose length product (DLP) of reported CT scans were retrieved from the picture archiving and communication system (PACS) of scanners, constituting 71.4% of the total CT scanners in Ghana. Overall, 3,960 data sets were collected for all the common and prioritised indications which included: cerebrovascular accident (CVA) or stroke, head trauma/injury, brain tumour/space occupying lesion (SOL), lung tumour/cancer, chest lesion with chronic kidney disease, abdominopelvic lesion, kidney stone, urothelial malignancy/CT intravenous urography (CT-IVU) and pulmonary embolism (PE).

ImageJ software version 1.52 was used to analyse the objective image qualities. Statistical Package for the Social Sciences (SPSS) version 23.0 was used to extract the DRL values for the common indications in CT examinations. Microsoft excel version 2013 was used to pictorially project the results and also develop a tool (**BOT^{B}**) for dose monitoring. Lifetime Attributable Risk (LAR) of cancer incidence and mortality were estimated for various organs using a Monte Carlo-based software (National Cancer Institute Dosimetry System CT software version 2.1) and the Biological Effects of Ionising Radiation (BEIR) VII model. An anthropomorphic Alderson RANDO phantom and patients' clinical data were used to explore an optimisation method for cerebrovascular accident (CVA) imaging. Regression analyses were further used to model equations for organ doses in CVA imaging. CT phantom PBU-60 was also used to evaluate automatic exposure control (AEC) dose impact in facilities operating without AEC systems. In all inferential analyses, a *p*-value of ≤ 0.05 was used to interpret the findings as statistically significant.

Main Results: The various indications and their respective projected DRL values in terms of $CTDI_{vol}$ (mGy) and DLP (mGy.cm) were CVA/stroke (77 mGy; 1313 mGy.cm), head trauma/injury (76 mGy; 1596 mGy.cm), brain tumour/SOL (77 mGy; 2696 mGy.cm), lung tumour/cancer (12 mGy; 828 mGy.cm) and chest lesion with chronic kidney disease (13 mGy; 467 mGy.cm). Others were abdominopelvic lesion (17 mGy; 1299 mGy.cm), kidney stone (15 mGy; 731 mGy.cm), urothelial malignancy/CT-IVU (11 mGy; 1449 mGy.cm) and pulmonary embolism (14 mGy; 942 mGy.cm). The risk of PE radiation-induced breast cancer ranged from 6-115.8 people in 100,000 procedures. Moreover, CT-IVU radiation-induced colon cancer risks ranged from 53.3-66.4 people in 100,000 procedures. About 1 in 38,462 to 1 in 14,706 patients were also likely to develop ovarian cancer due to CT-IVU examinations in Ghana. A novel examination protocol was further developed in the study that could be used to scan CVA related conditions

with optimal image quality, while reducing the mean effective dose of the facilities by 23.8%, and organ doses by 32% (lens), 70.7% (spinal cord), 57.2% (thyroid) and 75.6% (oral cavity). Moreover, eight organ dose equations were developed to aid in dose management. Finally, if AEC are used in facilities operating without such systems, radiation dose levels could also be reduced by a range of 46.4-58.3% without any significant compromise on image quality.

Conclusion: The projected indication-based DRL values and optimisation methods could be used to manage CT radiation dose in Ghana.

KEYWORDS

Diagnostic Reference Levels (DRLs);

Optimisation;

Computed Tomography;

Indication-Based DRLs;

Cancer Risk.

DEDICATION

This research is dedicated to the Ohene-Botwe, Kwarteng, Obeng-Nkansah and Andoh families.

ACKNOWLEDGEMENTS

I will forever thank the almighty God for His guidance, mercies, protection and love. My special thanks go to my supervisors: Professor Cyril Schandorf, Dr. Stephen Inkoom, and Professor Augustine Faanu for their kind advice, suggestions and constant help throughout the research period. I also thank Prof. Pål Erik Goa, Linn Rolstadaas, Atle Hegge and Tommy Berglund for their scholarly advice during my exchange experience at the Norwegian University of Science and Technology (NTNU). I am extremely grateful to Dr. D. Okoh Kpeglo (HOD) and faculty members of School of Nuclear and Allied Sciences for their support. I thank the Norwegian Partnership Programme for Global Academic Cooperation (NORPART), particularly, the Ghana-Norway NORPART project facilitators, especially, Prof. J.J. Fletcher and Dr. M. Afadzi. The student exchange opportunity I had with the help of the Ghana-Norway NORPART project was a great learning opportunity for me. My special thanks also go to Dr. S. Anim-Sampong, Dr. W.K. Antwi and Dr. F. Hasford and Dr. I. Shirazu for their encouragement and scholarly advice. Further, I express my heartfelt gratitude to Prof. Mary Boadu for her support. In addition, I wish to thank the Technical Heads of CT facilities who helped in this study. Particularly, I thank Mr. B.B. Ofori-Manteaw, Mr. Evan Tettey, Rev. D. Atawone, Dr. B. D. Sarkodie, Mr. N.O. Amoah, Mr F. Botwe, Mr. Kofi Antwi, Mr Atta Osei and Mr. T. Ntiri for their assistance. I am also grateful to Mr. C.E. Kokah, Miss J.A. Mensah-Doku, Miss R.N.A. Smillie, Mr. A.A. Adi and Mr. A-B Owusu. To Mr. N.S Korto, Mr. S. Basoa, Mr V.F. Dacosta, Mr. K. Etete, Mr. S. Fanusah, Madam A. Frimpong and all who helped in diverse ways, I say may God bless you. I am extremely thankful to the Sweden Ghana Medical Centre and the Nuclear Regulatory Authority (NRA), for their support. Finally, I thank the BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana and the ISRRT-Chesney research fund managers for their financial support.

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ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
ACS	Automatic Current Selection
AD	Achievable Dose
ADMIRE	Advanced Model-Based Iterative Reconstruction
AEC	Automatic Exposure Control
AIDR	Adaptive Iterative Dose Reduction
ALARA	As Low as Reasonably Achievable
AP	Anterior-Posterior
ASIR™	Adaptive Statistical Iterative Reconstruction
BEIR	Biological Effect of Ionising Radiation
CAT	Computed Axial Tomography
$CdWO_4$	Cadmium Tungstate
CKD	Chronic Kidney Disease
CNR	Contrast to Noise Ratio
CoV	Coefficient of Variation
CT	Angiography CT
CT	Computed Tomography
CTDI	CT Dose Index
$CTDI_{vol}$	Volume Weighted CT Dose Index
$CTDI_w$	Weighted CT Dose Index

CVA	Cerebrovascular Accident
DAUT	Distance Below Lower Target
DBUT	Distance Above Upper Target
DLP	Dose Length Product
DNA	Deoxyribonucleic Acid
DRLs	Diagnostic Reference Levels
EANM	European Association of Nuclear Medicine
EAR	Excess Absolute Risk
Deff	Effective Diameter
E_D	Effective Dose
EFOM	European Federation of Organisations for Medical Physics
EFRS	European Federation of Radiographer Societies
EPA	United State Environmental Protection Agency
ERR	Excess Relative Risk
ESR	European Society of Radiology
ESTRO	European Society for Radiotherapy and Oncology
FDA	United States Food and Drug Authority
FOV	Field of View
Gd_2O_2S	Gadolinium Oxysulphide
GE	Geometric Efficiency
Gy	Gray
HU	Hounsfield Unit
HVL	Half Value Layer

IAEA	International Atomic Energy Agency
ICC	Intraclass Correlation Coefficients
ICRP	International Commission on Radiological Protection
IMR	Iterative Model Reconstruction
IRIS	Iterative Reconstruction in Image Space
IVU	Intravenous Urogram
LAR	Lifetime Attributable Risk
LARi	Lifetime Attributable Risk of Cancer Incidence
LARm	Lifetime Attributable Risk of Cancer Mortality
LAT	Lateral Patient
LCL	Lower Control Limits
LDRLs	Local Diagnostic Reference Levels
LNT	Linear No-Threshold Model
MBIR	Model-Based Iterative Reconstruction
MDCT	Multi-Detector-Row Technology
MPD	Multipurpose Detector
MSAD	Multiple Scan Average Dose
NaI	Sodium Iodide
NCICT	National Cancer Institute Dosimetry System For CT
NCRP	National Council on Radiation Protection and Measurements
NDRLs	National Diagnostic Reference Levels
NRA	Nuclear Regulatory Authority
OSL	Optically Stimulated Luminescence

PACS	Picture Archiving and Communication System
PE	Pulmonary Embolism
PET-CT	Positron Emission Tomography-CT
PMMA	Polymethyl Methacrylate
QA	Quality Assurance
QC	Quality Control
QI	Quality Improvement
QMS	Quality Management System
RDSRs	Radiation Dose Structured Reports
RSN	Reactive Nitrogen Species
SD	Standard Deviation
SNR	Signal to Noise Ratio
SOL	Space-Occupying Lesion
SPECT-CT	Photon Emission Computed Tomography-CT
SPSS	Statistical Package for The Social Sciences
SSDE	Size-Specific Dose Estimate
TLD	Thermoluminescence Dosimeters
UCL	Upper Control Limits
UK	United Kingdom
UNSCEAR	United Nations Scientific Committee on The Effect of Atomic Radiation
USA	United States of America
VIF	Variance Inflator Factor

WHO	World Health Organisation
YGdO	Yttrium gadolinium oxide
YoI	Year of Installation
YoM	Year of Manufacture

CHAPTER ONE

INTRODUCTION

1.1 Background

Computed tomography (CT) is a special radiological imaging modality which utilises x-ray photons to create cross-sectional images of the human body (Imai et al., 2018). It was invented in the early 1970s by a British engineer, Godfrey Hounsfield, and a South-African born physicist, Allan Cormack (Imaginis, 2017). CT imaging modality is considered an invaluable diagnostic tool, which is applicable for an extensive range of clinical work and research activities (Gao et al., 2017). Some unique benefits of CT include very fast scanning abilities, the production of images of good resolution, assistance in disease staging, as well as planning and treatment (National Cancer Institute, 2019). It is also relatively cheaper than other radiological imaging modalities like magnetic resonance imaging (MRI) (Gao et al., 2017). Studies (Imai et al., 2018; Gao et al., 2017; Pandharipande et al., 2016) indicate that CT impacts enormously and positively on patient management, and it has assisted in saving many lives.

In spite of the enormous benefits of CT to patients, the radiation doses associated with it are high (Pyfferoen et al., 2017) and comparatively, far higher than those utilised in conventional x-ray examinations (Vawda et al., 2015). A publication (Storrs, 2013) argued that it would take about 150 to 1,100 conventional x-rays to obtain a similar radiation dose level in the range of a single CT scan. The International Commission on Radiological Protection (ICRP) and the World Health Organisation (WHO) have also stated that worldwide CT imaging constituted approximately 6% of all medical imaging examinations. However, out of the total dose of radiation acquired through imaging, CT examination-associated doses accounted for about 43% (ICRP, 2017; WHO, 2016).

These dose statistics make CT one of the largest contributors in the medical environment (Yeh et al., 2016). The need to solve a plethora of clinical problems, as well as easy accessibility of the modality, has currently led to an upsurge in CT usage globally (WHO, 2018; Bellolio et al., 2017).

Unfortunately, the relatively high radiation doses related with CT could cause genetic changes, and induce hereditary and cancerous effects in patients (Lim et al., 2018; Goodman, 2018; Liang et al., 2017; MacGregor et al., 2015). The cancer risk (probability) also increases linearly with dose (Goodman, 2018; Vassileva and Rehani, 2011; de Gonzalez et al., 2009). Some cancer predictive models used in the United States of America (USA) have even estimated that CT examinations and their associated radiations could generate up to about 2% of future neoplasms among residents, if the radiation levels are not optimised (Brenner and Hall, 2007).

The ICRP has suggested the use of the principles of justification and optimisation to control and optimise medical exposures which include CT examinations (ICRP, 2007). The justification principle implies that the utilisation of radiation in medical imaging needs to be justified at the practice, procedure and patient levels. In particular, it requires that medical decisions involving the usage of any ionising radiation to diagnose patient conditions, should produce more benefits than harmful effects (Cannata et al., 2017). Dose limitation does not apply in medical exposures, and the optimisation procedure involves that a justified procedure, having weighed the good and the harmful effects, should be performed with the least possible dose (Cannata et al., 2017; Council of the European Union; 2014; ICRP, 2007). The optimised dose should be as low as reasonably achievable (ALARA) to ensure that the clinical objectives are met, while considering the current state of societal, technical and economic factors (Cannata et al., 2017; ICRP, 2007). One of the commonly recognised tools in the optimisation method is the development and implementation of

diagnostic reference levels (DRLs), which was formally introduced in healthcare in 1996 by the ICRP (ICRP, 2017).

The International Atomic Energy Agency (IAEA, 2014 p. 387) defines a DRL as:

> *"A level used in medical imaging to indicate whether, in routine conditions, the dose to the patient or the amount of radiopharmaceuticals administered in a specified radiological procedure for medical imaging is unusually high or unusually low for that procedure"*

It is a numerically established optimal dose parameter that, in routine practice, practitioners should aim at not exceeding, following adherence to standards, good practices, and technical performances (Tsukamoto, 2017). Hence, it is employed as a trigger to detect radiological facilities, utilising unusually high doses (outliers) in a particular radiological task, for which optimisation measures are required (Martin and Vano, 2018; Kanal et al., 2017; Vassileva and Rehani, 2015; Vawda et al., 2015). In fact, the implementation and usage of DRLs in healthcare have been found to decrease the total scale of radiation doses observed in medical environments in many countries (Gao et al., 2017; Brink and Miller, 2015; MacGregor et al., 2015).

Currently, the two CT dose descriptor values employed in establishing DRLs, in CT imaging are the volume weighted CT dose index ($CTDI_{vol}$), and the dose length product (DLP) (ICRP, 2017; Tsukamoto, 2017; Bauhs et al., 2008). The $CTDI_{vol}$ characterises the average dose per slice, whereas the DLP represents the cumulative energy absorbed along the scan length (Vawda et al, 2015).

A few researchers are working in the area of clinical indication-based DRLs, which is a new paradigm in DRL establishment (Jarvinen et al., 2015; Lajunen, 2015). This study seeks to provide a national reference data for DRLs, based upon the clinical indication for some frequently

performed CT examinations, and also to extrapolate other relevant data which could help in dose optimisation in clinical practice in Ghana.

1.2 Statement of the Problem

It is well documented that the high doses linked with CT procedures are a major global health concern in medicine (Liang et al., 2017; Gao et al., 2017; Kanal et al., 2017; WHO, 2016; Yeh et al., 2016; IAEA, 2013; ICRP, 2007). Radiation dose from CT imaging represents about 43% of the collective dose resulting from all radiological imaging examinations in medicine worldwide and could induce cancer in patients (WHO, 2016). According to a study (Pyfferoen et al., 2017), the radiation doses utilised to achieve comparable CT examinations of relatively similar diagnostic quality across facilities have to be within a relatively smaller range. However, national and multinational surveys continue to demonstrate very wide-ranging dose levels across facilities and countries (Liang et al., 2017; Lajunen, 2015; Vassileva and Rehani, 2015). In particular, dose parameter variations by way of a factor of 20 or more, have been found in anatomical regions across certain CT facilities (Liang et al., 2017).

The ICRP has proposed DRL as one of the important means to optimising the high radiation dose levels in CT imaging (Vassileva and Rehani, 2015). Further, it has been recommended that each country ought to develop its own national diagnostic reference levels (NDRLs) because, among countries, the health care structure, socio-economic conditions, procedure guidelines and protocols, as well as the anatomical structures of their people, vary (ICRP, 2017). The WHO and the IAEA have also included in their Bonn Call for Action 2, the need for the establishment, usage of, and the frequent update of DRLs for radiological examinations (WHO, 2016; IAEA, 2013,

IAEA GSR Part 3, 2014), while the European Society of Radiology (ESR) has recently included it in its EuroSafe Imaging Call for Action 2018 (European Society of Radiology, 2018).

However, in Ghana there are no established NDRLs against which dose parameters could be compared with, to ensure effective dose monitoring and optimisation, despite the installation and utilisation of several CT scanners in the country. Although some studies (Anim-Sampong et al., 2016; Addo, 2016; Akyea-Larbi, 2015; Hasford et al., 2015; Inkoom et al., 2014; Muhogora et al., 2010, Muhogora et al., 2009) have provided some dosimetric data (usually a single or few centre-studies) on the anatomical parts of the body in some facilities in Ghana, no anatomical-based NDRLs were proposed from these studies. This is largely due to the lack of adequate data on which an NDRL could be built. Furthermore, the needed collaboration between the regulatory authority, relevant professional bodies and interested parties, to establish the relevant DRLs has not been exploited.

Currently, reports (Ridley, 2016; Vock and Frija, 2016) have suggested that indication-based CT scanner protocols and DRLs, instead of anatomical references, decrease patient radiation dose considerably. The European Society of Radiology (2017), has also indicated that NDRLs based on the anatomical region do not reflect clinical practice, and should be re-examined using clinical indications. It is further argued that image quality and dose requirements vary among the different indications for an anatomical region (European Society of Radiology, 2017; Vock and Frija, 2016). Hence, the clinical indications dictate the main parameters (e.g. collimation, contrast usage, scan length) which contribute to patient radiation doses from CT (European Society of Radiology, 2017). Therefore, DRLs in CT should be indication-based (Vock and Frija, 2016; Jarvinen et al., 2015; Lajunen, 2015). Vock and Frija (2016) have again argued that, it is not logical

to use, for instance, one abdomen DRL (anatomical) as a dose benchmark for diagnosis of liver metastases and kidney stones, as is presently the norm in many organisations.

As a result, there have been recent calls for CT indication-based (indication specific) DRL development and utilisation, for optimisation purposes by several international bodies, including the European Association of Nuclear Medicine (EANM), European Society of Radiology (ESR), European Federation of Organisations for Medical Physics (EFOM), European Federation of Radiographer Societies (EFRS), and the European Society for Radiotherapy and Oncology (ESTRO) (European Association of Nuclear Medicine et al., 2017).

In CT imaging, an indication is the medical condition for which a particular CT procedure is undertaken. As such, an indication-based DRL implies a DRL that is particular to a specific disease indication (Jarvinen et al., 2015). It is expected that the establishment and implementation of indication-based DRLs, has the potential to narrow down dose-monitoring and optimisation in CT examinations, and offer another level of accountability regarding the application of radiation in medicine. Also, an indication-based DRL offers the chance to utilise a DRL that adapts to a specific medical condition, and reduces the variability and ambiguities in using anatomical regions. For instance, a DRL for lung tumour could provide the chance to relate the dose parameters to CT chest procedures, with the suspicion of a lung tumour disease, and not just chest DRLs (Lajunen, 2015). Therefore, the absence of indication-based DRLs in Ghana prevents or limits the effort of effective dose monitoring and optimisation in certain clinical tasks, especially those which require diverse levels of exposure. This current study seeks to fill this knowledge gap by developing national indication-based DRLs, based on clinical data for dose optimisation in CT imaging in Ghana.

1.3 Scope of the Study

This study was directed at developing indication-based DRLs in adult CT examinations undertaken in Ghana. It also identifies areas and steps for dose optimisations. The ICRP (ICRP, 1996) has suggested that DRLs should be developed for the common and prioritised diagnostic procedures which contribute significantly to the population dose. Hence, this study was limited to common indications relating to the head, chest, and abdomino-pelvic regions for adult patients as they account for the highest number of CT cases in Ghana (Inkoom et al, 2014). The dose descriptors of interest in the DRLs development were the $CTDI_{vol}$ and the DLP. Moreover, to achieve the aims and objectives of the study, CT technical data, scanner performance characteristics, common indications, image quality and diagnostic imaging requirements, were all considered. Furthermore, to quantify the dose impact associated with undertaking these indication-based CT procedures, and for optimisation steps to be recommended, the lifetime attributable risk (*LAR*) of cancer incidence and cancer mortality for each indication were estimated, while different steps for dose optimisation were also evaluated.

1.4 Main Objective

The main objective of this study was to develop national indication-based DRL values for common and prioritised indications of the adult human body for clinical application in Ghana. It was also to assess the risk of undertaking each indication-based CT examination, and also propose some steps for dose optimisation.

1.5 Specific Objectives

The specific objectives included:

1. To obtain technical data on CT scanners in the country and information on common indications for adult CT examinations, and as well define the basic diagnostic imaging requirements for each common indication in Ghana;
2. To obtain performance characteristic data on CT scanners in the country;
3. To evaluate CT dose descriptors/quantities and image qualities of CT images of the indications prioritised for DRL development;
4. To establish the national indication-based DRL values for common and prioritised indications;
5. To estimate the dose impact and risk of cancer associated with undergoing CT imaging for each of the indications in Ghana;
6. To propose measures for dose optimisation for the protection of patients in CT examinations in Ghana; and

1.6 Relevance and Justifications for the Study

1.6.1 New Research Area in Ghana

CT application in healthcare in Ghana has increased dramatically in recent times (Inkoom et al, 2014). Although, CT scans have positively contributed immensely to patient care, it delivers a high radiation dose to patients compared to conventional x-rays in the diagnosis of diseases (Storrs, 2013; Pearce et al, 2012). Studies (Anim-Sampong et al, 2016; Inkoom et al, 2014), have established that there are appreciably high CT radiation dose levels in the few facilities they have studied in Ghana. As part of the optimisation process, there is a need to guarantee that the doses used in CT facilities are judiciously and adequately accounted for, so that the harmful effects connected with CT imaging are minimised. The development of national indication-based DRLs in this study would be the first study in Ghana to characterise and benchmark the dose needed for specific indications for CT investigations of body parts. This development and subsequent implementation of the indication-based DRLs is expected to decrease the range of doses observed in clinical practice (ICRP, 2017; European Society of Radiology, 2017; Lajunen, 2015; IAEA, 2013).

1.6.2 Policy Implications

The use of ionising radiation in medicine requires some binding policies and regulations. Many international recommendations (ICRP, 2017; European Society of Radiology, 2017; WHO, 2016; European Union, 2014; IAEA, 2013; American College of Radiology; 2013) have suggested the development or adoption and implementation of DRLs, and recently, indication-based DRLs in respective countries to further regulate radiation usage in diagnostic radiology. Ghana, (a member of IAEA and WHO), is yet to accomplish this by the national regulatory authorities. It is

believed that the lack of extensive research-based data to support the facilitation of this has been a drawback to the establishment of this policy. This study is timely, and its anticipated outcome should offer a data reference and foundation on which such policies and regulations can be built.

In addition, health authorities in partnership with medical professional organisations must be responsible for establishing or adopting DRLs, and ensuring that as much as possible, the doses from medical imaging remain within the set levels (IAEA, 2019). The results of this study will go a long way to provide a reliable basis on which such organisations can work together to promote sustainable programmes to ensure optimisation of patient protection and safety.

1.6.3 Health Implications

A report (Ridley, 2016) argued that indication-based DRLs from seven CT facilities in Switzerland have proven to significantly lower doses to patients. Therefore, the establishment and implementation of indication-based DRLs could also narrow down dose monitoring in CT examinations in Ghana, and offer another level of dose accountability in healthcare. Studies (Liang et al, 2017; MacGregor et al, 2015; Vassileva and Rehani, 2015; de González et al, 2009) have proven cancer risks associated with CT exposures. The DRLs proposed for Ghana could also be utilised to assess if a facility's dose index is remarkably high, and hence prompt corrective measures. This, in turn, would help to reduce adverse impacts such as radiation-induced cancer in patients.

Moreover, there is currently no national indication-based DRL developed for Ghanaian healthcare which radiographers, radiologists, medical physicists, etc., may use as a country-based guide to regulate and optimise their practices in Ghana. It is envisaged that the outcomes of this study would offer a required tool to resolve these inadequacies.

1.6.4 Research Implications

In Ghana, research activities on indication-based DRLs have just began with this study. It is anticipated that the outcome of this thesis would form the foundation on which future research studies could be based, and other DRLs developed for other pathological cases. This would not only serve Ghana, but would also serve as a model for other African countries that may like to develop a research focus in this area since there is no published work in the African sub-region on indication-based DRLs.

1.7 Organisation of Thesis

This dissertation consists of five chapters. Chapter One deals with the introduction, which outlines and explains the background, problem statement, objectives, relevance and scope of the thesis. Chapter Two deals with the literature review relevant to existing information on the study area under investigation. Chapter Three deals with the materials and methods used for undertaking the study. Chapter Four presents the results and the relevant discussions using relevant literature. Chapter Five covers the conclusions and recommendations to recognised stakeholders.

CHAPTER TWO

LITERATURE REVIEW

2.0 Overview

This Chapter presents information on the current knowledge and developments available in the literature on CT imaging, basic application of CT in medicine, CT dosimetry, typical radiation doses in CT, radiation risks, dose management, and optimisation in CT imaging and DRLs. Topics under DRLs include DRL in medicine, the role of DRLs in CT optimisation, anatomical DRLs in CT, indication-based DRLs, existing indication-based DRLs in CT, and theories guiding the DRL development in CT are discussed.

2.1 Computed Tomography Imaging

CT, also referred to as computed axial tomography (CAT) scanner is a specialised radiological equipment which employs x-rays to generate cross-sectional radiological images and diagnostic information of the human body, and was invented in the early 1970s by Godfrey Hounsfield and Allan Cormack (Imaginis, 2017).

A typical CT scanner is made up of an x-ray tube which revolves round a patient producing x-ray beams which transmit through a cross section of the body. It also features an array of detectors which receive the transmitted x-ray beam intensities, and are linked to a mathematical algorithm for image processing (Duncan and Panahipour, 2014). The x-ray tube is made up of a cathode from which an applied current heats up the filament, releasing electrons through thermionic emission (Radiologycafe, 2019). When a large potential difference is applied to the anode, the electrons are accelerated towards the anode, and collide with heavy atoms in the metal anode (Disher et al., 2006). A sudden slowdown of electrons as a result of the bombardment,

causes the electrons to lose their energies, while part of it is converted into x-rays through the *bremsstrahlung* effect. Alternatively, an incoming electron could eject an inner shell electron, which causes an outer shell electron to move down to replace the ejected one, thereby creating an x-ray called a "K-shell" emission (Radiologycafe, 2019). The generated photons are used in CT imaging. A schematic diagram of an x-ray tube, the interactions leading to the emission of x-rays, as well as a typical CT imaging setup consisting of the x-ray beam spectrum and its relationship with the patient and detectors for CT imaging, is shown in Figure 2.1.

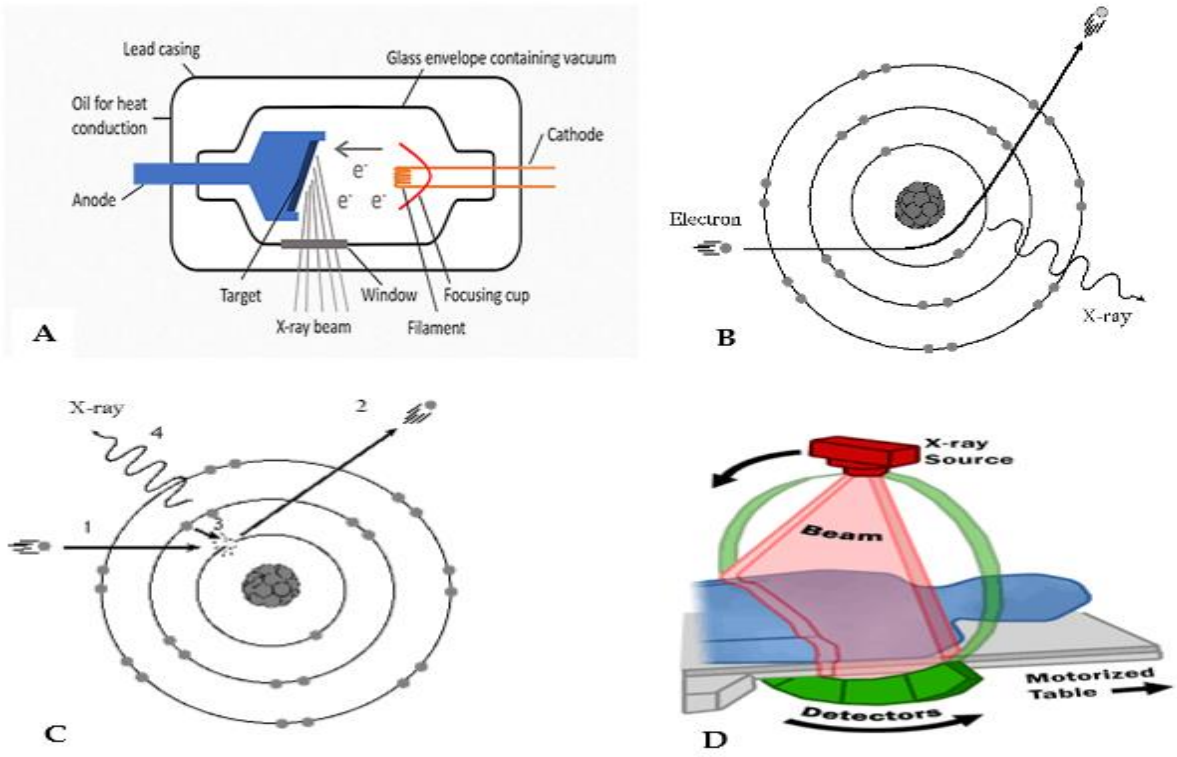


Figure 2.1: Schematic diagram of an x-ray tube and production (Plate A), *bremsstrahlung* interactions (Plate B), "K-shell" emission (Plate C) and a typical CT imaging setup consisting of the x-ray beam spectrum and its relationship with the patient and detectors for CT imaging (Plate D) (Radiologycafe, 2019; Disher et al., 2006).

In the CT setup, the basic principle of imaging involves the production of a photon attenuation map (image) of a body, as a result of the variable attenuation of an x-ray beam as it goes through the body of a patient, exposing a given volume of tissue from all directions (Bauhs et al., 2008). The philosophy underpinning CT imaging is grounded on the premise that the structural formation of an object obtained by a detector, can be reconstructed from multiple projections of the object, by utilising computer algorithms to create attenuation profiles of the variation of tissue radiodensity (Duncan and Panahipour, 2014). To create an image, several hundreds of attenuation coefficient spectra are formed in each rotation of the x-ray tube across the body of the patient under an examination (IAEA, 2012). These attenuation coefficients are then used to calculate the CT number values in Hounsfield units (HU) and subsequently, into a visible image characterised by diverse shades of grey (IAEA, 2012). Older scanners used back projection techniques to generate images (Padole et al., 2015). Filtered back projection has been used on modern scanners for a long time. Currently, iterative reconstruction is also used to reconstruct millions of data points when radiation transmits through a tissue in CT imaging (Ozdiev et al., 2018). Figure 2.2 presents a simple schematic diagram of CT imaging process.

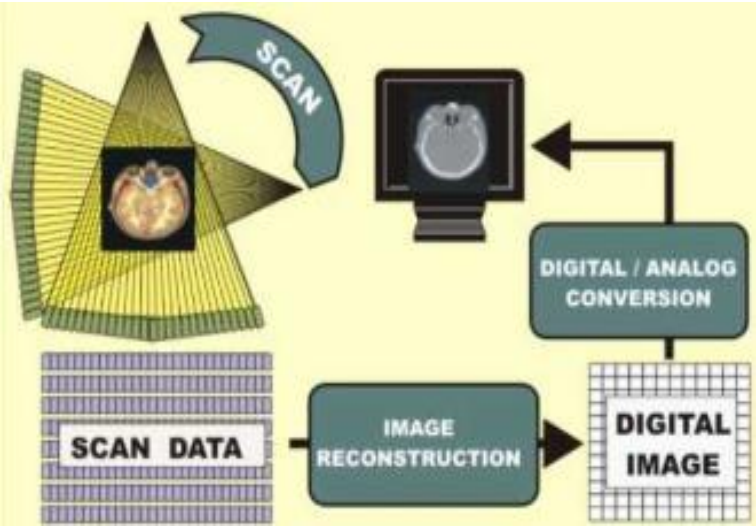


Figure 2.2: A simple schematic diagram of CT imaging process (Sprawls, 2019).

CT scanners have undergone a number of design changes, and there have been seven generations since the discovery (Ali, 2015). The early generation CT scanners generated an image per one complete tube rotation in about 5 minutes (Ali, 2015). These machines were called single-slice CT scanners (Ali, 2015). In modern scanners, multiple slices (presently reaching 640) are produced instantaneously in a rotation within 0.5 second and are referred to as multidetector CT scanners (MDCT) or multislice CT scanners (MSCT) (IAEA, 2012). Early CT machines utilised scintillation detectors including sodium iodide (NaI) or cadmium tungstate ($CdWO_4$) (IAEA, 2012). Subsequently, these early detectors were largely replaced by high-pressure xenon systems. Scintillator doped ceramics like gadolinium oxysulphide (Gd_2O_2S) or yttrium gadolinium oxide (YGdO) (IAEA, 2012) have been utilised in recent years. High dynamic range, superior quantum absorption efficiency, and a fast temporal response with low afterglow, are the essential specifications and factors in their development that make them very reliable detectors (IAEA, 2012).

2.2 Basic Application of Computed Tomography in Medicine

CT modality is considered a very valuable diagnostic tool, which is applicable for an extensive range of clinical and research purposes (Gao et al., 2017). Faster scanning speed, isotropic spatial resolution, shorter computer reconstruction times, affordability compared to other imaging modalities like MRI, applications in staging, and the planning and treatment of cancer, are some of its exceptional benefits to mankind (de Basea et al., 2016; Abdulkadir et al., 2016; Yu et al., 2009; Tsukagoshi et al, 2007). It is presently one of the extensively utilised medical imaging machines in clinical applications, because it is often the most appropriate modality for

certain types of screening, diagnosis, treatment and the management of patients' diseases (Gao et al., 2017; Dauer and Hricak, 2014).

In emergency departments for instance, CT results substantially influence diagnostic confidence, and admission decisions (Pandharipande et al, 2016). Studies (Imai et al., 2018; Furugori et al., 2018; Cheung et al., 2018) have shown that CT utilisation has significantly reduced mortality levels in hospitals. The development of MDCT technology with sub-second acquisition and CT fluoroscopy (enabling interventional radiological procedures to be undertaken) have advanced CT applications in medicine (European Society of Radiology, 2017). Furthermore, the development of hybrid radiological modalities such as single photon emission computed tomography-CT (SPECT-CT), positron emission tomography-CT (PET-CT), and CT simulation machine in radiotherapy treatment planning amongst others, is strengthening CT utilisation and applications in radiotherapy, nuclear medicine, and other treatment planning workups in healthcare (Sergieva et al, 2014). The positive impact of CT in medicine, has created an upsurge in its utilisation globally. In the USA for example over 70 million CT scans are undertaken yearly, and over 5 million in the United Kingdom (UK) with an increasing annual rate of 10% (de Basea et al., 2016).

In Ghana, the first CT scanner was installed in 1994 at the Korle Bu Teaching Hospital. Since then, there has been an increased number of installations in the public, private and private-government (quasi) organisations (Schandorf and Tetteh, 1998). In 2012, the Government of Ghana undertook a large-scale old equipment replacement exercise and also planned to provide at least one CT scanner in each teaching or regional hospital (Ministry of Health, 2014). These initiatives, coupled with the development of private health facilities, have resulted in the installation of a greater number of CT scanners in the country, with the intention of improving

patients' access to good healthcare (Ministry of Health, 2014). Although there is no documented data on the extent of the impact of CT scanners in Ghana, they are well known to impact positively on patients' care, as they are used to diagnose, plan, stage disease processes, and carry out interventional radiological procedures.

2.3 Computed Tomography Dosimetry

The principal CT dosimetry formalism is grounded on the CT dose index (CTDI) and its variants, which are measured in gray (Gy) (McLean and Chapple, 2015). Although it does not explicitly provide patients' individual doses, it characterises the average absorbed dose output per slice, in a standard geometry, from which a patient's dose estimation can be made (McCollough et al., 2011).

2.3.1 Computed Tomography Dose Index (CTDI)

The term CTDI is "the integral of the single scan radiation dose profile along the z-axis, normalized to the thickness of the imaged section (slice thickness)" (Bauhs et al., 2008 p. 246). During CT imaging, the radiation energy deposition in the body extends outside the collimated area, owing to scatter radiation effects, divergence of the beam, and the penumbral and restricted efficiency of the collimator (Boone et al., 2012). CTDI accounts for the scatter tails to obtain correct integration limits in a standardised and convenient manner. Mathematically, the CTDI is defined in equation 2.1 as:

$$CTDI = \frac{1}{NT}\int_{-\infty}^{+\infty} D(z)dz \qquad (2.1)$$

where

$D(z)$ is a radiation dose profile (air kerma in a phantom) along the z-axis, z, centred at $z = 0$, N is the number of detector channels and T is the width of each channel (Bujila et al., 2018). The quantity NT denotes the nominal total collimation width of the scan. In MDCT scanners, many detector elements could be organised to make one data channel, hence $N > 1$ (American Association of Physicists in Medicine [AAPM], 2007). In single-detector-row CT, N=1, hence the z-axis collimation (T) at the isocentre is the nominal scan width (Huda, 2011).

2.3.2 $CTDI_{FDA}$

The dose contribution from the scanner along the z-axis and penumbral radiation dose profile should be accounted for in CTDI measurements. However, the exact integration limits were not defined in CTDI (Boone et al., 2012). To normalise CTDI measurements (as infinity is not a possible measurement quantity), the United States Food and Drug Authority (FDA) introduced the integration limits of ± 7T ($CTDI_{FDA}$ *over 14 slices)*, where T signified the nominal slice width (United States Food and Drug Administration, 1984). Mathematically, the $CTDI_{FDA}$ is calculated from equation 2.2 as:

$$CTDI_{FDA} = \frac{1}{NT}\int_{-7T}^{+7T} D(z)dz \qquad (2.2)$$

where

$D(z)$, z, N and T maintain their usual meanings as defined in equation 2.1, and +7T and -7T are the integration limits of radiation dose profile/output.

However, the limits of integration in $CTDI_{FDA}$ were not equally estimated in terms of NT, permitting for the possible underestimation of the multiple scan average dose (MSAD) by the CTDI, especially in thin slices or narrow slice widths (Bauhs et al., 2008; Dixon and Ballard, 2007).

2.3.3 $CTDI_{100}$

In order to standardise the measurement length and limits as observed in the $CTDI_{FDA}$, the $CTDI_{100}$ was defined with the integration limits fixed at the standard length of a commercially accessible pencil ionisation chamber (100 mm) (AAPM, 2008). It was introduced to produce an integration of the radiation dose profile of the accumulated scan dose distribution over a 100-mm pencil ionisation chamber from a single axial scan (McCollough et al., 2011). Mathematically, the $CTDI_{100}$ is expressed from equation 2.3 as:

$$CTDI_{100} = \frac{1}{NT}\int_{-50mm}^{+50mm} D(z)dz \qquad (2.3)$$

where

+50 mm and -50 mm are the integration limits of radiation dose profile/output 100-mm using a pencil ionisation chamber and $D(z)$, z, N and T maintain their usual meanings as defined in equation 2.1.

However, $CTDI_{100}$ only characterises the total multiple scan dose at the middle of a 100-mm scan and could underestimate the total dose for scan lengths greater that 100 mm (McCollough et al, 2011).

2.3.4 Weighted CT Dose Index ($CTDI_w$)

During CT imaging, radiation dose reaching the peripherals and the centre of a phantom under investigation are not exactly the same. To account for dose levels across varying fields of view, and not just at the centre, and avoid the limitations of other variants of CTDI, the weighted CT dose index ($CTDI_w$) was developed. The $CTDI_w$ represents the weighted average radiation dose

assessed at the centre ($CTDI_{100}c$) and peripherals ($CTDI_{100}p$) of a standard phantom, polymethyl methacrylate (PMMA), across a field of view (Baughs et al., 2008). It is expressed mathematically using equation 2.4 as:

$$CTDI_w = \frac{1}{3}\left(CTDI_{100,centre}\right) + \frac{2}{3}\left(CTDI_{100,periphery}\right) \qquad (2.4)$$

where the symbols bear their defined meanings.

However, $CTDI_w$ does not describe doses for helical scans. Moreover, it has a limitation in estimations of doses for non-adjacent slices frequently seen in helical scanning where the x-ray beams may overlap (common with MDCT), or where extended pitch leaves gaps between rotations.

2.3.5 Volume Weighted CT Dose Index ($CTDI_{vol}$)

Helical scan technology utilises continuous gantry-rotation and incremental table feed to provide for a longer anatomic coverage in a shorter time (Fukuda et al., 2014). In estimating the dose in a helical scan, it is crucial to consider gaps or overlays between the radiation beams from successive revolutions of the x-ray source, when helical scans are used (Bujila et al., 2018). The volume weighted CTDI ($CTDI_{vol}$) embodies the average dose output in the central region of a multiple scan examination, and considers scan spacing and helical pitch (Huda, 2011; AAPM, 2008). Mathematically, it is written using equation 2.5 as:

$$CTDI_{vol} = \frac{1}{pitch} CTDI_w \qquad (2.5)$$

where

$CTDI_{vol}$ is volume weighted CTDI and $CTDI_w$ is weighted CTDI.

$CTDI_{vol}$ is measured using a100-mm long ionisation chamber or linear array of point dose measurements utilising thermoluminescence dosimeters (TLDs), film, metal-oxide-semiconductor field-effect transistors (MOSFET), optically stimulated luminescence (OSL), or solid state (diode) detectors. The RTI Electronics Group (Mölndal, Sweden) in particular, makes a solid-state detector probe known as the CT dose profiler that has proven reliability for this application (RTI Group, 2016; Bauhs et al., 2008).

2.3.6 Dose Length Product

To be able to easily calculate the absorbed radiation dose along the entire scan length of a CT examination, the dose length product (DLP), measured in milligray-centimetres (mGy.cm) was introduced in CT dosimetry (Fukuda et al., 2014; Boone et al., 2012; Huda, 2011; AAPM, 2008). The concept of DLP integrates both the mean $CTDI_{vol}$ and the total distance (L_s) scanned (IAEA, 2013). Since the DLP is not a satisfactory risk indicator, it requires a conversion factor to express in effective dose. Currently, it is mandatory that CT scanners display both $CTDI_{vol}$ and DLP on the operator's console (ICRP, 2017; International Electrotechnical Commission, 2011). Mathematically, DLP is expressed in equation 2.6 as:

$$DLP = CTDI_{vol} \cdot L_s \qquad (2.6)$$

where L_s is the scan length and $CTDI_{vol}$ is the volume weighted computed tomography dose index.

2.3.7 Effective Dose

Effective dose (E_D) is "the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the human body and represents the stochastic health risk to the whole body" (ICRP, 2007 p.23). It is a single radiation dose descriptor that expresses the risk of a non-uniform radiation exposure in respect of an equivalent whole-body exposure (Mullenders et al., 2009). E_D has a unit of Sievert (Sv) and one Sv indicates a 5.5% risk of cancer development (ICRP, 2007). Generally, the ICRP (2007) expresses E_D by the equation 2.7:

$$E_D = \sum_T w_T \sum_R w_R \, D_{T,R} \quad or \quad E_D = \sum_z \left[\sum_T w_T H_T \right] \qquad (2.7)$$

where

w_T = the ICRP tissue-specified weighting factor for tissue or organ *T* under examination.

w_R = radiation weighting factor

$D_{T,R}$ = absorbed dose in tissue *T* by radiation type *R*

H_T *or* $w_R D_{T,R}$ = the corresponding equivalent dose to the specified tissue or organ, *T* (ICRP, 2007).

However, in CT imaging, this dose quantity could be estimated via multiplying the DLP with derived conversion factors or appropriately normalised coefficients that are specific to age, scanned region and CT geometry. This is expressed by equation 2.8 as.

$$E_D = kxDLP = kLCTDI_{vol} \qquad (2.8)$$

where *k* is the conversion factor for changing DLP to effective dose (E_D) and unit is mSv/mGy.cm. *DLP* is dose length product, $CTDI_{vol}$ is volume weighted CT dose index and *L* is scan length.

2.3.8 Size-Specific Dose Estimate (SSDE)

Measured in milligray (mGy), the size-specific dose estimate **(**SSDE), is a newer CT-derived descriptor that integrates patient-size-adjusted correction factor (*f*) based on patient's effective diameter (d_{eff}) to efficiently predict patient dose (AAPM, 2014). The effective diameter is defined as "the square root of the product of the anterior-posterior (AP) and lateral patient diameter (LAT)" (AAPM, 2014, p.4). With knowledge of the d_{eff}, the *f f*actor could be derived from the AAPM Report 204 to estimate SSDE (Boone et al., 2011). A diagram of AP and LAT diameter is shown in Figure 2.3.

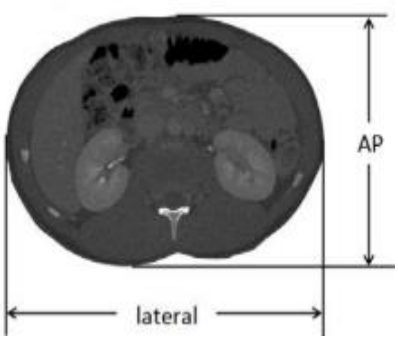


Figure 2.3: AP and LAT diameter measurements

Mathematically, d_{eff} and SSDE (from 16 or 32 phantom size) are expressed in equations 2.9 and 2.10, respectively as:

$$d_{eff} = \sqrt{(APxLAT)} \tag{2.9}$$

$$SSDE = CTDI_{vol}^{16or32} xf^{16or32} \tag{2.10}$$

where *f* factor is patient-size-adjusted correction factor, AP is antero-posterior, LAT is lateral patient diameter, d_{eff} is effective diameter and $CTDI_{vol}$ is volume weighted CT dose index.

2.4 Typical Radiation Doses in Computed Tomography

According to the WHO, the global CT usage represented about 6% of all medical imaging procedures performed, but it accounted for about 43% of the total dose resulting from those procedures (WHO, 2016). Recent publications (Smith-Bindman et al., 2019; Canadian Nuclear Safety Commission, 2019; Pyfferoen et al., 2017; Liang et al., 2017) continue to suggest CT as the major contributor to patient radiation exposure in medicine. Particularly, national and multinational surveys continue to indicate wide-ranging CT radiation dose levels across facilities and countries (Smith-Bindman et al., 2019).

Reviewed international publications, with emphasis on commonly performed procedures, indicate typical paediatric CT effective doses in the range of head (0.8-2.0 mSv), chest (1.1-5.1 mSv), abdomino/pelvic (0.6-23.5 mSv) and spine (0.6-10 mSv) (Strauss et al., 2019; Ekpo et al., 2019; Saravanakumar et al., 2017; Kanal et al., 2017; Public Health England, 2016; European Union, 2014; Miglioretti et al., 2013; Brady et al., 2012; Muhogora et al., 2010). Adult CT effective doses also fall in the range of head (1.5- 5.8 mSv), abdomen (8.0- 39 mSv), chest (2.7-24 mSv), thorax high resolution (13.4-25 mSv), CT pulmonary angiogram (2.7-30 mSv), abdomen low-dose for kidney stones (3.3-11 mSv), CT urography (2.5-45 mSv) and thorax-abdomen (11.5-40 mSv) (Canadian Nuclear Safety Commission, 2019; IAEA, 2019; Ekpo et al., 2018; United States Food and Drug Administration, 2017; Public Health England, 2016; van der Molen et al., 2013; Korir, 2012; Muhogora et al., 2009; Smith-Bindman et al., 2009; ICRP, 2000). A recent study (Smith-Bindman et al., 2019) which evaluated the variation in adult radiation dose for CT procedures among countries also found a large variation of about a 4-fold range (7.0-25.7 mSv) in the mean effective dose for adult abdominal CT procedures.. The mean effective dose for chest CT examination also ranged from 1.7-6.4 mSv, while that of combined chest and abdomen CT

examinations varied from 10.0-37.9 mSv. Head and pulmonary embolism CT effective doses also varied from 1.4-1.9 mSv, 8-27% and 5. 0- 33.2 mSv, respectively.

In Ghana, there is a paucity of studies on national radiation dose levels in CT. However, available studies, mainly among few facilities, provide pertinent information on the dose levels across some facilities in the country. In particular, studies (Sackey et al., 2018; Akyea-Larbi et al., 2016; Anim-sampong et al., 2015; Hasford et al., 2015; Inkoom et al., 2014) reported adult CT effective doses in the range of head (1.1-5.2 mSv), chest (2.7 - 13.5 mSv), abdomen (5.3-24.0 mSv), neck (2.58-4.5 mSv), pelvis (4.82-9.1 mSv), and lumbar spine (9.2-11.2 mSv). Another study (Shirazu et al., 2017a) has quite recently reported mean renal doses of 10.36 mSv for females and 11.58 mSv for males in Ghana. With respect to paediatrics, a couple of studies (Addo, 2016; Gedel and Gablah, 2014) have reported CT effective doses in the range of head (0.9-3.2 mSv), chest (1.14-13.3 mSv) and abdomen (1.42-17.7 mSv). These evidences indicate that the radiation doses associated with CT imaging are high (more than 150 times) compared with conventional x-rays (Pyfferoen et al., 2017; Storrs, 2013). Therefore, there is the need for dose management and optimisation methods to reduce the potential health risks associated with CT radiation in Ghana and beyond (Pyfferoen et al., 2017; Storrs, 2013; Pearce et al., 2012).

2.5 Radiation Risks

Ionising radiation could cause detrimental effects to living tissues and the mechanisms leading to these effects are complex. Basically, during exposure of living tissues to ionising radiation, energy is deposited in the tissues which could disrupt the organic molecules causing direct or indirect damage to the deoxyribonucleic acid (DNA) (Desouky et al., 2015). A DNA that is directly struck by ionising radiation could suffer direct damage, disrupting the genetic information. Indirect damage also arises when radiation interacts near the genetic material and releases electrons which react with a water molecule, forming a strong free radical (Pearce et al., 2012). The radiation interactions can create several highly reactive radicals that could react with DNA molecules to cause molecular structural injuries (Alkhorayef et al., 2017; Desouky et al., 2015; Mazrani et al., 2007). Due to the small volume of the DNA in relation to that of the cell, the probability of the occurrence of direct radiation damage of DNA is small (Goodman, 2018). Most (2 in 3) x-ray radiation induced damages are caused by indirect processes, as a cell is made up of nearly 70% water (Pearce et al., 2012). Apart from the effect of water radiolysis products, some evidence (Wardman, 2009) suggests that radiation activated reactive nitrogen species (RNS,) among others, could also cause molecular damage in the DNA. Damage to a DNA, through direct or indirect means, may be repaired correctly, or have several consequences. These include cell apoptosis or genetic mutations and alterations, which could induce health abnormalities and carcinogenesis (manifesting themselves over several years, even decades later) (Shah et al., 2012). The risk is much higher among children than in adults, because of the radiosensitivity of their developing tissues as a result of their rapidly dividing cells, high metabolic rate and developing cells (Goodman, 2018; Minami and Kudo, 2015). Figure 2.4 illustrates the direct and indirect impact of radiation dose on the DNA.

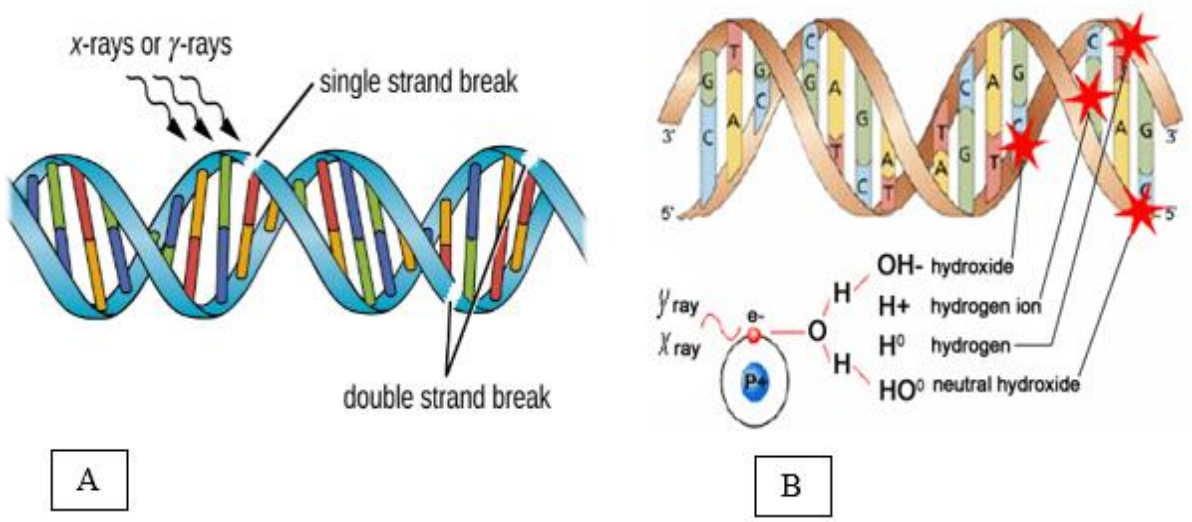


Figure 2.4: Schematic diagram of radiation impact on DNA, where plates A and B show direct and indirect impacts of radiation, respectively (Teach Nuclear, 2019).

The effect of radiation on humans has been classed into deterministic and stochastic effects. Deterministic effects are those that ensue when a threshold of dose has been exceeded, and the severity of the effect increases with radiation dose (Shah et al., 2012; Hall and Brenner, 2008). Some deterministic effects and their radiation threshold levels include erythema (2 Gy), epilation (3 Gy), cataract (2-10 Gy), sterility (2.5-3.5 Gy) and death (> 10 Gy to whole body) (Goodman, 2018).

Any radiation effects (primarily cancer and genetic effects) which occur by chance, without exceeding a radiation threshold level are referred to as *stochastic effects*. The probability of its incidence increases with dose (Alkhorayef et al., 2017; Desouky et al., 2015). At low dose levels (below 100 mSv), including CT doses, stochastic effects could occur, though, there are considerable uncertainties in estimating the risk of developing a radiation-induced cancer (National Research Council, 2006). Statistical models indicate that higher radiation levels (as used in CT) may cause more stochastic effects than low levels (as in conventional x-rays) (National

Research Council, 2006). Radiation-induced effect responses for both deterministic (a) and stochastic effects (b), are presented in Figure 2.5.

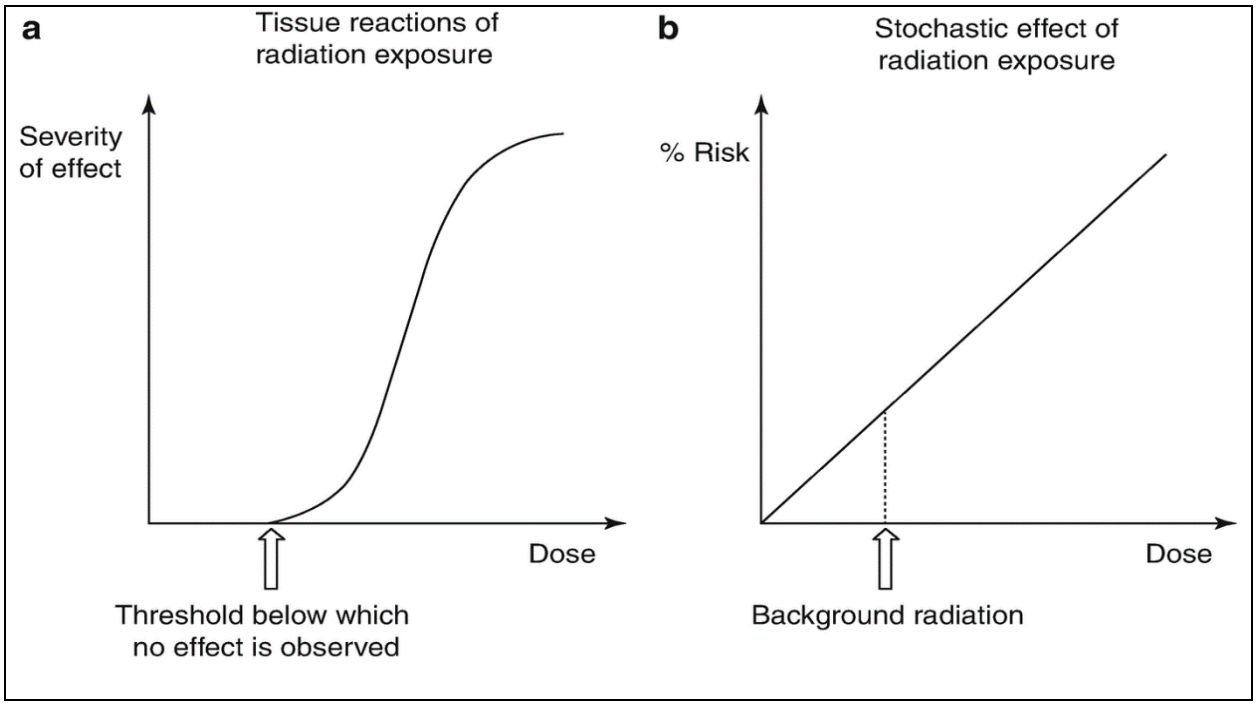


Figure 2.5: Diagram of deterministic (a) and stochastic (b) effect-dose response curves (Rahman, 2018).

Models used to predict radiation risks have been established by organisations such as the National Council on Radiation Protection and Measurements (NCRP, 1993), the United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR, 2000), the United States Environmental Protection Agency (1999), the Biological Effect of Ionising Radiation (BEIR VII) Committee (National Research Council, 2006), and the ICRP (ICRP, 2007). In literature, the BEIR VII Report of 2006 (phase 2) is considered the most widely used model for estimating risk of cancer, based on the magnitude of a single radiation exposure, and a patient's age and sex at exposure (National Research Council, 2006). The model was developed based on the extensive studies on the survivors of Hiroshima and Nagasaki atomic bombs explosion, and is centred on the

linear no-threshold model (LNT) concept, with the assumption that the smallest dose has the potential to cause a small increase in radiation risk to humans (National Research Council, 2006).

Specific models used to express cancer risks include the excess relative risk (ERR), which is the proportional increase in risk over the background absolute risk (in the absence of exposure), and the excess absolute risk (EAR) which is the additional risk above the background absolute risk (Lim et al., 2018). The lifetime attributable risk (LAR) uses different final risk models such as EAR and ERR to predict risks for different organs (Lim et al., 2018). The LAR is defined as the probability of radiation-induced cancers or related mortality in a population of 100,000 who have been exposed to 100 mGy (Halid et al., 2018). The LAR at the age of "*a"* for a gender "*g*" given an exposure of *"D*" at an exposure age "*e*" can be expressed as follows (equation 2.11).

$$LAR(D,e,g) = \int_{e+L}^{a\max} M(D,e,a,g)\frac{S_{aj}(a,g)}{S_{aj}(e,g)}da \qquad (2.11)$$

where L = minimal latent period (5 year for solid cancers, 2 year for leukaemia),

$S_{aj}(a, g)$ = a survival rate for gender "*g*" aged "*a*" unless the person suffers exposure to radiation,

$S_{aj}(a,g)/S_{aj}(e,g)$ = a conditional probability that a person survives from the exposure age "*e*" till an attained age, $M(a,g)$ = baseline risk, ω = risk transport weight factor obtained from the BEIR VII report (Lim et al., 2018).

In EAR model: $M(D,e,a,g) = EAR(D,e,a,g)$ (2.12)

ERR model: $M(D,e,a,g) = ERR(D,e,a,g)$ (2.13)

Combined model: $M(D,e,a,g) = \omega EAR(D,e,a,g) + (1-\omega)ERR(D,e,a,g)m(a,g)$ (2.14)

For simplicity, the BEIR VII report has generated lifetime attributable risk of cancer incidence and mortality coefficients. They have been aggregated with cancer rates in 100,000 lives for various organs based on a single dose of 0.1 Gy at several specific ages, from which many explorations on radiation risks could be estimated (National Research Council, 2006). Tables 2.1 and 2.2 show the lifetime attributable risk of cancer and mortality coefficients, as aggregated by the BEIR model.

Table 2.1: Lifetime attributable risk of cancer incidence coefficients from Table 12D-1 of BEIR Report (National Research Council, 2006)

	Age at Exposure (years)										
Cancer Site	0	5	10	15	20	30	40	50	60	70	80
Males											
Stomach	76	65	55	46	40	28	27	25	20	14	7
Colon	336	285	241	204	173	125	122	113	94	65	30
Liver	61	50	43	36	30	22	21	19	14	8	3
Lung	314	261	216	180	149	105	104	101	89	65	34
Prostate	93	80	67	57	48	35	35	33	26	14	5
Bladder	209	177	150	127	108	79	79	76	66	47	23
Other	1123	672	503	394	312	198	172	140	98	57	23
Thyroid	115	76	50	33	21	9	3	1	0.3	0.1	0.0
All solid	2326	1667	1325	1076	881	602	564	507	407	270	126
Leukemia	237	149	120	105	96	84	84	84	82	73	48
All cancers	2563	1816	1445	1182	977	686	648	591	489	343	174
Females											
Stomach	101	85	72	61	52	36	35	32	27	19	11
Colon	220	187	158	134	114	82	79	73	62	45	23
Liver	28	23	20	16	14	10	10	9	7	5	2
Lung	733	608	504	417	346	242	240	230	201	147	77
Breast	1171	914	712	553	429	253	141	70	31	12	4
Uterus	50	42	36	30	26	18	16	13	9	5	2
Ovary	104	87	73	60	50	34	31	25	18	11	5
Bladder	212	180	152	129	109	79	78	74	64	47	24
Other	1339	719	523	409	323	207	181	148	109	68	30
Thyroid	634	419	275	178	113	41	14	4	1	0.3	0.0
All solid	4592	3265	2525	1988	1575	1002	824	678	529	358	177
Leukemia	185	112	86	76	71	63	62	62	57	51	37
All cancers	4777	3377	2611	2064	1646	1065	886	740	586	409	214

NOTE: Number of cases per 100,000 persons exposed to a single dose of 0.1 Gy.

Table 2.2: Lifetime attributable risk of cancer mortality coefficients from Table 12D-2 of BEIR report (National Research Council, 2006)

	Age at Exposure (years)										
Cancer Site	0	5	10	15	20	30	40	50	60	70	80
Males											
Stomach	41	34	30	25	21	16	15	13	11	8	4
Colon	163	139	117	99	84	61	60	57	49	36	21
Liver	44	37	31	27	23	16	16	14	12	8	4
Lung	318	264	219	182	151	107	107	104	93	71	42
Prostate	17	15	12	10	9	7	6	7	7	7	5
Bladder	45	38	32	27	23	17	17	17	17	15	10
Other	400	255	200	162	134	94	88	77	58	36	17
All solid	1028	781	641	533	444	317	310	289	246	181	102
Leukemia	71	71	71	70	67	64	67	71	73	69	51
All cancers	1099	852	712	603	511	381	377	360	319	250	153
Females											
Stomach	57	48	41	34	29	21	20	19	16	13	8
Colon	102	86	73	62	53	38	37	35	31	25	15
Liver	24	20	17	14	12	9	8	8	7	5	3
Lung	643	534	442	367	305	213	212	204	183	140	81
Breast	274	214	167	130	101	61	35	19	9	5	2
Uterus	11	10	8	7	6	4	4	3	3	2	1
Ovary	55	47	39	34	28	20	20	18	15	10	5
Bladder	59	51	43	36	31	23	23	22	22	19	13
Other	491	287	220	179	147	103	97	86	69	47	24
All solid	1717	1295	1051	862	711	491	455	415	354	265	152
Leukemia	53	52	53	52	51	51	52	54	55	52	38
All cancers	1770	1347	1104	914	762	542	507	469	409	317	190

NOTE: Number of deaths per 100,000 persons exposed to a single dose of 0.1 Gy.

A number of publications have estimated the risk of cancer using the LAR model (Lim et al, 2018; Pai et al., 2018). In a recently published work, a group of scientists (Lim et al, 2018) found that CT examinations could induce LAR of cancer in 10 (bladder), 36 (colon), 48 (liver), 59 (lung), 81 (stomach), 32 (thyroid), 66 (breast) and 6 (leukaemia) per 100,000 people exposed to CT imaging. The associated LAR of radiation-induced mortality were 3 (bladder), 9 (colon), 33 (liver), 46 (lung), 23 (stomach), 1 (thyroid), 8 (breast) and 3 (leukaemia) per 100,000 population. These values present some worrying situations. Indeed, the ICRP models have long predicted the excessive relative risk of cancer mortality to be 5%/Sv. Therefore, there is a collective need for effective dose management and optimisation of radiation levels in medical exposures (ICRP, 2007).

2.6 Dose Management and Optimisation in Computed Tomography Imaging

Due to the potential risks of radiation dose levels in medical exposures, there is the need for effective dose management and optimisation (IAEA Safety Standards Series, 2018; ICRP, 2017). The main mechanism and technical factors that play crucial roles in the management and optimisation of patients' doses in CT are discussed in this section.

2.6.1 Quality Management Systems

In CT imaging, quality management systems (QMS) are essential to ensure effective radiation protection and well-being of patients (Delis et al., 2017). QMS refers to the organisational structures, procedures and resources needed to implement quality management in an organisation (American Society for Quality, 2019). It includes quality assurance (QA) and quality control (QC), as well as quality improvement (QI) systems (Kruskal et al., 2009). The QA component is defined as an interdisciplinary management tool, including policies which offers a means for guaranteeing that all activities, including CT imaging, are effectively planned, correctly performed and assessed, while QC is a means of applying controls to the process to ensure that the product or service (CT imaging and care) consistently meets specifications such as providing optimal diagnostic information while delivering low doses (IAEA, 2006). QI, on the other hand, is a systematic, recognised approach to the assessment of practice performance and efforts to advance performance or a means of progressing from a particular level of performance, to a higher level of quality performance (Delis et al., 2017). A well implemented QMS, which encompasses appropriate policies, protocols, training and activities, enables the organisations to plan effectively, do the needed work, check that the system is functioning properly as they have been planned, and act by addressing any issues found in the check-up process that would ultimately lead to improved

performance. It also involves collaboration between multiple stakeholders from referring physicians, radiologists, radiographers, medical physicists, and patients, to ensure effective patient care and optimal image quality for diagnosis, with the aim of preventing unnecessary radiation to people (Vano et al., 2014; Manghani, 2011).

2.6.2 Justification

In the absence of dose limitation in medical exposures, the ICRP has long recommended the use of the principle of justification and optimisations to further manage and optimise radiation doses in healthcare (ICRP, 2007). The justification principle implies that the exposure of patients to radiation in medicine needs to be justified at the practice, procedure, and patient level (ICRP, 2007). In particular, it requires that medical exposures should be justified, and should produce more benefits than harmful effects (Cannata et al., 2017). A collaboration between the referring clinician and the radiological practitioners (radiologists and radiographers), is needed to justify procedures, and where appropriate, a non-ionising modality should be considered (IAEA Safety Standards Series, 2018). Referrer guidelines and clinical decision software solutions are known tools in the justification process, and a study (Vom and Williams, 2017) has indicated that, 58% of unjustified radiographic examinations could be prevented by using referral guidelines.

2.6.3 Optimisation

Optimisation is the process of ensuring the radiation dose associated with imaging procedures are optimised as low as reasonably achievable (ALARA), while the clinical objectives are met with a consideration of societal, technical and economic factors (Cannata et al., 2017; ICRP, 2007). In CT imaging, this is usually applied at the design of equipment and facility level,

as well as the day to day radiological practice level (ICRP, 2007). The design, construction of equipment, and installation of facilities play a crucial role in avoiding radiation leakages, scatter, and excessive exposure to patients and staff (Amaoui et al., 2020). The optimisation associated with the radiological practice requires that all the necessary tools needed for optimisation action in any justified radiological procedure, should be applied for radiation protection and safety (Amaoui et al., 2020). Various methods, with the majority involving the adjustment of exposure and technical factors, have been reported for radiation dose optimisation in CT imaging (Trattner et al., 2014); and they include the points indicated in Sections 2.6.3.1 to 2.6.3.10, and 2.7.

2.6.3.1 Tube Current and Tube Loading (mAs)

There is a direct proportional relationship between radiation dose and tube load (the product of tube current and the exposure time per rotation), which determines primarily the intensity or the number of x-ray photons (photon fluence) (Raman et al., 2013) incident on a given area of the patient. Where all parameters remain constant, a 50% reduction in tube load will produce halve the dose (Aweda et al., 2007). However, since the image noise is inversely proportional to the square root of the mAs ($\text{Noise} \propto = \frac{1}{\sqrt{\text{mAs}}}$), the noise will increase by a factor of $\sqrt{2}$, (40% increase), if mAs is reduced by half of its original value (Guberina et al., 2016). This is because a reduction in mAs would result in fewer photons forming the image (Lira, et al., 2015). Therefore, it is important that image quality acceptability levels be considered when utilising mAs in optimisation (Guberina et al., 2016).

2.6.3.2 Tube Voltage (kVp)

Tube potential measured in voltage or kilovoltage (kV) is defined "as the electrical "potential" difference between anode and cathode of the x-ray tube" (Lira et al., 2015 p.1). Increasing the tube voltage will increase the primary energy, and to some extent, the intensity of photons energy emitted, and dose (Raman et al., 2013). A recent study (Rusandu et al., 2018) has indicated that reducing the kilovoltage peak (kVp) factor from 100 to 80 during a pulmonary CT angiography could produce a desirable image quality, with approximately, 50% dose reduction. Another study (Yu et al., 2009) has also reported a dose reduction of 23% with an improved contrast and visualisation of mural stratification, when kVp was reduced from 120 to 100. However, the noise change is approximately inversely proportional to the change in voltage (Kalra et al., 2004). Therefore, there is always a need for a trade-off between kVp and image quality, to keep the patient's dose optimised.

2.6.3.3 Pitch

In modern CT scanners, pitch is referred to as the table distance travelled (as result of the incremental table movement) in one gantry scan revolution (360°) divided by combined thickness of all concurrently acquired slices (Guberina et al., 2016). Using a pitch of greater than (>) 1 or increasing table speed and table increment per gantry rotation (pitch factors) decreases scan duration and reduces the impacted radiation dose, although image quality can be compromised (Stradiott et al., 2009). Conversely, a pitch of less than (<) 1 could produce a better image quality with an associated higher patient dose, therefore, an appropriate trade-off would be needed to ensure optimisation (Stradiott et al., 2009).

2.6.3.4 Scan Thickness

For a given anatomical scan coverage, decreasing the slice thickness also increases scan images, the spatial resolution along the z-axis and the dose within the given body (Raman et al., 2013; European Commission, 1999). The number of photons per a voxel decreases with decreasing thickness (Raman et al., 2013). This leads to increased levels of image noise, which will require an increased radiation dose to reduce the image noise levels (Raman et al., 2013). A prudent selection of slice thickness for a particular clinical task could, therefore, be used to optimise radiation doses in CT (Guberina et al., 2016).

2.6.3.5 X-ray Beam-Shaping Filter

In CT imaging, x-ray beam-shaping filters are used to attenuate low energy x-rays emitted by CT x-ray tubes to allow hard enough energy to generate the needed diagnostic information (American College of Radiology, 2010). A bowtie filter compensates for this by attenuating the peripheral edges of the beam more than the centre to improve image quality and lower radiation dose, particularly to the skin and peripheral organs (Yu et al., 2009).

2.6.3.6 Scan Length and Z-Axis Overscan

CT dose output (DLP) depends on the field coverage along the z-axis. Reducing the scan range to cover just the area of interest would reduce unnecessary radiation (Rahman et al., 2018). A study (Zinsse et al., 2019) demonstrated a dose reduction of 39.2% (without compromise on quality) after optimising the scan length for patients with suspected acute appendicitis. In helical imaging, overscanning (z-axis overscan) circumstances are possible where additional layers of tissues at the start and end positions (along the z-axis) are exposed. This is needed for interpolation

of data from algorithms. Unfortunately, this could increase patients' effective dose by 13.1% (in head and neck), 35.8% (in chest), and 29.0% (in abdomen) (Tzedakis et al., 2005). The use of dynamic z-axis collimation (collimator shutter action) decreases overscanning.

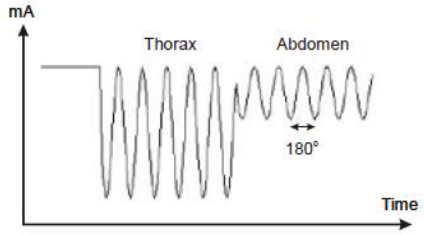
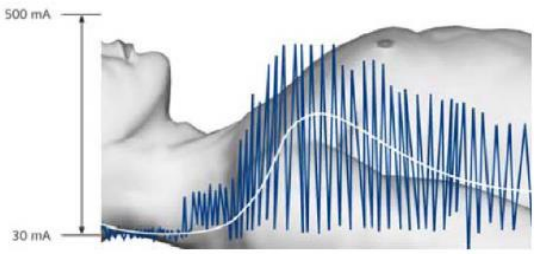
2.6.3.7 Detector Configuration

Radiation dose could also be optimised by the detector configuration (Guberina et al., 2016). Due to the wider x-ray beam and penumbra effect (overbeaming), unnecessary radiation is common in detectors with smaller beam collimation and vice versa (Raman et al., 2013). Moreover, detectors with high quantum detection efficiency and geometric efficiency are known to produce optimised dose levels (Yu et al., 2009).

2.6.3.8 Automatic Exposure Control/Tube Current Modulation

Contrary to a fixed mAs system which applies the same tube load across a body of varying thickness, the automatic exposure control (AEC) system modulates the tube current based on the different attenuation profiles of the various part of the object under consideration to achieve a target image quality through the scan (Merzan et al., 2017). By adjusting the mAs, doses vary according to the varying thicknesses of the object, unlike the fixed mAs system, where smaller and bigger volumes of a body receive similar doses. This optimisation process is reported to have reduced radiation to patients by about 20–40%, with an opportunity to further reduce more while ensuring good image quality (Higaki et al., 2019; Merzan et al., 2017). Modern CT scanners utilise three (AEC) techniques, namely the angular, longitudinal (z-axis) and combined modulations (Higaki et al., 2019). Table 2.3 presents the principles and modulation planes supporting each technique.

Table 2.3: AEC techniques available in modern CT systems

AEC modulation	Angular	Longitudinal (z-axis)	Combined
Technique	The tube current is adjusted during each gantry rotation, according to the size, shape and attenuation of body region being scanned.	The tube current is adjusted along the scanning direction of the patient, according to the size and attenuation of the anatomic region being scanned and the predetermined image quality	The tube current is adjusted both during each gantry rotation and for each slice position.
Modulation plane	x, y 	z 	z, y, z Both

Reference: (Higaki et al., 2019).

Different principles of AEC are utilised by each manufacturer. In each, there is an image quality (IQ) reference parameter [such as noise index, standard deviation (*SD*), reference mAs, reference image etc.] by which the tube current is modulated to ensure its consistency across the body part being scanned (Higaki et al., 2019; Merzan et al., 2017). Moreover, some manufacturers (Siemens and GE Healthcare) have recently introduced organ dose modulation to decrease the radiation dose to radiosensitive anterior organs by effectively lowering the tube current once the x-ray tube is situated in the anterior area of the human body (Dixon et al., 2016). A study (Fillon et al., 2018) found that organ dose modulation in combination with standard AEC could further reduce breast dose by 23% with negligible effect on image quality. Table 2.4 presents the major CT manufacturers and their reference parameter as well as their AEC systems.

Table 2.4: The AEC systems from major manufacturers

	Siemens	Philips	GE	Toshiba
AEC type and technique	CareDose4D: A combined modulation together with real time, online, controlled tube current modulation. $^{\Delta}$X-CARE similar as CareDose4D but for modulation doses to anterior organs	DoseRight: Consist of Automatic Current Selection (ACS) that provides patient-based AEC, D-DOM that provides angular AEC and Z-DOM that provides longitudinal AEC. All do not work together except ACS which combine with the other two.	A combine AEC (AutomA 3D) which is made up of AutomA (z-axis modulation) and SmartmA (angular modulation). $^{\Delta}$ Organ Dose Modulation (ODM) similar as SmartmA but for modulation doses to anterior organs	SureExposure 3D: A combined AEC
IQ reference parameter	*Quality reference mAs* (effective mAs) for a reference patient (70-80kg) is used as a reference, and subsequently modulates the mAs when different patient size is scanned. $^{\Delta}$ X-CARE uses *Quality reference mAs* but reduces mAs when beam is facing anterior side at an arc of 120^0	*A reference image* of a suitable patient examination is stored. AEC modulates specific mAs values for each patient to achieve a constant image noise level as that of the reference image.	*Noise index* corresponding to a required image quality is set. Based on patients' characteristics, AEC modulates the tube current to preserve the same level of noise in each image. $^{\Delta}$ ODM uses *Noise index* but reduces mAs when beam is facing anterior side at an arc of 180° arc for body protocols and a 90° for head protocols	It provides desired *SD (or image quality level)* of pixel values in patient-equivalent water phantom. In a given body, the tube current is modulated to achieve the stated value throughout the scan.

$^{\Delta}$: are new AEC systems commonly referred to as organ dose modulation AEC; AEC: automatic exposure control, SD: standard deviation. Reference: (*Higaki et al., 2019; Merzan et al., 2017).*

2.6.3.9 Reconstruction Algorithm

Older generations of CT scanners used filtered back projection to reconstruct CT images. However, because of its algorithm, images reconstructed at reduced doses present image noise and artifacts (Kim et al., 2014). Improvement in reconstruction algorithms such as iterative reconstruction (IR) techniques iterate CT image reconstruction several times, using mathematical algorithms to create images with lower noise (Padole et al., 2015). Different algorithmic approaches are used by CT manufacturers; Siemens Healthcare [Iterative Reconstruction in Image Space (IRIS), Sinogram-Affirmed Iterative Reconstruction (SAFIRE), and Advanced Model-Based Iterative Reconstruction (ADMIRE)], Toshiba America Medical Systems [Adaptive Iterative Dose Reduction (AIDR)], GE Healthcare [Adaptive Statistical Iterative Reconstruction (ASIR™) and Model-Based Iterative Reconstruction [MBIR or Veo™], Philips Healthcare [iDose™, iDose^{4}™ and Iterative Model Reconstruction (IMR)] and Medic Vision [SafeCT] (Padole et al., 2015; Kim et al., 2014). Some authors (Greffier et al., 2016) have reported that the combination of AEC and IR with adequate optimisations could reduce radiation levels by 43-91% with good image quality.

2.6.3.10 Patient Positioning

Bowtie filters and AEC systems in CT operate with the assumptions that the patient is isocentered during scanning (Kaasalainen et al., 2014). Off-centering of a patient away from the isocentre and closer to the tube leads to geometric magnification of the localiser radiograph and subsequently overestimation of the amount of attenuation in the field of view (AAPM, 2014). The reverse is also true. Unfortunately, the errors in size estimation result in wrong calculation and application of photon flux to the patient (AAPM, 2014). These could result in image noise and

variation in CT number and dose (Kaasalainen et al., 2014). A study found that improper positioning of patients in the isocentre could increase breast and thyroid surface dose by 16% and 24%, respectively (Raman et al., 2013).

2.7 Diagnostic Reference Level

DRL's introduction in medicine, its optimisation role in CT, types (anatomical, indication-based) and existing values, and theories guiding DRL development in CT have been covered in Section 2.7.1- 2.7.6.

2.7.1 Diagnostic Reference Level in Medicine

A Diagnostic Reference Level (DRL) is defined by the ICRP as;

> *"a form of investigation level, applied to an easily measured quantity, usually the absorbed dose in air, or tissue-equivalent material at the surface of a simple phantom or a representative patient*" (ICRP, 1996 p.2).

The term "diagnostic reference level" (DRL) was first introduced in 1996 in the ICRP Publication 73 (ICRP, 1996), and then developed further in subsequently publications. The activities that preceded the development of the DRL concept were many. However, consensus in literature indicate that the commencement of national dose surveys promulgated the idea in medicine (ICRP, 2017; Vassileva and Rehani, 2015; Sutton et al., 2014; IAEA, 2013; ICRP, 1996; ICRP, 1991; Shrimpton et al., 1989). The ICRP noted that, proceedings from the first nationwide x-ray dose levels conducted in the 1970s in USA, and later in the UK during the 1980s were crucial in the DRL concept. The consequences of these and other surveys were the reason for proposals for

radiographic technique and dose benchmarks, of which USA and UK were the pioneers (ICRP, 2017).

The initial recommendations, which aimed at benchmarking radiation exposure level to prevent unnecessary radiation in medicine, have been mentioned variously as exposure guides, guideline doses, guidance levels, and reference doses (ICRP, 2017). In the UK specifically, the Royal College of Radiologists and the National Radiological Protection Board (NRPB) jointly agreed and introduced the concept of reference doses (Sutton et al., 2014). This was first introduced in general radiography, and later surveys indicated "some 1300-man Sv could be saved by persuading the 25% of hospitals with the higher doses for the six examinations they investigated to change their technique to fall in line with the remaining 75%" (Sutton et al., 2014 p.1).

In the ICRP's 1991 Publication 60, the concept of investigation levels (which was later referred to as diagnostic reference levels) for diagnostic medical exposures was first proposed by the ICRP (Hart et al., 2008). Particularly, the publication recommended the establishment of "investigation levels, selected by the appropriate professional or regulatory agency, for application in some common diagnostic procedures" (ICRP, 2017 p.138). Reference levels were referred to as values of measured dose descriptors. Beyond that, specified measures or decisions ought to be taken (ICRP, 1991; ICRP, 2007). They involved "recording levels, above which a result is recorded, lower values being reported; investigation levels, above which the cause of the implications of the results should be examined and interventional levels, above which some remedial action should be taken" (ICRP, 1991; ICRP, 2007). However, these levels were not decoupled from the principle of dose constraint, hence the need for it to be utilised with flexibility, to permit higher doses if required in accordance with sound clinical judgment (ICRP, 1991; ICRP, 2007).

In the ICRP Publication 73 (ICRP, 1996), the Commission decoupled the two principles and introduced the term of diagnostic reference levels and discussed the concept in more details (ICRP, 1996). The European Commission subsequently included DRLs in a recommendation on diagnostic medical exposures in 1997, and the concept was advanced further, and practical advice was given in 2001 increasing the application of DRLs to interventional radiology and providing further guidance on flexibility in their development and implementation (ICRP, 2016). In the ICRP publication 103, the DRLs role in optimisations were further highlighted (ICRP, 2007).

The current ICRP Publication 135 on DRLs (ICRP, 2017), was also introduced following the need for additional advice regarding "definitions of the terms used in previous guidance, determination of the values for DRLs, the appropriate interval for re-evaluating and updating these values, appropriate use of DRLs in clinical practice, methods for practical application of DRL process, and application of the DRL concept to newer imaging technologies" (ICRP, 2017 p.9). These technologies include PET-CT, cone beam CT, dual-energy computed tomography (CT), SPECT-CT, digital radiography, and tomosynthesis (ICRP, 2017). Recommendations to address the challenges in paediatric practice, especially due to the broad range in sizes, were also provided. The new definition introduced by the ICRP includes:

i. DRL, which is a form of investigation level used as a tool to aid optimisation of protection, in the medical exposure of patients for diagnostic and interventional procedures.

ii. DRL quantity, which is a commonly and easily measured or determined radiation metric that assesses the amount of ionising radiation used to perform a medical imaging task.

iii. DRL value, which is an arbitrary notional value of a DRL quantity, set at the 75th percentile of the distribution of the medians of distributions of the DRL quantity obtained from surveys or other means.

iv. DRL process, which is the cyclical process of establishing DRL values, using them as a tool for optimisation, and then determining updated DRL values as tools for further optimisation (ICRP, 2017).

2.7.2 Role of DRLs in Computed Tomography Dose Optimisation

As compared to a screen film-radiograph, CT images do not easily give indication of over/underexposure, hence, images may appear good (often better) even if excessive and unnecessary radiation is used (Bauhs et al., 2008). The concept of DRLs was introduced in medicine as an additional tool to basically manage, optimise, monitor and control radiation use in medicine without compromising image quality or patient care (ICRP, 2017, Vassileva and Rehani, 2015). It should be noted that the application of patient dose management strategies requires the monitoring of low doses as well as high doses to ensure the preservation of the acceptable image quality (O'Connel, 2015). DRLs are critical in addressing the wide variations in doses often observed for same examination and similar patient groups (Kanal et al., 2017). They are not applied to occupational and public exposures but only medical exposure (McCollough, 2017). It is also not an ideal or a regulatory dose limit for a specific examination or an absolute upper limit for dose, but it represents the dose level at which an inquiry into the appropriateness of the dose ought to be initiated (McCollough, 2017). They are numerically established values expected not to be exceeded in routine practice when standards and good practices are adhered to (Tsukamoto, 2017).

It is simply an indicative value for identifying circumstances where the level of patient dose or administered activity is remarkably high (Australian Government, 2016; EANM et al., 2017).

If the dose delivered by an imaging facility consistently exceeds the established DRLs, it is a sign that the facility (including both the procedure and the equipment) should be reviewed locally for possible causes (ICRP, 2017). The regular review of possible causes using the DRLs as benchmarks at national, regional and local levels provides a feedback loop that ensures good practice (IAEA, 2013). Subsequently, a corrective action could be taken to further optimise the scanning protocols or whatever the problem might be unless clinically, the unusually high doses could be; justified or considered necessary for that particular task (Liang et al., 2017; Australian Government, 2016; Martin, 2016; Alessio et al., 2015; Vassileva and Rehani, 2015).

Although DRLs are considered supplements to professional judgment, and therefore do not always offer a boundary between the 'good' and 'bad' medicine, they make a significant contribution to good radiological practice in healthcare (Do, 2016; Rehani, 2009). As such, a DRL is an essential tool for effective radiation dose management and QA/QC system (Tsukamoto, 2017; Edmonds, 2009).

In jurisdictions where DRLs are well established, studies (Liang et al., 2017; MacGregor et al., 2015; Vassileva and Rehani, 2015; Brink and Miller, 2015; Hard and Wall, 2004) have shown that the usage of DRLs helped in reducing the range of doses in clinical practice for some procedures. In particular, the U.K national dose surveys established a 30% reduction in representative radiation doses for the period of 1984 to 1995, and a mean decline of approximately 50% for the period of 1985-2000 as a consequence of the establishment of DRLs and its variants (Hard and Wall, 2004). In Canada, MacGregor et al. (2015) reported a mean radiation dose reduction of 22% for $CTDI_{vol}$ and 13% for DLP during the period of 2010 - 2013 as a result of

DRLs implementation. In Finland, a study (Lajunen, 2015) has also reported a decrease of approximately 20% in radiation dose levels between the year 2007 to 2013 following the implementation of DRLs and other optimisation programmes. The role of the DRL implementations in the above dose reductions is that they serve as a watch-mark for radiographers, radiologists, medical physicists, and other medical practitioners to be mindful of in order to optimise practices, in order to stay below the reference values.

Owing to the benefits of DRL, adult-related DRLs have been instituted in 72% of the 36 European countries, and in 81% of European Union (EU) and European free trade association (EFTA) countries (Iceland, Norway and Switzerland) (European Commission, 2014). Moreover, 39% of the countries have instituted DRLs and 45% of EU and EFTA countries have done same for paediatric x-ray examinations (European Commission, 2014). The WHO and the IAEA have also included in their Bonn Call for Action 2, the need for the establishment, use of, and the frequent update of DRLs for radiological examinations (WHO, 2016; IAEA, 2013, IAEA GSR Part 3, 2014), while the European Society of Radiology (ESR) has recently included it in its EuroSafe Imaging Call for Action 2018 (European Society of Radiology, 2018).

2.7.3 Anatomical DRLs in Computed Tomography

Anatomical CT DRLs are developed for a specific anatomical part/region of the body. The most common anatomical regions of the body for which DRLs are developed include the head, chest, abdomen, abdominopelvic, lumbar spine, pelvis, neck and a combined chest and abdomen. Anatomical DRLs are used to benchmark radiation dose levels for examinations undertaken around these body parts and are the most widely developed DRLs in CT (Damilakis et al., 2018). However, the limitation associated with this type of DRLs is that, only one DRL is used to account

for benchmark and monitor all the procedures associated with the specific anatomical area. It is strongly argued that in CT imaging, the procedures are tailored tailed to a specific clinical question and different imaging protocols and image quality requirements are needed for each clinical question. Therefore, great variations in radiation dose exist among procedures performed under the same anatomical imaging (Vocks and Frija, 2016; European Society of Radiology, 2017). Hence, an anatomical DRL as a QA/QC tool presents some ambiguities which could lead to unnecessary radiations (European Society of Radiology, 2017; Lajunen, 2015; Järvinen et al., 2015). The European Society of Radiology (2017), has further argued that NDRLs based on anatomical regions do not reflect clinical practice and should be re-examined using clinical indications.

A literature search produced no established NDRLs in Ghana. However, a couple of studies provided local anatomical reference levels. In particular, a study (Anim-Sampong, 2016) reported anatomical adult local DRLs (LDRLs) of head (63.29 mGy; 1008.26 mGy.cm), chest (5.92 mGy; 282.14 mGy.cm) and abdomen (6.79 mGy; 353.48 mGy.cm) for the Korle Bu Teaching Hospital. The paediatric values were head (23.87 mGy; 406.59 mGy), chest (1.70 mGy; 67.20 mGy.cm) and abdomen (2.70 mGy; 93 mGy.cm). The adult head examination especially was 5.5 % higher than the ICRP DRL value (ICRP, 2001). Another study (Addo, 2016) proposed a local paediatric DRLs for the Greater Accra Region in Ghana using only four facilities. For the head region, the age category and their DRLs were < 1 year (28 mGy; 395 mGy.cm), 1-5 years (38 mGy; 487 mGy.cm), 6-10 years (48 mGy; 601 mGy.cm) and 11-15 years (86 mGy; 1614 mGy.cm). In the chest region, DRLs for < 1 year and 1-5 years groupings were (1 mGy; 18 mGy.cm) and (5 mGy; 110 mGy.cm), respectively. Their abdominopelvic DRLs were (3 mGy; 71 mGy.cm, < 1 year), (3 mGy; 120 mGy.cm, 1-5 years) and (10 mGy; 494 mGy.cm, 6-10 years).

Meanwhile, other studies (Inkoom et al., 2014; Muhogora et al., 2010; Muhogora et al., 2010) have tried to benchmark radiation doses in Ghana. However, the mean dose distribution, instead of the 75^{th} percentile of the dose surveyed, were reported, and therefore could not be considered as DRLs values.

Internationally, studies on anatomical DRLs are very vast. Since anatomical DRL is not the direct focus of the study, a few of the current studies (< 8 years) have been reviewed here to present a reflection of the current global trend on anatomical DRL values. Tables 2.5 and 2.6 present a summary of the reviewed national anatomical DRLs for adults and paediatrics, respectively. The NDRLs for adult head $CTDI_{vol}$ examinations ranged from 30.4-75 mGy, while the DLP ranged from 760 - 1358.6 mGy.cm. Other observed anatomical DRLs were in the range of chest (9.3-30 mGy; 270-735 mGy.cm); abdomen (13.3-18 mGy; 204-555 mGy.cm); abdominopelvic (13-35 mGy; 460-1486 mGy.cm); and a combined procedure of chest, abdomen and pelvis (11-32.8 mGy; 421-1322 mGy.cm). Paediatric head DRLs for age groupings < 1 year, 1–5 years, > 5–10 years and > 10–15 years were in a range of (20-31 mGy; 207-1060 mGy.cm); (35-48 mGy; 308-1493 mGy.cm); (40.3-54 mGy; 4467-1824 mGy.cm); and (35-53 mGy, 600-920 mGy.cm), respectively. The details of the reviewed DRLs are shown in Tables 2.5 and 2.6.

Table 2.5: Reviewed existing adult national anatomical DRLs

Authors/location	Head		Chest		Abdomen [A] /Abdominopelvic[AP]		Chest+abd+pelvis	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Ekpo et al., (2018), NG.	61	1310	17	735	20	1486*	-	-
Simantirakis et al., (2015),GR.	66.7	1053	14.4	470	16.3	758*	-	-
Salama et al., (2017), EG.	30.4	1358.6	-	-	31	1323*	32.8	1322
Butler and Kanal, (2018), US.	57	1011	13	353	16	639*	15	779
Public Health England (2016), UK,	63	973	12	610	13	745*	14	1000
Ataç et al., (2015), TR.	66.4	810	11.6	289	13.3	204[#]	19.4	421
van der Molen et al., (2013), NL.	-	813.7	-	320	-	567[#]	-	-
Palorini et al., (2014), IT.	69	1312	15	569	18	555[#]	18	-
Foley et al., (2012),IE	66.2	940	9.3	393	11.6	845*	-	-
Zhou et al., (2019), CN.	51.7	906.5	10.3	412.6	18.2	886.9*	-	-
Santos et al., (2014), PT.	75	1010	14	470	18	800*	-	-
ARPANSA, (2018), AU	52	880	10	390	13	600*	11	940
American College of Radiology, (2018)	56	962	13	353	16	639*	15	779
European Union, (2014)	50-75	760-1300	10-30	270-700	13-35	460-1200*	-	-

Key: *[A] = abdomen (abd), [AP] = Abdominopelvic, NG= Nigeria, GR= Greece, EG= Egypt, US = United States of America, UK= United Kingdom, TR= Turkey, NL=Netherlands, IT= Italy, IE= Ireland, CN= China, PT= Portugal, AU= Australia, ARPANSA=Australian Radiation Protection and Nuclear Safety Agency; EU= European Union. $CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product.* ***Unit;*** *$CTDI_{vol}$ =mGy; DLP=mGy.cm*

Table 2.6: Reviewed existing paediatric national anatomical DRLs

Paediatric CT part/authors		< 1 year		1–5 years		> 5–10 years		>10–15 years	
		$CTDI_{vol}$	DRL	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Head	Ataç et al., (2015), TR.	31	288	33.4	368	40.3	467	51.3	625
Head	Ekpo et al., (2019), NG	27	1040	48	1493	54	1824	-	-
Head	European Union, (2014), EU	20-27	270-340	35-40	470-600	50	620-900	-	850-920
Head	Vassileva et al., (2015), IAEA	26	440	36.0	540	43.0	690	53.0	840
Head	ARPANSA, (2018), AU.	30	470	-	-	-	-	35	600
Chest	Ataç et al., (2015),TR.	7.1	181	3.8	214	3.6	277	4.0	287
Chest	European Union, (2014), EU	-	12-200	-	55-230	-	105-370	-	200-205
Chest	Vassileva et al., (2015), IAEA	5.2	130	6.0	140	6.8	170	7.3	300
Chest	Santos et al., (2014), PT	2.42	42.75	5.6	138.5	5.65	186	7.19	194.5
Chest	ARPANSA, (2018), AU.	2	60	-	-	-	-	5	110
AP	European Union, (2014), EU	-	27-130	-	125-230	-	240-400	-	400-500
AP	Vassileva et al., (2015), IAEA	5.2	130	7.0	250	7.8	310	9.8	460
AP	ARPANSA, (2018), AU	7	170	-	-	-	-	10	390
AP	Ataç et al., (2015), TR.	3.1	104	2.5	125	2.7	179	3.1	210

***Key**: AP= abdomen/pelvis, TR= Turkey, NG= Nigeria; EU= European Union. IAEA= International atomic energy agency, AU= Australia, $CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product.* ***Unit;** $CTDI_{vol}$ =mGy; DLP=mGy.cm*

The reviewed literature presents great variations across countries, and thus there is the need for optimisations to harmonise the dose levels. Studies (Smith-Bindman et al., 2019; Rehani, 2015; Vassileva and Rehani, 2015; Kalra et al., 2004) have linked the wide variations in doses, to the use of over-age CT scanners in some jurisdictions, differences in technique factors, variation in protocols, anatomical size and characteristics of a population, equipment technical factors, operationalisation of scanners, and a general lack of harmonisation and application of the same optimisation methods across countries, to improve radiation protection for patients.

2.7.4 Indication-Based Diagnostic Reference Levels

In medicine, an indication is a medical reason or a condition that leads to the recommendation of a test, procedure or treatment (National Cancer Institute, 2017). In the diagnostic radiology department, patients are referred for various examinations, based on their indications.

These CT indications are several in literature. Notwithstanding, studies (Fertikh, 2015; Marder et al., 2014) have indicated that head trauma (mostly through road traffic accidents), stroke or cerebrovascular accident (CVA) and headaches are the most prevalent head indications in CT imaging. In the case of stroke, a study (Marder et al., 2014) indicated that CT could differentiate infarction from haemorrhage, and distinguish from other causes like the extracerebral haemorrhage or glioma. Moreover, if CT is performed within 48-72 hours, it could diagnose subarachnoid haemorrhage in over 90% of cases (Marder et al., 2014). A publication (Hamed et al., 2015) explained that the suspicion of space occupying lesion (SOL) (usually because of malignancy, abscess or a haematoma) is the most common reason for headache related CT examinations. In the chest region, some literature (Purysko, 2016; Willson et al., 2014) indicated that lung cancer and other primary neoplastic conditions affecting the chest and metastatic diseases are the most

common chest CT indications. Other authors (Skinner, 2015; Gould et al., 2013) reported that suspected pulmonary fibrosis, pneumonia, and solitary pulmonary nodule are the most indications in CT chest imaging. A study (Wilson et al., 2014) also found that in emergency CT scans, pulmonary embolism accounts for about 80% of the indications. Moreover, publications (Garcia et al., 2018; Taylor, 2017) suggest that the common CT indications of the abdomen and the pelvic regions include: abdominal pain, abdominal tumour or lesion, renal calculi or kidney stones and abdominal injury. Others included acute appendicitis, bowel obstruction, obstructive jaundice and metastasis (spread of cancer from the primary site) (Taylor, 2017).

In CT imaging in particular, different imaging protocols are set for specific indications (Trattner et al., 2014). For instance, in the case of brain tumour, there are different sets of imaging protocols compared to CVA indications, although they are all head-related procedures. Each specific indication requires a specific diagnostic imaging requirement for its diagnosis. A DRL that is based upon a radiation dose data derived as a result of CT imaging for a specific indication, is referred to as an indication-based DRL (Järvinen et al., 2015; EANM et al., 2017). It is also referred to as a clinical DRL in some publications (Damilakis et al., 2018). The concept of indication-based DRLs was mentioned many years ago by the ICRP (ICRP, 2017), however, the vast majority of published DRLs have been on anatomical locations (Damilakis et al., 2018). The anatomical approach has bracketed all indications for a particular anatomical region into one DRL. For example, presently, an abdominal DRL is used as a dose benchmark for diagnosing kidney stones, appendicitis, lesions in the abdomen and liver metastases in many establishments (Vock and Frija, 2016). However, as mentioned earlier, the scanning protocols (such as collimation, contrast usage, scan length, series, etc.) which have a corresponding effect on image quality and dose, differ amongst the different indications for the anatomical part (European Society of

Radiology, 2017). Some authors (García-Mónaco et al., 2019; Vock and Frija, 2016) have argued that it is not logical to use the same (e.g. abdominal) DRL for the diagnosis of kidney stones and of liver metastases. Hence, a single anatomical DRL for many indications of a body region is not a very reasonable indictor for dose optimisation, unless the clinical indication is considered (García-Mónaco et al., 2019). Reports (Ridley, 2016; Vock and Frija, 2016) have revealed that indication-based DRLs based on CT protocols could decrease patients' dose considerably. A recent publication (EANM et al., 2017) further indicated that indication-based DRLs and its implementation could narrow down dose monitoring in CT examination and offer another level of accountability concerning the usage of radiation in medicine. It also argued that setting up indication–based DRLs would involve more classification of patient diseases where different dose outputs for one anatomical part are realistic, but this will help to reduce the overall dose to patients since, it could complement the other existing DRLs (Bujila, et al., 2018).

Due to the many indications in CT, DRLs cannot be set simultaneously for all of them. Moreover, some indications share similar diagnostic requirement and protocols hence they could have common DRL values. However, it is advised that initial indication DRLs should centre on the most common ones contributing enormously to a population dose (Vock and Frija, 2016). These could include "acute head trauma, acute stroke, pulmonary embolus, pulmonary metastases, diffuse parenchymal disease, liver metastases, urinary calculus (stone), appendicitis, CT colonography and calcium coronary scoring" (Vock and Frija, 2016 p. 7-8).

2.7.5 Existing Indication-Based DRLs in Computed Tomography

There was no literature on either local or national indication-based DRLs in Ghana. International publications on indication-based DRLs are few, unlike the anatomical DRLs. The available DRLs are largely from Europe, with none from Africa, to re-emphasise the importance of this current study as a model indication-based DRLs for Africa.

Based on the literature, the most common adult indications and their DRLs were CVA/stroke (60-80 mGy; 970mGy.cm), brain haemorrhage (58-65 mGy, 930-1000 mGy.cm), sinusitis (9-25 mGy, 120-350 mGy.cm), lung cancer (9-16 mGy; 350-610 mGy.cm), pulmonary embolism (13-19 mGy, 300-557 mGy.cm) and Coronary CT angiogram (20-90 mGy; 173-1510 mGy.cm). Tables 2.7-2.10 summarise the available adult indication-based DRLs as obtained from the literature.

Table 2.7: Adult head CT DRLs, based on clinical indications

Ind. / Ref.	Acute stroke/post fossa		Acute stroke/ Cerebrum		Acute stroke/brain (whole)		Head trauma/ Injury		Haemorrhage, aneurysms, arteriovenous malformations		Brain metastases, SOL abscess		Sinusitis		cholesteatoma	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
I[a]	-	-	-	-	-	-	-	-	58	930*	-	-	-	-	-	-
II[a]	80	-	60	-	60	970*	-		-	-	-	-	-	-	-	-
III[a]	-	-	-	-	-	-	-	-	-	-	-	-	9	120*	-	-
IV[a]	-	-	-	-	-	-	-	-	65	1000*	65	1000	25	350*	50	250*
V[a]	-	-	-	-	-	-	-	-	-	936*	-	-	-	133*	-	-
VI[a]	-	-	-	-	-	-	-	-	-	-	-	-	-	90*	-	-
VII[a]	-	-	-	-	-	-	60	950	-	-	-	-	-	-	-	-

***Key**: Ind.= indication, Ref. = Reference. SOL= space occupying lesion. $CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product. **Unit;** $CTDI_{vol}$ =mGy; DLP=mGy.cm. **References**: [I: Danish Health Authority, (2015), DK; II: Public Health England, (2016), UK; III: Schegerer et al., (2017), DE;* IV: *Treier et al., (2010), CH;* V: *Van der Molen et al., (2013), NL;* VI: *Wachabauer et al., (2017), AT; VII: Widmark, (2018), NO].*

[a] *Data with regulatory value implemented * single sequence procedure.*

Table 2.8: Adult chest CT DRLs, based on clinical indications

Indication / Reference	Lung cancer		Interstitial lung disease (axial)		Interstitial lung disease (helical)		Pulmonary embolism		Coronary CT angiogram (CCTA)		Calcium Scoring	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Danish Health Authority, (DK) (2015)[a]	16	620[?]	-	-	13	500*	-	-	29	230*	-	-
Public Health England, (UK), (2016)[a]	12	610[?]	4	140*	12	350*	13	440*	-	-	-	-
Schegerer et al., (DE), (2017)[a]	-	-	-	-	-	-	15	300*	-	-	8	119*
Treier et al., (CH), (2010)[a]	-	-	-	-	-	-	-	-	-	1000[?]		150*
Van der Molen et al., (NL), (2013)[a]	-	-	-	-	-	276*	-	371*	-	671*	-	51*
Wachabauer et al., (AT), (2017)[a]	-	-	-	-	-	-	-	400*	-	-	-	
Widmark, (NO), (2018)[a]	9	350*										
Castellano et al., (UK), (2017)[a]	-	-	-	-	-	-	-	-	-	173*	-	-
Foley et al., (IR), (2012)			7	276*			13	432*	-	-	-	-
Fukushima et al., (JP), (2012)	-	-	-	-	-	-	-	-	-	1510[?]	-	-
German Federal Office for Radiation Protection, (DE), (2016)[a]	-	-	-	-	-	-	-	-	20	330*	-	-
Hausleiter et al., (2009)	-	-	-	-	-	-	-	-	-	1152[?]	-	-
Japan Network for Research and Information on Medical Exposures, (JP), (2015)[a]	-	-	-	-	-	-	-	-	90	1400[?]	-	-
Kanal et al., (USA), (2017)	-	-	-	-	-	-	19	557[?]	-	-	-	-
Mafalanka et al., (FR), (2015)[a]	-	-	-	-	-	-	-	-	-	870*	-	-
Palorini et al., (IT), (2014)	-	-	-	-	-	-	-	-	-	1208[?]	-	131*
Radiation and Nuclear Safety Authority (FI), (2013)[a] and Lajunen, (2015), (FI)	11	430*	-	-	-	-	-	-	-	-	-	-
Salama et al., (EG), (2017)	-	-	-	-	22	421*	-	-	-	-	-	-

Key: *$CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product.* ***Unit;*** *$CTDI_{vol}$ =mGy; DLP=mGy.cm).* [a] *Data with regulatory value implemented * single sequence procedure,* [?]*undeclared* number of sequences. Letters in bracket eg. DK, UK are internationally accepted country abbreviations. [a] *Data with regulatory value implemented.*

Table 2.9: Adult abdomen and pelvic region CT DRLs, based on clinical indications

Indication / Reference	Liver Metastases		Abdomen-pelvic abscess		Kidney stones/colic		Kidney tumour/colic CT-IVU		Acute Abdomen		Pancreas Cancer	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Danish Health Authority, (DK), (2015)[a]	-	-	-	-	-	-	-	-	17	700	-	-
Public Health England, (UK), (2016)[a]	14	910	15	745	10	460*	13	1150	-	-	-	-
Radiation and Nuclear Safety Authority (FI) (2013) [a] and Lajunen, (2015), FI.	-	-	-	-	7	330*	-	-	-	-	-	-
Salama et al., (EG), (2017)	31	1423	-	-	-	-	-	-	-	-	-	-
Treier et al., (CH), (2010)[a]	15	400	-	-	-	-	-	-	-	-	-	-
Van der Molen et al., (NL), (2013)[a]	-	-	-	-	-	329*	-	1371	-	-	-	1000
Wachabauer et al., (AT), (2017)[a]	-	400	-	-	-	-	-	-	-	-	-	-
Widmark, (NO), (2018)[a]	11	800	-	-	-	-	13	1300	-	-	-	-

Key: *$CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product.* ***Unit;*** *$CTDI_{vol}$ =mGy; DLP=mGy.cm). CT-IVU= computed tomography intravenous urography. [a] Data with regulatory value implemented * single sequence procedure. Letters in bracket eg. DK, UK are internationally accepted country abbreviations.*

Cont'd Table 2.9: Adult abdomen and pelvic region CT DRLs based on clinical indications

Indication. / Reference	Abscess Lymphadenopathy		Virtual colonoscopy (VC) - polyps/tumour		CT angiography for abdominal aortic aneurysm (AAA)		Suspicion of lymphoma	
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)
Public Health England, (UK), (2016)[a]	15	745	11	950	-	-	-	-
Treier et al., (CH), (2010)[a]	15	650	-	-	15	650	-	-
Van der Molen et al., (NL) (2013)[a]	-	-	-	-	-	727	-	-
Wachabauer et al., (AT), (2017)[a]	-	650	-	-	-	-	-	-
Lajunen, (FI), (2015)	-	-	12	930	-	-	17	970

Key: *$CTDI_{vol}$ =volume weighted CT dose index, DLP= dose length product.* ***Unit;*** *$CTDI_{vol}$ =mGy; DLP=mGy.cm).* [a] *Data with regulatory value implemented * single sequence procedure. Letters in bracket eg. UK, CH are internationally accepted country abbreviations.*

Table 2.10: Adult cervical CT DRLs, based on clinical indications

Indication. / Reference	Fracture		Disk pathology		Adenopathy, abscesses	
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)
German Federal Office for Radiation Protection, (DE), (2016)[a]	20*	-	25*	-	-	-
Public Health England (UK), (2016)[a]	26*	600*	-	-	-	-
Treier et al., (CH), (2010)[a]	-	-	-	-	30*	600*

Key: *$CTDI_{vol}$ =volume weighted CTDI, DLP= dose length product.* ***Unit;*** *$CTDI_{vol}$ =mGy; DLP=mGy.cm).* [a] *Data with regulatory value implemented * single sequence procedure. Letters in bracket eg. DE, CH are internationally accepted country abbreviations.*

2.7.6 Theories Guiding DRL Development in Computed Tomography

Studies (American College of Radiology, 2018; ICRP, 2017; ICRP, 2007) show that the process leading to the establishment of DRLs requires co-operations among stakeholders within an organisation responsible for the establishment and implementations of DRLs. Other publications (Do, 2016; Korir et al., 2016) have suggested that although government, through the authorised regulatory body has a duty to ensure that NDRLs are established for a country, the development of DRL values could be conducted by an individual, institutions or professional medical bodies. However, such derived numerical values are advisory, and the implementation is supposed to be done by an authorised body (Do, 2016). According to the IAEA, in certain countries, a national governmental body manages the national patient dose database for DRLs whereas in other countries, this role is taken by a regulatory body or a professional body (IAEA, 2013). A publication (Järvinen et al., 2017) has further stressed that successful DRLs developments have largely been based on three factors, namely, national actions, efforts at the level of local institutions and efforts by individuals. The current ICRP recommendation on DRLs (ICRP, 2017) suggests that DRLs could also be adopted by institutions based upon published values that are suitable for local conditions, yet managements must take responsibilities for such DRLs. Same can also be done for countries where responsible bodies failed to establish DRLs based on their own dose registry or dosimetry (IAEA, 2013). A publication (European Commission, 2014), indicates that about 77% of adult DRLs in Europe are based on the countries' own national dose surveys, while the remainder are adopted values. However, the disadvantage of adopting existing DRLs is that local levels may be far lower than the set DRLs and sometimes could defeat the purpose of dose optimisation (Rogers, 2014).

Available literature (ICRP, 2017; IAEA, 2013) further indicates that, the DRL descriptors (quantity) on which DRLs are developed should be centred on metric that can easily and directly be measured in a practical way to reflect what is used in the clinical practice. Particularly, dose descriptors from a direct measurement for a procedure, or that obtainable from the imaging equipment which indicate the amount of radiation used are preferred (ICRP, 2017; IAEA, 2013). The IAEA has argued that effective dose, for instance, is a key indicator for estimating radiation risks statistically; however, in DRL it is not applicable as a key indicator because the quantity requires additional assumptions (IAEA, 2013). Currently, in MDCTs technology, dose quantities for DRL establishments are the $CTDI_{vol}$ of each sequence and cumulative DLP for the entire examination (ICRP, 2017), which are mandatory to display on the console of CT scanners, post examination (International Electrotechnical Commission, 2011; Institute of Physics and Engineering in Medicine, 2005). Size-specific dose estimate (SSDE) is thought to provide a more accurate estimate in the future, particularly, of paediatric patient doses than the aforementioned metrics, when scanner technology provides automatic calculation (ICRP, 2017; AAPM, 2014).

Studies (ICRP, 2017; Public Health England, 2016; IAEA, 2013, Smith-Bindman and Miglioretti, 2011) have ascertained that CT-console-displayed quantities are reliable for establishing DRLs, provided equipment status and validation checks are performed as part of local QA/QC measures. This requires that scanner performance characteristics (in particular $CTDI_{vol}$ and DLP) shown on CT console are comparable to the results of a well calibrated CT dose quantity measuring device (such as ionisation chamber traceable to a primary or secondary standard laboratory) which has been scanned under same conditions (ICRP, 2017; Public Health England, 2016; IAEA, 2013; ICRP, 2007). In instances where a particular scanner fails a performance test, it could be excluded, or a correction factor could be applied in the DRL study (IAEA, 2012).

There are two methods of measuring doses and developing DRLs in diagnostic imaging like CT examinations. These involve the use of phantom data (phantom-based dosimetry) and patient data (patient-based dosimetry) (National Council on Radiation Protection and Measurements, 2012; Vassileva and Rehani, 2015). An advantage of the phantom-based dosimetry is that it requires only one or two exposures for each procedure type, and for each radiologic facility. However, the drawback of this approach is that phantom-based dosimetry does not characterise actual clinical state (Vassileva and Rehani, 2015). In the case of patient-based dosimetry, patients' data are generated during a clinical task to reflect practice. Many international bodies (ICRP, (2017; Public Health England, 2016; IAEA, 2013) strongly recommend patient-based dosimetry as the gold standard in CT-based DRLs. Table 2.11 shows the ICRP's recommended method of dose assessment/survey for DRL development for various modalities in medical imaging (ICRP, 2017).

Table 2.11 Examination selection and ICRP's recommended assessment method for DRLs (ICRP, 2017).

Examination	DRL recommended	Method of assessment
Mammography	Yes	Patient survey to set DRL and phantom measurements as standard dose comparator
Intra-oral dental radiography	Yes	Output measurement on standard settings
Panoramic dental radiography	Yes	Measurement of air kerma-area product on standard settings
CT	Yes	Patient survey
Radiography of the trunk	Yes	Patient survey preferred
Skull radiography	Yes	Patient survey
Paediatric radiology	Yes	Patient survey
Paediatric CT	Yes	Patient survey
Extremity radiography	Yes (lower priority)	Patient survey
Mobile radiography	Yes (lower priority)	Patient survey
Neonatal radiography	Yes	Patient survey
Paediatric mobile radiography	Yes (for dedicated children's hospitals)	Patient survey
Barium studies	Yes	Patient survey
Interventional radiology and cardiology	Yes	Patient survey
Other fluoroscopy	Possibly, depending on level of use	Patient survey
Nuclear medicine – adult	Yes	Based on administered activity or, preferably, activity per body weight
Nuclear medicine – paediatric	Yes	Based on administered activity with adjustments for the size or weight of the child
Bone densitometry	Yes (lower priority)	Patient survey

DRL, diagnostic reference level; CT, computed tomography.

Studies (ICRP, 2017; IAEA, 2013; American College of Radiology, 2014; ICRP, 2001), have further suggested that if patient-based dosimetry or measurements are used in DRL developments, a large and representative patient sample, typically of 10 or more, should be selected from each of the facilities involved. However, the current ICRP recommendation on DRLs has suggested at least 20 patients, with 30 as its preferred sample size (ICRP, 2017). A report (Vassileva and Rehani, 2015) further indicated that the total inclusion of available scanners in DRLs development produces a generalisable result. However, this may not be possible in places where there are too many facilities. Many publications (ICRP, 2017; Kanal et al., 2017; Vock and Frija, 2016; IAEA, 2013) have also indicated that a national survey of dose quantities on which initial DRLs could be set should randomly cover about 20-30 of the facilities including medium- and large-sized healthcare facilities. They further suggested that the national survey should include 30-50% of facilities in small countries, while LDRLs should comprise much of the facilities.

The ICRP Publication, 135 in particular, also indicated that the development of DRLs should take into consideration the populations' pertinent characteristics like weight and height or the body mass indexes (ICRP, 2017). Many authors (Kanal et al., 2017; ICRP, 2017; Tsukamoto, 2017; Vassileva and Rehani, 2015, IAEA, 2013) agreed that x-ray beam attenuation depends on the amount of body tissue through which the beam has to penetrate. Therefore, it is important that DRLs are developed for a specific body size by the use of weight restrictions that reflect the common characteristics of a population of study. According to some publications (European Commission, 2014; IAEA, 2013), the standard mean body weight of an adult population is often defined as 70 ± 10 kg and this has been mostly used in setting DRLs. However, a study (Tsukamoto, 2017) noted that country populations vary in weight. Hence, using the 70 ± 10 kg as the reference weight for adult populations may not be necessarily appropriate for all countries. In

the case of Japan for instance, it was noted that the weight category of 50-70 kg was a suitable standard weight for establishing DRLs for routine procedures for Japanese adults (Tsukamoto, 2017). Some authors (Vock and Frija, 2016) have also argued that, often patients vary in size from country to country, hence setting DRLs with a standardised sample may not cover very obese and thin patients, and thus, would have some adverse implications on its universal implementation. Consequently, the ICRP Publication 135 has recommended a mean weight of 70 ± 10 kg; or a range of 50–90 kg with 70-kg mean; or an appropriate weight standardisation/restriction set for each population of interest to be used in adult DRLs (ICRP, 2017). This is particularly, crucial if the number of patients per each facility for whom data is collected is limited (< 50), unless large samples (≥ 50) are used (ICRP, 2017).

In the case of paediatrics, it has been suggested that the weight band should be categorised at <5 kg, 5–<15 kg, 15 –<30 kg, 30 –<50 kg, and 50–< 80 kg; and where ages are required, it should involve around the ages of 0, 1, 5, 10, and 15 years (ICRP, 2017). A study (Vock and Frija, 2016) has further suggested "age-grouping" for head related DRLs while trunk examinations should be based on "weight and body size groupings" if possible.

There are three categories of DRLs namely, local (LDRL), national (NDRL) and regional (RDRL) (ICRP, 2017). Both LDRL and NDRL are established using the 75^{th} percentile of the median values of dose distribution, although the 50^{th} (also referred to as the achievable dose) and 25^{th} percentiles among other values, are sometimes estimated (ICRP, 2017; Vassileva and Rehani, 2015). The LDRL is calculated on the dose distribution gained from radiology facilities in a single large medical unit or a group of medical units within a hospital, surveyed for standardised patient groupings, while the NDRL is calculated from a representative sample of radiology departments in a country (ICRP, 2017). The RDRL on the other hand, is based on median value of NDRLs of

countries within a geographic region or a continent (ICRP, 2017). One key philosophy of a DRL is to offer the 25% of the facilities or the practices with median radiation dose outputs above the established DRL to work hard towards dose optimisation (American College of Radiology, 2018; Rogers, 2014). However, it is argued that the DRL on its own is no encouragement to the other 75% of facilities that attained dose outputs lower than the DRL but should guide them to further manage their dose and investigate those that are below the 25th percentile (Zira and Nzotta, 2016; Rogers, 2014). A pictorial view of how a DRL is estimated at the 75th percentile is presented in Figure 2.6.

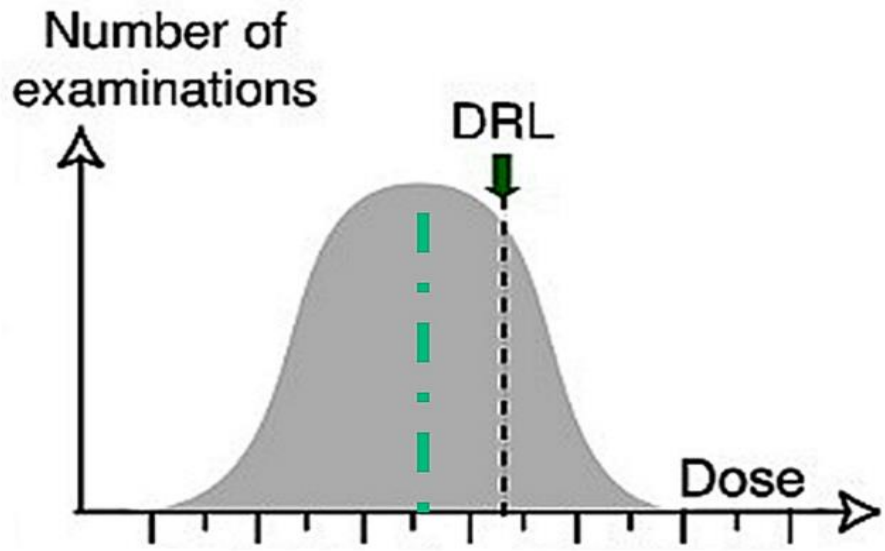


Figure 2.6: A diagram showing the 75th percentile value of a dose distribution (Vock and Frija, 2016).

Reviewed older publications (Foley et al., 2012; McCollough et al., 2011; Watson and Coakley, 2010; Treier et al., 2010; Matthews and Brennan, 2009; Institute of Physics and Engineering in Medicine, 2005; ICRP, 1996) have statistically used the mean value of dose descriptors/quantities of each facility in the DRLs estimation. However, more recent studies (Razali et al., 2019; European Union, 2018; Wagner et al., 2018; ICRP, 2017; European commission, 2015; IAEA, 2013) recommend the use of statistical median value, as it is noted that a few outliers could significantly influence mean values.

Studies (Ria et al., 2019; ICRP, 2017) further indicated that for effective development of DRLs, it is needful that all the images associated with the dose descriptors are within the acceptable diagnostic quality. They argued that the greatest importance for any diagnostic radiological procedure is to obtain image quality enough for the clinical task. Therefore, developing a DRL, particularly an indication-based DRL, without considering the image quality may significantly limit its objective. Structurally, the anatomical DRLs and indication-based DRLs are similar in their development approaches except that the former is set using radiation dose information associated with anatomical region of the body, while the latter is developed using data from specific clinical indications. Of particular importance in indication-based DRLs, is that the basic diagnostic imaging requirements and the image quality have to be taken into account during data collection (ICRP, 2017). Radiologists or approved documented protocols could be used to define these requirements to select the appropriate images and their corresponding dose descriptors deemed required without including the unnecessary ones (Brat et al., 2019; Healthmanagement, 2018; ICRP, 2017).

CHAPTER THREE

MATERIALS AND METHODS

3.0 Overview

This Chapter presents the materials and methods used for conducting the study. It highlights the study design, study area and components, procedures, and data analyses for all the phases (1-6) of the study, as well as ethical consideration and data handling.

3.1 Study Design

A research design is a blueprint adopted by a researcher to validly, objectively, accurately and economically answer a research question (Bowling, 2014). There are many available research designs. However, in DRL studies, designs based on numerical data are the gold standard (ICRP, 2017). Therefore, as the study was directed at using numerical data on the CT facilities across the country to develop indication-based DRLs, and propose optimisation approaches for radiation protection of patients in clinical practice in Ghana, it was necessary to use quantitative, prospective, cross-sectional, and experimental study designs in this study. A quantitative cross-sectional design allows a researcher to empirically gather information at one point in time to describe a population of interest (e.g. CT facilities), while experimental design allows interventions to be deliberately introduced, to observe their effects (Mitchell, 2015). In particular, the prospective component of these designs offers opportunities to undertake very crucial QC assessments of the CT scanners prior to the collection and manipulation of needed data. The decision to use these study designs is also supported by literature, as international recommendations (American College of Radiology, 2018; European Society of Radiology, 2018;

ICRP, 2017, European Commission, 2015; IAEA, 2013; AAPM, 2008; ICRP, 2007; ICRP, 1996), on DRLs have all been grounded on this approach.

3.2 Study Area and Components

In order to situate the study within a research frame and outline the major component of the project, a methodological framework was used (Figure 3.1). Many publications (American College of Radiology, 2018; European Society of Radiology, 2018; ICRP, 2017, Vassileva and Rehani; 2015; European Commission, 2015; IAEA, 2013; Treier et al., 2010; AAPM, 2008; ICRP, 2007; ICRP, 1996), provided the theoretical basis for the successful composition and development of the indication-based DRL methodological framework for this study.

Specifically, it is recommended that data for determining NDRL values ought to be based on extensive CT data obtained from surveys or registries (ICRP, 2017). To ensure this, there was the need to first obtain technical data on the CT scanners in the country, since there was a very limited information on the status of the infrastructure that was expected to be used in the study.

Secondly, indication-based DRLs require information on the common indications for CT examinations in the country (European Society of Radiology, 2018); therefore, this was part of the scope of the study. For the needed technical dose descriptors (quantity data) of the various indications to be appropriately selected, the basic diagnostic imaging requirements for each indication were also considered, and the concept defined.

Moreover, scanner performance characteristics data were also considered. Since these data constitute a dosimetry standard that radiation dose (or quantity) assessments involving CT must relate to, they should be considered in order to account for any technical challenges that may be associated with the scanners in a study framework (IAEA, 2012; ICRP, 2007; European

Commission, 1999). Subsequently, CT dose quantity surveys and the image quality assessments of the CT images of the prioritised indications were also considered crucial for the DRL development. In addition, radiation dose impact such as cancer risks associated with the indication-based CT examinations and steps for radiation dose optimisation for the protection of patients in CT examinations in Ghana were also explored. The study was accordingly conducted in phases as indicated in Figure 3.1, where P1-P6 denotes Phases 1 to 6.

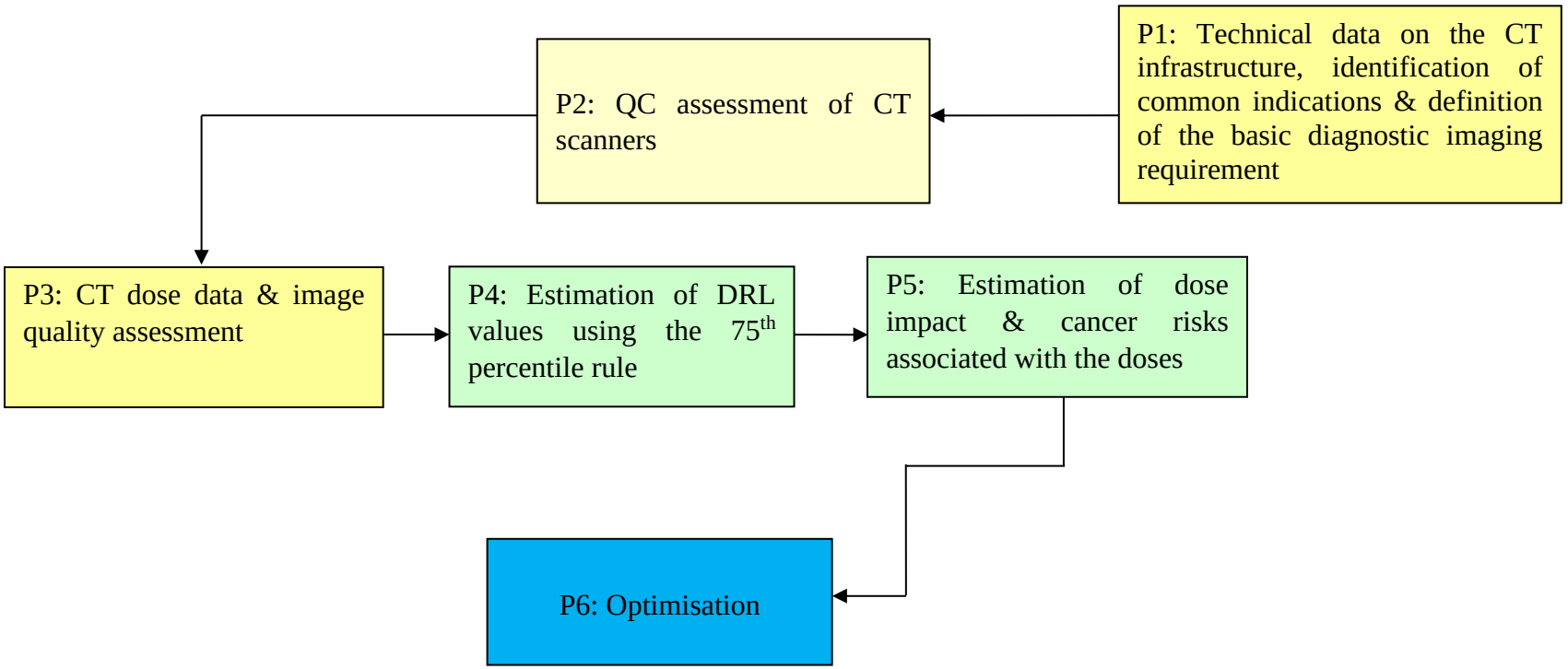


Figure 3.1 Methodological framework and flow chart.
Key: CT; computed tomography, QC; quality control, DRL; diagnostic reference level

3.3 Phase 1 Study: CT Technical Data, Common Indications and Imaging Requirements

The Phase 1 of the study centred on survey of technical data on the CT scanners, identification of common indications and definition of basic diagnostic imaging requirements of the common indications. The procedures for Phase 1 are outlined in Sections 3.3.1 to 3.3.6.

3.3.1 Study Site and Population

According to the current ICRP recommendation 135 (ICRP, 2017) on DRLs, a NDRL should be set using a representative number of facilities across the country. According to the Nuclear Regulatory Authority (NRA) of Ghana (Appendix 1), there were 35 CT scanners in Ghana at the time of the study (December 2017). All the CT facilities were targeted for the study and the technical heads responsible for the CT scanners were also invited to participate in the study using an introductory letter from NRA (Appendix II) and an information sheet (Appendix III). The study sites were the CT Units in the Radiology Departments of all participating facilities which comprised public, private and quasi-government hospitals in Ghana. Figure 3.2 displays the regional distribution (number) of CT scanners in Ghana as at December 2017.

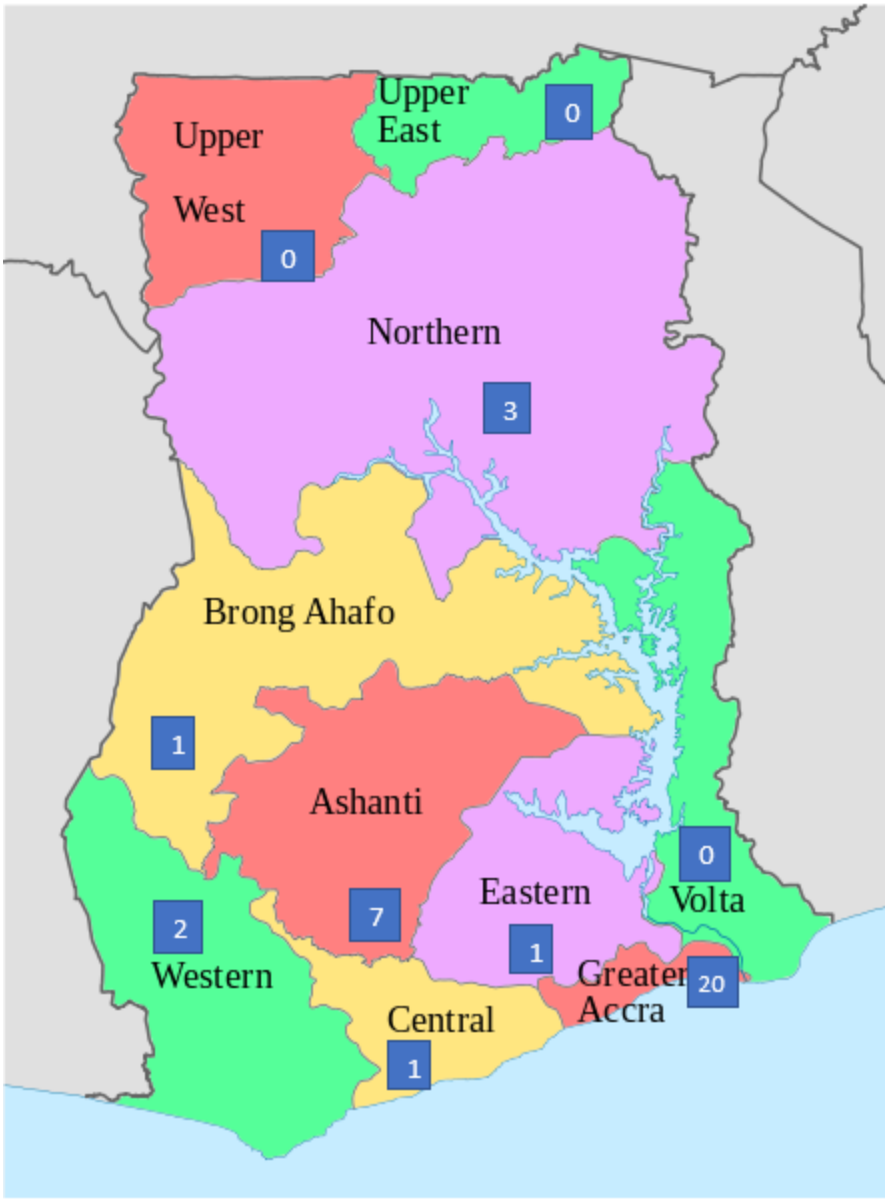


Figure 3.2: Regional distribution of CT scanners in Ghana as at December 2017

Note: *Number of administrative regions in Ghana changed from 10 to 16 since 2019. This occurred after data on regional distribution of CT for this study were collected.*

3.3.2 Sample Size, Inclusion and Exclusion Criteria

A sample size typically refers to the number of chosen units from which data is gathered (Bowling, 2014). The IAEA has suggested that NDRLs must be established, based on extensive scale surveys of the doses corresponding to typical clinical practice, for a patient group at a range of representative medical facilities (IAEA, 2013). A study (Vock and Frija, 2016) has also indicated that a national survey facility, from which NDRLs could be set, should cover about 30-50% of the facilities in small countries, while LDRLs should cover much of local facilities in the population. In order to obtain broad data across the country, a total enumeration sample size determination method (Laerd, 2012) was used to include all the scanners in the study, in order to deepen the representativeness of the findings. However, four (4) of the technical heads responsible for the scanners did not sign the consent form (Appendix IV) to involve their equipment in this study, and were subsequently excluded (Phase 1). Therefore, 31 CT scanners and their respective technical heads participated in Phase 1 of the study.

3.3.3 Data Collection Tool

According to studies (McElroy and Ladner, 2014; Choudhurg, 2017), a questionnaire is a reliable, very robust and very convenient means of collecting large amounts of technical information and useful comparable survey data from a large number of individuals in a study. The data collection tools utilised in Phase 1 of the study therefore consisted of two self-designed, semi-structured questionnaires, A and B (A = Appendix V; B = Appendix VI). The questionnaires in Phase 1 of the study were used to determine the status of CT infrastructure in Ghana within a short period of time and provided a decision roadmap for the DRL development. Questionnaire A was developed to generally gather technical data on CT scanners and common indications from the

assigned technical heads of the authorised CT scanners. Variables considered on the questionnaire included respondents' demographics (such as professional grade and gender), CT types, features and characteristics, equipment functionality, quality management systems and driving policies, attending professionals, nature of procedures and common indications for which CT scans were requested.

Further to this, respondents were asked to specify indications (among the most common) that use similar scanning protocols by using same identification (alphabet) letters to denote them. This was done to ensure that DRLs were set for indications with different scan protocols and dose descriptors, while those with similar protocols were grouped together. Other sub-sectioned variables/items accounted for a total of 67 questions and statements for which answers were required. Many studies (Adejoh et al., 2017; Ngoya et al., 2016; Maskell et al., 2015; Korir et al., 2013; IAEA, 2013; Ofori et al., 2013; Kruskal et al., 2011; Wambani et al., 2010) provided the theoretical background and framework for the questionnaire and based on the outcome of the first questionnaire, the second was also developed.

The second questionnaire was aimed at defining local diagnostic imaging requirements for each indication using mainly radiologists, since they determine the diagnostic requirements of each indication. Dedicated documented scanning protocols for various indications were not readily available in most facilities. Knowledge of diagnostic imaging requirements for each indication was necessary for the selection of only appropriate images (excluding the unnecessary ones) and their associated dose descriptors for the proposed DRLs. This was in line with the ICRP recommendation (ICRP, 2017). The items on Questionnaire B required data on scan coverage, scan series number including contrast usage, image quality acceptability level, required scan thickness, acceptable scan mode, preferred scan techniques, AEC usage acceptability and

preferred phantom type. The existing literature (ICRP, 2017; IAEA, 2012; European Commission, 1999; ICRP, 2007) on scan protocols served as a guideline to identify the number of items that should be included in the questionnaire for the basic technical parameters.

3.3.4 Questionnaire Validity and Reliability

Validity and reliability tests are crucial for self-designed questionnaires to ensure research accuracy and robustness. Validity is referred to as the degree to which a concept is correctly measured in a quantitative study while reliability entails the consistency of a measure or the ability of a tool to consistently produce the same result under the same conditions over time (Heale and Twycross, 2015). To guarantee the validity of the questionnaires, a content validity technique (the use of a review expert panel to evaluate the questionnaire), was employed to ensure that questionnaires adequately covered all the required contents with respect to the variables under investigation in Phase 1 of the study (Lobiondo-Wood and Haber, 2013). Two clinically qualified medical physicists at the University of Ghana School of Nuclear and Allied Sciences assessed and validated the suitability of the questionnaires. First, the developed tools (based on broad literature reviews) were sent to each of them with a categorical rater scale (0 not important to 1 important) to rate the importance of the items on the questionnaires. It was decided that any item/question which scored 0 from both raters would be rejected or removed. However, any question which scored a total of 1 or 2 from both raters was maintained. The raters were also asked to make suggestions on the questionnaires where applicable. Finally, none of the items on the questionnaire were rejected. However, sentences were eventually refined, and grammatical errors corrected.

Cohen's Kappa Statistic was then applied to test the agreement between scores obtained from the first and second rater. Cohen's Kappa Statistic tool is a very reliable tool for inter-rater agreement testing (McHugh, 2012). The kappa scale ranges from 0 - 1 and graded as: 0 – 0.20: no agreement; 0.21– 0.39: minimal agreement; 0.40–0.59: weak agreement; 0.60–0.79 moderate agreement; 0.80–0.90: strong agreement; and ≥ 0.90: almost perfect agreement (McHugh, 2012). The 0.71 and 0.80 kappa values recorded on Questionnaire A and Questionnaire B, respectively, suggested moderate to strong agreement in responses between the two raters for both research instruments.

Subsequently, a pilot study (using two technical heads responsible for CT facilities) and a test-retest reliability analysis (with one-week interval) were used to further assess the reliability of the questionnaires. For questionnaire A, the observed test-retest reliability coefficient was 0.81 (on a reliability coefficient scale ranging from 0-1, where 1: perfect reliability; ≥ 0.9: excellent reliability; ≥ 0.8 < 0.9: good reliability; ≥ 0.7 < 0.8: acceptable reliability; ≥ 0.6 < 0.7: questionable reliability; ≥ 0.5 < 0.6: poor reliability; < 0.5: unacceptable reliability; and 0: no reliability), while questionnaire B recorded a coefficient of 0.76 to suggest an acceptable reliability (Statisticshowto, 2019).

3.3.5 Data Collection Procedure

According to ICRP, the establishment of NDRL values should be coordinated with support from national regulatory authorities (ICRP, 2017). The NRA of Ghana supported the data collection process by issuing an introductory letter (Appendix II) to facilitate the researcher's access to the facilities. The NRA letter and the study's information sheet and consent form were first sent by the researcher to all the facilities, while email addresses and telephone contacts of

those who consented to participate were also retrieved for the study purposes. Questionnaire A was then administered to them by an online survey platform (www.esurvey.org) (eSurvey, 2017). Their email addresses constituted the medium for sending uncompleted and receiving completed questionnaires. This online survey platform was chosen because it was very reliable, free and fast. Moreover, survey responses collected could be viewed in real time.

After follow-up calls, the technical heads responsible for 31 scanners responded and completed their respective questionnaires. This took place from December 2017 to March 2018. Questionnaire B was also administered through the same methods to the reporting radiologists and responsible radiographers (officers in charge, where there were no resident radiologists) for data acquisition on the basic diagnostic imaging requirements.

3.3.6 Data Analysis

After the survey responses were received by email, the raw data were visually inspected and where necessary, respondents were called for verification. For example, typographical errors, missing of key data, misplaced data, and inconsistencies were checked and addressed. Descriptive analyses of the data in Phase 1 of the study were done using Microsoft Excel version 2013, and basic descriptive statistics such as frequencies and percentages were generated. Graphs, pie charts and tables were then used to present the results. Details of the results are presented in section 4.2. of Chapter Four.

3.4 Phase 2 Study: Scanners' Performance Characteristics (QC tests)

3.4.1 Outline

According to ICRP (2017), the quantity used for DRL establishment should be acquired in a practical method. Currently, MDCT dose descriptors for DRL establishments are $CTDI_{vol}$ and DLP, which are mandatorily displayed on the console of CT scanners (ICRP, 2017; International Electrotechnical Commission, 2011; Institute of Physics and Engineering in Medicine, 2005). Many studies (ICRP, 2017; Public Health England, 2016; IAEA, 2013; Smith-Bindman and Miglioretti, 2011; ICRP, 2007; ICRP, 1996) have indicated that CT-console-displayed quantities could be used to establish DRLs, if validation checks are performed as part of local QC measures. This dictates that scanner performance characteristics shown on CT consoles are comparable to the results of a well calibrated CT dose quantity measuring device (such as an ionisation chamber) scanned under same conditions.

Since the study needed to use console-displayed CT data, dose delivery validation (QC testing) of the displayed quantities were undertaken to ensure that scanners accurately displayed measured quantities. This was also necessary to identify poorly functioning scanners to enable application of appropriate corrective factors in the DRL development, where necessary (Treier et al., 2010). The QC tests undertaken were CT dose delivery accuracy, reproducibility and geometric efficiency. Other assessments included tube voltage accuracy, half value layer (HVL), CT number (water), homogeneity and image noise testing. In all, twenty-five (25) scanners were involved in Phase 2 of the study, following the exclusion of non-functional, specially dedicated and technically challenged (inability to display dose descriptors) CT scanners that were determined in the Phase 1 study. Figure 3.3 presents a flow chart of how the scanners were selected for the Phase 2 of the study.

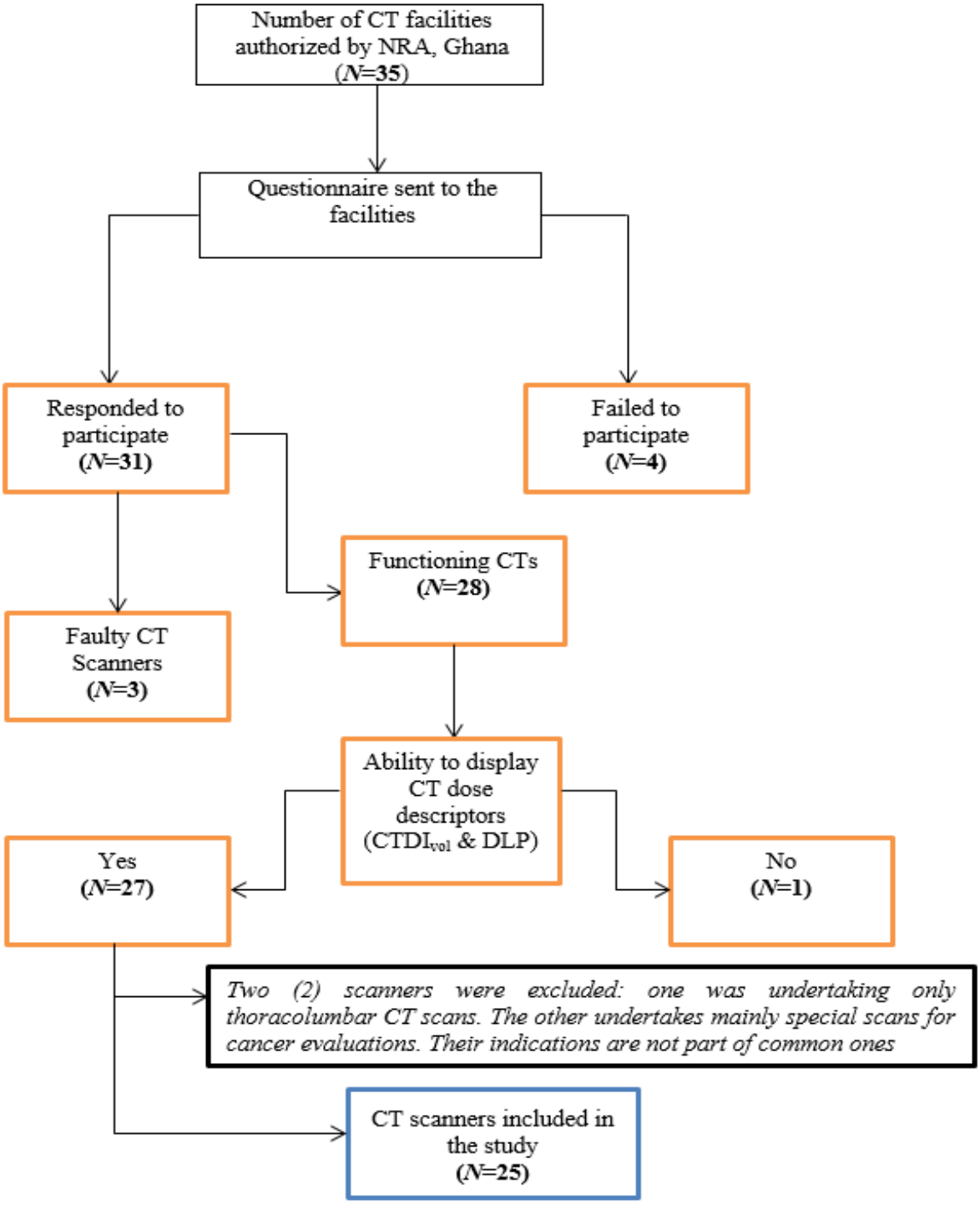


Figure 3.3: Flowchart of scanner selection.

NRA: Nuclear Regulatory Authority, CT: computed tomography, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.

3.4.2 Materials

The materials used in the QC assessment included:

1. CT dose profiler probe (RTI Electronics, Mölndal, Sweden). The calibration was undertaken by Swedac Ackreditering of RTI Electronics (ISO 17025) on 11th February, 2017. (Serial number; DP2-11110079, Certificate number; 1111F7445). A diagram of an RTI CT dose profiler is shown in Figure 3.4.

Figure 3.4: RTI CT dose profiler (RTI Group, 2016).

2. Barracuda set with Ocean Software Interface (RTI Electronics, Mölndal, Sweden). The set was made up of two components, the cabinet and multipurpose detector (MPD). The calibration was undertaken by Swedac Ackreditering of RTI Electronics (ISO 17025) on 01 January, 2017. The serial number and certificate number for each device were, cabinet (EBW-11100142; 1111G2964) and MPD (MPD-12010026; 121AB74B, respectively). A diagram of Barracuda set is shown in Figure 3.5.

Figure 3.5: Barracuda set (A= Cabinet, and B=Multipurpose Detector, MPD) (RTI Group, 2016).

3. Standard CT head and body polymethyl methacrylate (PMMA) phantom (PTW, Freighburg, Germany). The head phantom is 16 cm in diameter while the body phantom is 32 cm in diameter. Both were 15 cm long. For the placement of dose profiler or ionisation chamber, five probe holes were provided (one in the centre and four around the perimeter) in the PMMA combined phantom of head and body. Figure 3.6 shows the PMMA phantoms used in the study.

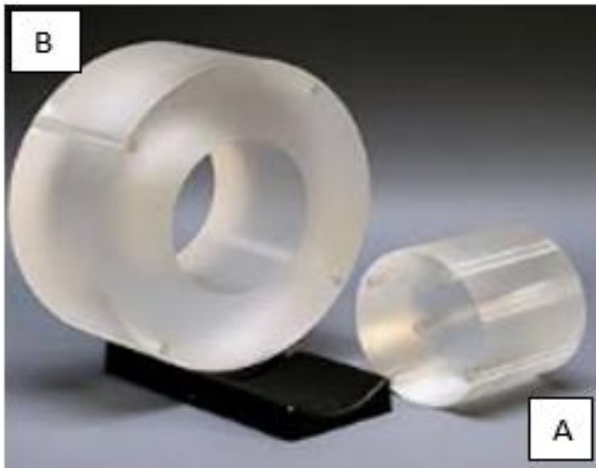


Figure 3.6: Standard PMMA Phantoms (A; head, A and B fused together to form body phantom) (RTI Group, 2016).

4. A laptop computer (Toshiba Satellite S55-C5274, 2016 model)
5. A uniform water phantom (PTW, Freighburg, Germany).
6. Microsoft excel spreadsheet installed on a computer (Microsoft version 2013).
7. ImageQC software v.1.43 (EllenWasbo, 2018; Stavanger, Norway).

3.4.3 Data Collection Procedure

Dose assessments for CTDI were performed using a standard CT head and body PMMA phantoms (PTW, Freighburg, Germany) together with an RTI CT dose profiler probe (RTI Electronics, Mölndal, Sweden) with Barracuda set connected to Ocean Software Interface (RTI Electronics, Mölndal, Sweden). The advantage of the RTI CT dose profiler probe over the traditional pencil-shaped 10-cm ionisation chamber is that it limits inaccurate dose measurements due to underestimation of the dose profile for wide beams (RTI Group, 2016). The RTI CT dose profiler probe provides an opportunity for dose measurements in every point of the x-ray beam and the total dose profile is attained irrespective of beam width (RTI Group, 2016). Moreover, the CT dose profiler is grounded on solid-state technology, robust and fits into existing standard phantoms used for CTDI measurements (RTI Group, 2016). Another reason for using it in this study was that, it was based on an accurate algorithm that allows the placement of a CT dose profiler probe in the centre of a phantom and could generate a completed picture of the dose profile such as CTDI (100), $CTDI_{(w)}$, $CTDI_{vol}$ and DLP in one exposure (RTI Group, 2016). The allowance of only one helical scan, instead of the normal five axial scans (because of the automatic compensations in the program) supports the comparison of measured and console-displayed values for all the selected CT scanners in a timely manner.

3.4.3.1 CT Dose Delivery Accuracy

CT dose delivery accuracy is a QC test used to examine the accuracy level of displayed dose quantities. To measure this, both head and body PMMA phantoms were used with the CT dose profiler in situ. The dose delivery accuracy QC was conducted separately for each phantom type. The CT dose profiler probe (detector) was connected to a Barracuda set with a cable which

was also connected to a laptop computer with Ocean Software Interface (RTI Electronics, Mölndal, Sweden). The detector was placed in the central hole of the phantom (centred in the gantry), and the other holes were blocked with PMMA rods and secured with a tape to prevent movement during the experiment. The phantom was adjusted and secured to align with the lasers to ensure that the CT dose profiler was in the isocentre. Routine standard protocols for head and body (depending on the phantom in place) were selected. Scanograms of the phantoms under examination was undertaken and the helical scan was planned.

The planning phase of the scan utilised the scan-measuring parameter template proposed by the CT dose profile software manual. The parameters included tube voltage, CT phantom type (either head or body), collimation (thickness of total detector area used), pitch (in helical mode), scan length, and tube rotation time. Scan speed and measuring time were also calculated automictically, after inputting the aforementioned exposure parameters. Scan types were selected to acquire the correct *k*-factor that allowed the CT scanner to extract all the parameters in one exposure. The total filtration was also selected.

To begin each experiment, it was ensured that both the scanners and ocean software of the CT profiler had same exposure parameters and features. The measurement processing on the computer and the CT scanner were then initiated at the same time. Once the CT scan was complete, the displayed CT dose profile on the laptop and the CT console were compared. In each accuracy test, two experiments were conducted for both head and body phantoms using tube voltage values commonly used at each CT centre. The accuracy level of dose delivery values (CTDI) was estimated with equation 3.1:

$$\%\quad error = \frac{(D_0 - D_1)}{D_1} x100 \qquad (3.1)$$

where *% error* represents percentage of dose delivery accuracy error; D_0 represents the Ocean software measured value of the dose profiler, and D_1 is the console-displayed CT dose descriptor/parameter.

Scanners with a deviation of less than ±20% of the measured values were considered to deliver acceptable CT dose reports on the CT console (IAEA, 2012). The experimental set up, and a CT dose profiler dose output for dose delivery accuracy are presented in Figures 3.7. and 3.8, respectively.

Figure 3.7: Experimental set up for dose delivery accuracy tests.
CT: computed tomography

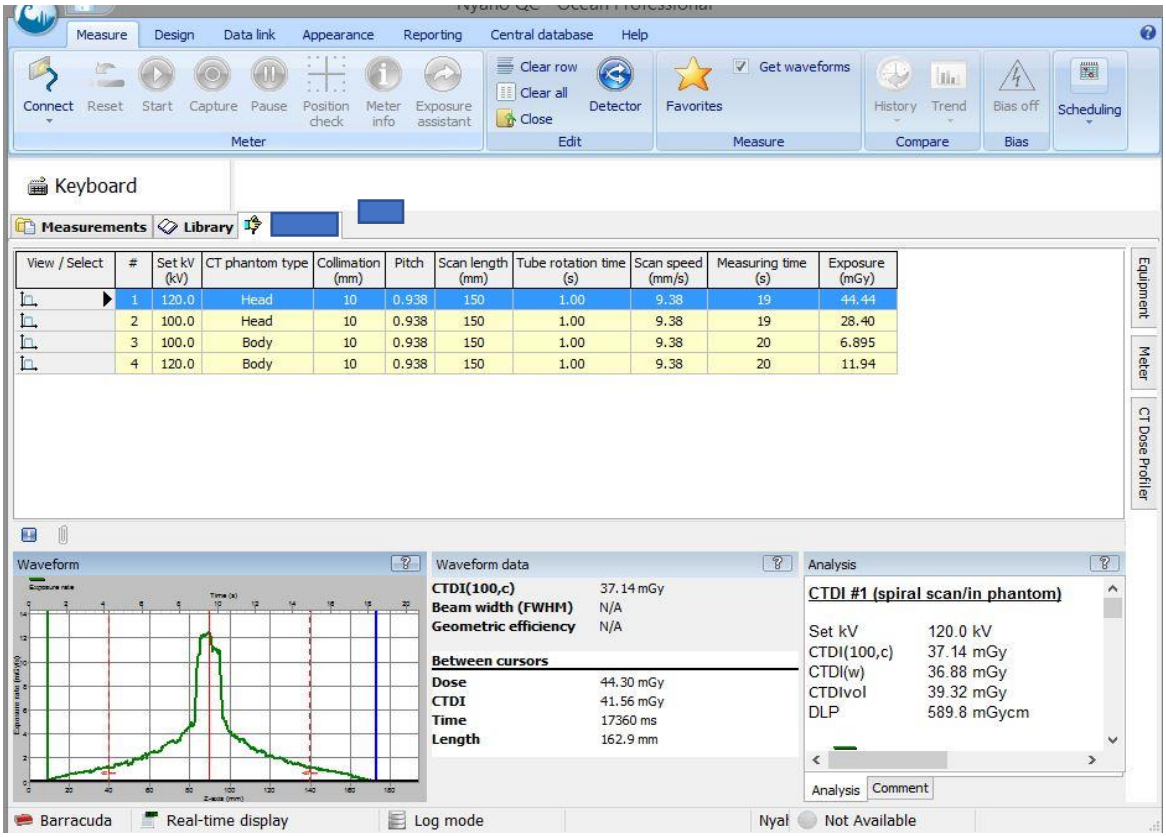


Figure 3.8: CT Dose profiler dose output for dose delivery accuracy.

3.4.3.2 CT Dose Delivery Reproducibility

For dose delivery reproductivity testing, the method outlined for dose accuracy was used with the exception of comparing the results with the console dose reports. Additionally, the scans were repeated three (3) times with the same scan parameters and settings for each phantom and the consistency level of the dose values were determined with the Ocean software. The coefficient of variation was used to determine the level of reproducibility of the doses for each experiment in the three measurements via equation 3.2:

$$CoV = \frac{SD}{\bar{x}} x100 \qquad (3.2)$$

where *CoV* is the coefficient of variation of measurements, *SD* is the standard deviation of all measurements, and $\bar{x}$ is the average of all measurements. An acceptable limit of $\leq \pm 5\%$ based on the recommendation of AAPM Report No. 35 (AAPM, 1992) was used to decide the suitability of the scanners' dose delivery reproducibility.

3.4.3.3 Geometric Efficiency

The geometric efficiency is defined as the ratio of the number of incident radiation quanta on the detector in a given interval to the number emitted by the radiation source in the same interval, expressed in percentage (Shefer et al., 2013). With respect to the geometric efficiency, free in air profiler measurements were conducted across the facilities. The CT dose profiler was adjusted so that the sensitive area was out of the phantom and positioned in the beam while the body phantom served as a holder. With the help of the lasers, the detector area of the profiler was positioned in the isocentre of the CT scanner. A scout scan was conducted for each scanner over the CT dose profiler detector. The measuring process of the Ocean software was engaged simultaneously with the CT scan. It was ensured that only the detector area was scanned free in air by avoiding the phantom holding areas in the scan.

In each accuracy test, two experiments were conducted for both head and body phantoms using tube voltage values that were commonly used at each CT centre. The measuring parameter template proposed by the CT dose profile software manual and which included tube voltage, collimation, pitch, and tube rotation time, were used. Scan speed and time were also calculated automatically after inputting the aforementioned exposure parameters. Data saved in Ocean reports were downloaded from the software to determine the geometric efficiency. Scanners with a geometric efficiency >70% were considered to perform optimally good (Shefer et al., 2013).

3.4.3.4 Tube Voltage Accuracy and Half Value Layer

Tube voltage accuracy test is used to test the correctness of the displayed tube voltage on the console of a CT machine (Public Health England, 2016). This is achieved by experimentally measuring and comparing the true values with the displayed values using the same equipment. The RTI MPD (RTI Electronics, Mölndal, Sweden) connected with a laptop computer with Ocean Software Interface (RTI Electronics, Mölndal, Sweden) was used for kVp accuracy testing. At each CT scanner, the RTI MPD was placed at the bottom rim of the inner portion of the CT gantry directly opposite the x-ray tube. This was achieved by ensuring that the vertical lasers coincided at the middle of the RTI MPD detector mark. A position check was then conducted to ensure that the detector was positioned in the middle of the beam and the lasers were correctly positioned. A topogram scan with the tube positioned at 12 o'clock was undertaken and the right position was ascertained with the Ocean software prior to the commencement of the scans. Subsequently, topogram scans were obtained for each scanner using the two commonly used tube voltage factors for head and body procedures. The results of the tube voltage accuracy measurements were generated by Ocean software for analysis.

For each testing, the RTI MPD detector, together with the Ocean software provided additional data of the HVL (in total filtration of aluminium) value in a single exposure. For a specified voltage, a measurement of the HVL provides data on the total filtration (specified quality) in the x-ray beam. Low filtration provides unnecessary radiation dose to the patient while higher filtration leads to beam hardening (AL-Jasim et al., 2017). The RTI Group indicates that HVL results generated by Ocean software with a single exposure is very comparable to the standard test where 5-mm thickness of aluminium filters are used (RTI Group, 2016). The mathematical equation used in the kVp accuracy/error calculation is given by equation 3.3:

$$\%\quad kV_p\quad error = \left(\frac{V_o - V_s}{V_s}\right)100 \qquad (3.3)$$

where V_0 and V_s represent the measured and set voltages, respectively. The acceptable limit of ≤ ±5% of nominal values was used to assess the CT scanners, while total filtration ≥ 2.5 mm Al for tube voltages >100 kV was used as the acceptable HVL limit (IAEA, 2012).

3.4.3.5 CT Number (Water), Image Noise Testing and Homogeneity

A water filled phantom (PTW, Freighburg, Germany), (Figure 3.9), was utilised for the CT number (water), homogeneity and image noise testing. It was made up of a thin uniform plastic container filled with distilled water.

Figure 3.9: Water-filled phantom for CT number, homogeneity and image noise testing.

During the testing procedure, the phantom was centred in the tomographic plane of each scanner to ensure that the middle of the phantom was in the isocentre. A routine body scan parameter was used to scan the phantom in each facility. In the absence of any image artefacts, a centrally located image slice of each scan was selected for analysis. The QC image analysis tool - ImageQC v.1.43 (EllenWasbo, 2018; Stavanger, Norway), was utilised in the analysis (ImageQC,

2017). In the software, CT number and image noise were measured in a centrally placed circular ROI (region of interest) of recommended diameter of 40% of the phantom image (ImageQC, 2017). Practically, the CT number was determined at the measured ROI mean value and the noise was determined at the ROI standard deviation as suggested by IAEA (IAEA, 2012).

Mathematically, the CT number (H_s) of a sample of material (s) is defined by the equation 3.4:

$$H_s = \left(\frac{\mu_s(E) - \mu_w(E)}{\mu_w(E)} \right) K \qquad (3.4)$$

where: $\mu_s(E)$ and $\mu_w(E)$ are the linear attenuation coefficients at the energy (E) of the x-ray beam for the scanned sample and water, respectively and K is a constant (K=1000) if the CT value scale is in HU as in the case of all modern CT units (IAEA, 2012). From equation 3.4, the CT number for water is zero and, since the attenuation is negligible for air, the CT number for air is –1000.

Therefore, scanners that recorded CT water number of ≤ ± 4 HU and noise derivation ≤ ± 10% of baseline values were considered to operate within the acceptable limits (IAEA, 2012). Figure 3.10 shows how the CT water number and image noise were analysed in the ImageQC software version 1.43. Arrows A and B in Figure 3.10 show how the results of CT number (water) and image noise are displayed in the software.

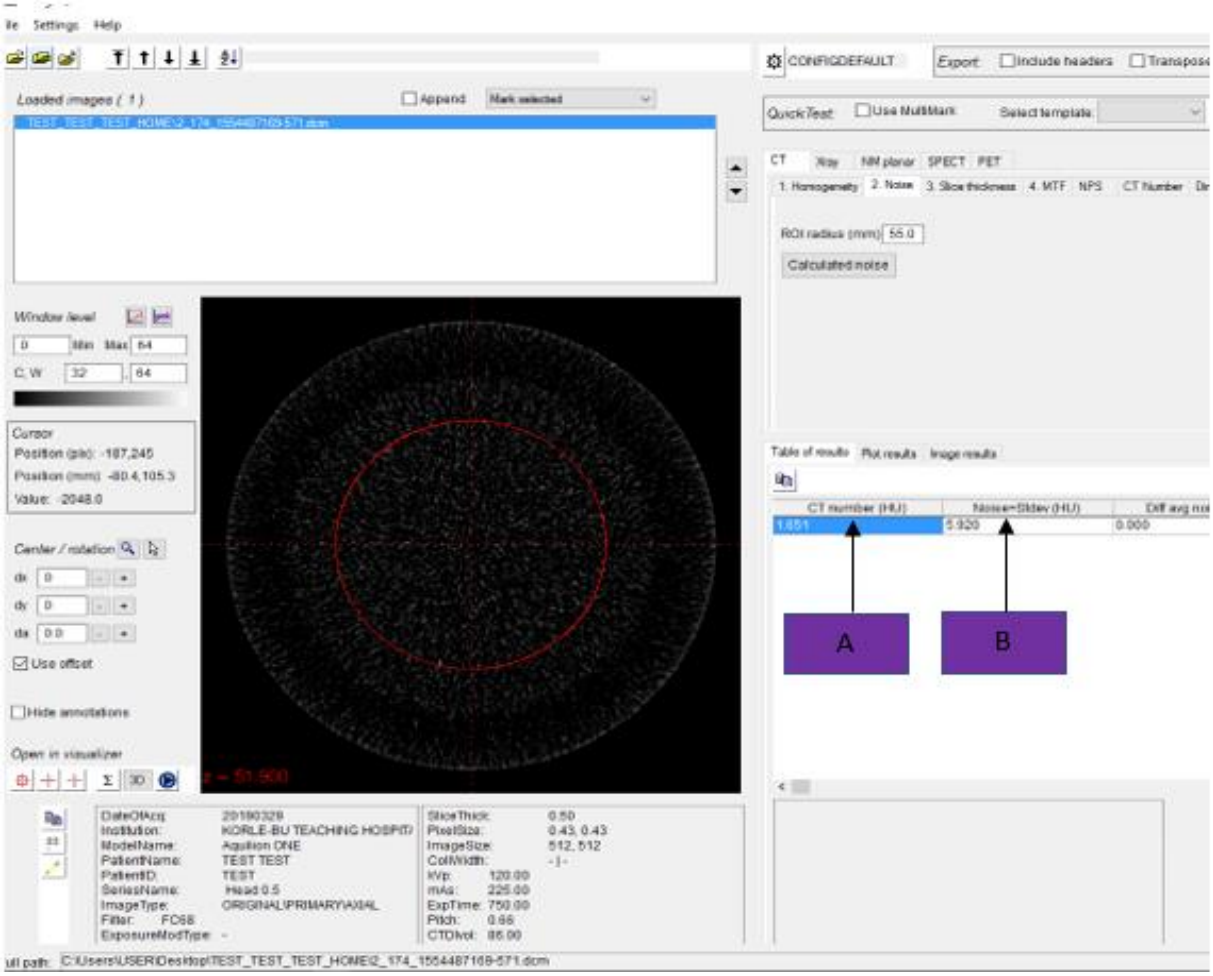


Figure 3.10 : CT number (arrow A), image noise (arrow B) analysis using ImageQC v.1.43.

In the case of the homogeneity (uniformity) testing, five ROIs of 10 mm each were measured at 12 o'clock, 15 o'clock, 18 o'clock, 21 o'clock and centre of the selected image slice. The uniformity was measured as the absolute difference of CT numbers between a centrally placed ROI with each of four ROIs placed on the edge. The ImageQC software v.1.43 was used in the homogeneity analyses. Each of these four values and their deviations from the central value were compared with the given tolerance of ±10 HU for head and body (IAEA, 2012).

Figure 3.11 shows how the CT uniformity/homogeneity analysis was performed using the ImageQC v.1.43.

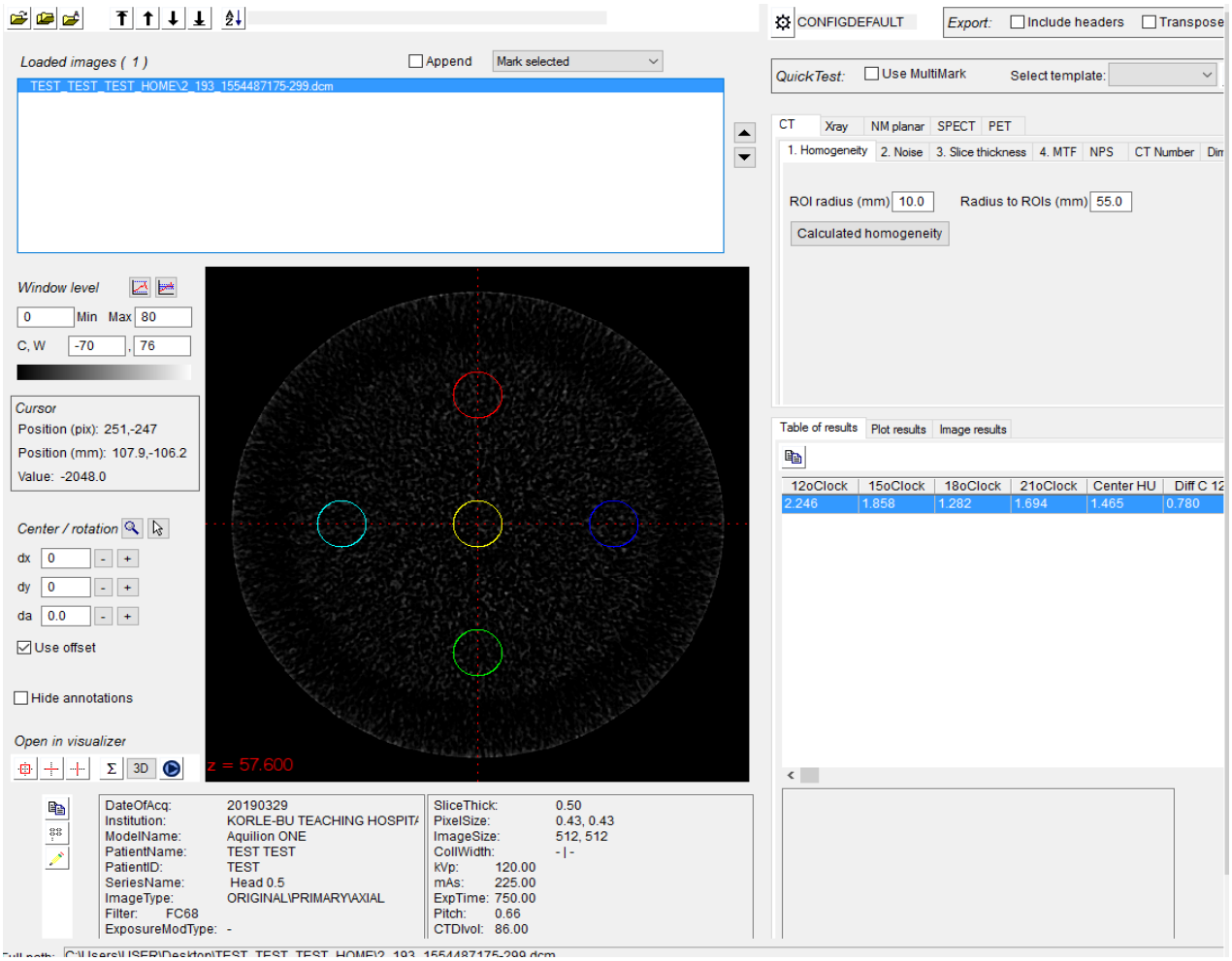


Figure 3.11: Uniformity/homogeneity analysis using ImageQC v.1.43.

3.5 Phase 3 Study: CT Dose Data and Image Quality Assessment

3.5.1 Outline

The Phase 3 of the study collected dose descriptor data and image quality information on patients' examinations. A prospective data collection process was used following the QC assessments to ensure that only CT quantity data generated after the QC tests were included. This ensured that the data (e.g. $CTDI_{vol}$ and DLP) displayed by the CT console for collection were valid. Details of the procedure for Phase 3 of the study are presented in Sections 3.5.2 to 3.5.7.

3.5.2 Study Population

ICRP Publication 135 recommends setting DRL values based on wide scale surveys of the suitable DRL quantities for examinations of a representative group of patients in an agreed weight range (ICRP, 2017). According to the Public Health England (2016), to ensure representative results for NDRLs, a successful national survey needs a timely gathering of important scan data from a robust sample of key procedures covering common CT practice. In line with the scope of this study, and as justified in Chapter One, the study population consisted of adults (18 years and above). Adults were used for this DRLs development because they accounted for the highest number of CT examinations in Ghana (Inkoom et al., 2014).

Since the attenuation of the x-ray beam depends on the tissue penetration depth, standardisation of patient size (weight restriction) was needed in DRL development (ICRP, 2017). A study (Shirazu et al., 2017b) suggested that the commonest weight range of average Ghanaians was 48.6 - 90.0 kg. Therefore, a population of weight range of 50–90 kg was chosen as the reference weight for the DRLs. This was in line with the ICRP's recommendations (ICRP, 2017).

3.5.3 Type of Data Set Collected

The ICRP has suggested that data collected for CT dose quantity surveys should, when possible, involve the equipment manufacturer/model, procedure name, patient weight and DRL quantities (e.g. $CTDI_{vol}$, DLP) (ICRP, 2017). The data must also include relevant scan parameters, if appropriate and available, for the examination types being surveyed (ICRP, 2017). In this study, the data collected in Phase 3 included equipment manufacturer/model, procedure name, patient weight, gender, age, $CTDI_{vol}$ and DLP. Where multiple scan sequences were undertaken, total DLP per indication were recorded. Other scan parameters collected included tube voltages (kVp) and tube loading (mAs), pitch, rotation time, scan thickness, number of series, number of slices per scan series, scan length, and the type of CT phantom used in estimating the dose quantities. Scanning mode, AEC application and contrast usage were also collected.

A study (Vock and Frija, 2016) has also argued that data collection for indication-based DRLs should take into consideration image quality, since the greatest priority for any diagnostic imaging procedure is producing image quality satisfactory for the clinical purpose. Consequently, for each patient image, one selected slice (at the centre of a set of images) was collected alongside the aforementioned parameters for objective image quality analysis (Section 3.5.6). Subjective image quality information was also obtained prior to the data collection, by requesting the scanning radiographers' comments on whether or not the acquired images in a particular CT folder/unit were diagnostically acceptable, not repeated, and had been accepted and reported by a radiologist. Practically, images accepted and reported by radiologists were considered as being of sufficient diagnostic quality to their need for the clinical purpose. Therefore, those images that the radiologists had reported without any image quality issues were considered "good data" sets for the study. This approach was used as the data sets were very large.

3.5.4 Patients' Data Size

It has been recommended in the literature (ICRP, 2017; Vock and Frija, 2016; Public Health England, 2016; IAEA, 2013) that it is very appropriate to collect data of 20 patients per indication in every selected CT centre for the development of NDRL. Accordingly, at every CT unit, 20 patients who had undertaken CT procedures for the same indication were selected at random. For indications such as CVA/stroke, head injury/trauma and suspicion of brain tumour/SOL, 20 data sets were collected from all the 25 CT units that passed the QC tests. However, for indications such as suspicion of lung cancer/tumour and CT lung lesion with CKD, 23 of the CT scanners undertook such examinations, and hence such data were not taken from the other two CT units. With regards to suspicion of abdomino-pelvic lesion and kidney stones, data were acquired from 24 CT units as such procedures were not undertaken at one CT unit. Nineteen and 10 CT units undertook examinations for suspicion of urothelial malignancy (CT-IVU) and PE, respectively. Therefore, 20 sets of data were selected from each unit for each indication, in order to provide better suggestions of typical practice at each CT centre. In total, 3,960 data sets were collected for the development of the indication-based DRLs.

3.5.5 Data Acquisition Tool and Process

This section describes in detail how the data sets mentioned in section 3.5.3 and 3.5.4 were collected. In Ghana, patient dose information recording and automatic dose tracking systems were not mandatory and readily available in most facilities at the time of the study. Data collection forms 1-9 (Appendix VII) were designed for the CT quantity data collection process using a similar validation process as described in Section 3.3.4. The scanning parameters and quantity data that were considered "good data" sets were received from the CT Picture Archiving and Communication System (PACS), workstations and Radiation Dose Structured Reports (RDSRs).

A 2-TB (Terabyte) hard-drive was used to store the soft copies of images, one each of selected examination for subjective analysis.

The data collection process used in this Phase of the study was first tested and refined in a pilot survey conducted at two hospitals in Accra. This process effectively managed the study, including protocol assortment to suitability, ease of usage of the data collection forms, and data recording. Following the pilot study, the researcher visited all the 25 facilities for the data. The initial data were entered into Microsoft Excel spreadsheet version 2013 and errors checked. The data was further analysed for statistical control (detailed in section 3.5.7) using a Microsoft Excel version 2013 and Statistical Package for the Social Sciences (SPSS) version 23.0 (SPSS Inc., Chicago, IL USA) prior to the DRL estimation. The data collection process in this Phase of the study took a year to complete.

3.5.6 Image Quality Assessment of the Collected Image Data

The quality of all the various images (of which CT descriptors were used in DRLs) was assessed prior to using the data for the DRLs. The image quality was used as a QC measure of a scanner's performance and to optimise practice. For effective development of DRLs, it was needful to ensure that all the images, whose quantity data or parameters were used, were within the acceptable diagnostic limit. Images of poor quality could lead to diagnostic challenges. As indicated earlier (Section 3.5.3), due to the large data sets involved, radiographers at the CT units of the study sites provided subjective image quality remarks on all the collected imaging folders prior to data collection.

Objectively, the images were again assessed for their signal to noise ratio (SNR) properties. Though the contrast to noise ratio (CNR) and SNR are currently the mainly used objective image quality parameters in CT imaging, there is incoherent limitation concerning the use of CNR (Lu

and Nishikawa, 2012). This is because at low-contrast signals, the CNR does not account for background noise correlations across different types of reconstruction algorithms (Lu and Nishikawa, 2012). The SNR, on the other hand, associates well with objective analysis (Lu and Nishikawa, 2012). Mathematically, the SNR for the images at specific region of interests (*ROI*) were estimated using equation 3.5:

$$\mathrm{SNR} = \frac{\text{Mean signal value witnin ROI}}{\text{SD within ROI}} \qquad (3.5)$$

where the symbols bear their defined meanings and *SD* is standard deviation.

An ImageJ software programme version 1.52 manufactured by the National Institute of Health, USA, which is reliable for objective image quality assessment (Ferreira and Rasband, 2012) was used to mathematically predict the mean signal and SD values within a given ROI. The mean signal and SD values were inputted in equation 3.5 to determine the SNR. Figure 3.12 shows how the ROI was structured in each of the anatomical region.

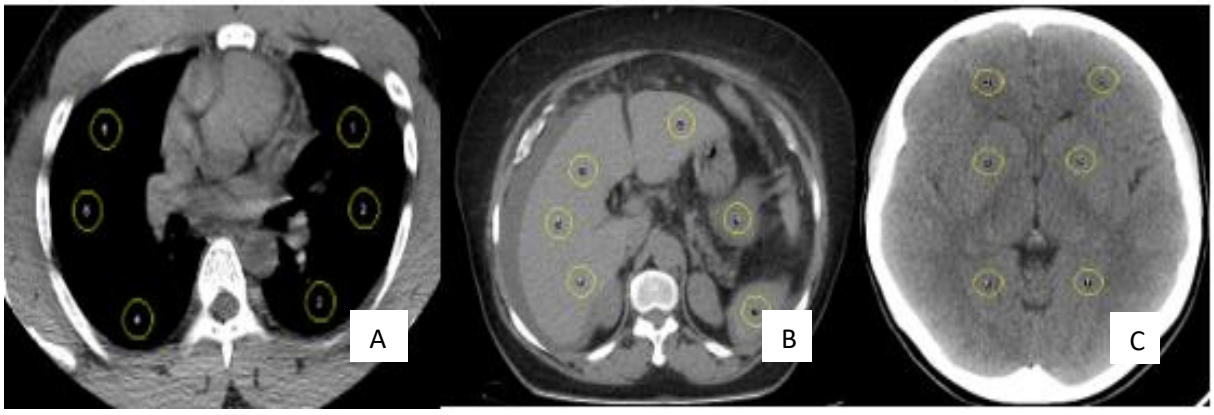


Figure 3.12: Positioning of ROI in chest (A), abdomen and pelvis (B) and head (C) examinations.

The Rose criterion (model), which states that an SNR of at least 5 (≥ 5) is required to distinguish image features at 100% certainty (Bushberg et al., 2011), was used to evaluate the suitability of the SNR in the images.

3.5.7 Statistical Control of Collected Dose Descriptors

In the data collection process, an unexpected outcome could happen as a result of errors (Neuburger et al., 2017). Particularly, during the collection and entering of large data sets such as the CT dose descriptors used in this study. Quality assessments in relation to both raw data and their analyses, represented an important feature of data management for the national CT survey to reinforce confidence in reported results (Public Health England, 2016). In addition to the CT QC tests performed in the Phase 2 study to assess the performances of the CT scanners, statistical control analyses were also used to assess the internal QC of the raw data. Internal data QC involves a continuous, critical evaluation of the data collection process or acquired data and working routines using a statistical method to mitigate errors (Neuburger et al., 2017). To ensure reliability in the data entering consistency, the first 20 data sets were re-evaluated, and data re-entered and compared with the original entries using SPSS version 23.0 (SPSS Inc., Chicago, IL USA). A successful data entering consistency was assumed when discrepancies between the initial and follow up entries were < 2% (Pedersen et al., 2018).

Subsequently, statistical control charts (Shewharts) (Neuburger et al., 2017) were used to analyse performance through data collection time and also ensured no problems with the data entering process. To generate the control chart, the mean, the standard deviation, as well as the upper and lower control limit values of the critical dose descriptors such as $CTDI_{vol}$ and DLP were calculated.

The upper control limit (UCL) was derived from the equation 3.6:

$$UCL = M + (3 \text{ x SD}) \quad (3.6)$$

while the lower control limit (LCL) was calculated from equation 3.7:

$$LCL = M - (3 \text{ x SD}) \quad (3.7)$$

where: *M* and *SD* are the mean and standard deviation, respectively.

The mean UCL and LCL were plotted using Microsoft Excel to generate the X-charts for quantity data sets. Data points above the UCL and below LCL were double-checked to ensure that the true data sets were entered. All wrong entries were then corrected. The charts are shown in Appendix VIII and indicate a good final control X-charts for all indications, which made the data suitable for DRL estimation. Once the statistical control process was over and image qualities were acceptable, the CT quantity data values for all the various indications were transferred to SPSS version 23.0 (SPSS Inc., Chicago, IL USA) for DRLs estimation.

3.6 Phase 4 Study: DRL Values Estimation and Dose Monitoring Tool

3.6.1 Outline

The procedures used in estimating the DRL values and developing a tool for dose monitoring are discussed in Sections 3.6.2 and 3.6.3.

3.6.2 DRL Values Estimation

The ICRP (2017) has recommended that NDRL values ought to be established at the 75th percentile of median values obtained in a sample of representative facilities. The median value has been recommended over the mean values in the ICRP Publication 135 for DRL estimation, as it is recognised to be more robust in DRLs. Accordingly, SPSS version 23.0 (SPSS Inc., Chicago, IL USA) was used to analyse the data.

For each indication, the median, minimum, maximum, and standard deviations were estimated. Moreover, quartiles (25th, 50th and 75th percentiles) were estimated. The 50th percentile was referred to as the achievable dose (AD). Microsoft Excel Version 2013 was used to produce bar charts for visual presentation of frequency distribution for various key dose descriptors in the survey. The developed DRLs were compared with previously established NDRLs reported in literature. The results are presented in Section 4.4 of Chapter Four.

3.6.3 Tool for Dose Monitoring

For the proposed indication-based DRLs to be well established in Ghana, a simple Microsoft Excel-based tool (also called **BOT^{B}** in this study) was developed for its application in periodic inspection and monitoring of DRLs compliance purposes. It was based on the assumption that there would be a need for compliance assessment across the facilities once the DRLs are

established by the appropriate authority. However, without an easy-to-use tool for assessment, the compliance assessment exercise could be limited.

On a Microsoft Excel page, the proposed DRLs ($CTDI_{vol}$ and DLP) values were used as benchmarks and formatting rules were set. Columns and rows (entering space) were provided for demographics and dose descriptors/quantity data. Conditions in terms of weight and examination sequences were also set based on the study's results. Excel formulas were developed using equation functions, and conditional and formatting tools. Also, colours were used to communicate results output. The Excel interphase (Figure 4.24; for each indication) included a results box that shows the DRLs, and a results interpretation/action section that gives interpretation to the results. When a sample of patients' data is entered into the entering space, the functions calculate the DRLs and equate them to that of the national values automatically. When the calculated values are above the NDRLs, the colour appears red; when it turns black it indicates an acceptable level; however when it turns blue, it indicates that the facility's doses are below the 25^{th} percentile and hence, image quality tests are required to ensure that examinations of acceptable diagnostic quality are produced.

3.7 Phase 5 Study: Dose Impact on Patients and Cancer Risk

3.7.1 Outline

The procedures used in studying the dose impact and possible cancer risk of CT imaging of the various indications on patients are presented in Sections 3.7.2 and 3.7.3.

3.7.2 Effective Dose

To understand the radiation dose impact associated with each of the indications and propose appropriate optimisation methods, effective doses were first estimated for each indication using the equation 2.8 expressed in Chapter Two. The *k*-factors suggested by the ICRP Publication 103 (ICRP, 2007) were used in the estimation of the effective dose for each indication with respect to the anatomical region. The *k*-factors (conversion factors for changing DLP to effective dose) for the respective anatomical regions are presented in Table 3.1.

Table 3.1: ICRP Publication 103 recommended region-specific DLP-E_D conversion factors

Anatomical region	DLP to E_D coefficients (mSv /mGy cm)
Head	0.0023
Chest	0.0170
Pelvis	0.0190
Abdomen	0.0153
Abdomen-Pelvis	0.0150

DLP; dose length product, E_D; effective dose; ICRP; International Commission on Radiological Protection

To better understand the magnitude of the doses, the average effective doses for the indications were then compared to the global average natural background radiation of approximately 2.4 mSv (Canadian Nuclear Safety Commission, 2019). The results are presented in Table 4.51.

3.7.3 Cancer Risk

To understand the cancer risk associated with the observed radiation doses across the CT facilities, the BEIR VII model was applied to predict the Lifetime Attributable Risk (LAR) of cancer based on the magnitude of a single radiation exposure, patient's age and gender (National Research Council, 2006). The LAR is defined as additional cancer risk above and beyond baseline cancer risk (Lee et al., 2012). The model was developed based on the extensive studies on the survivors of Hiroshima and Nagasaki atomic bombs and medical, occupational and environmental radiation studies (National Research Council, 2006). Theoretically, the model is grounded on the linear no-threshold model (LNT) concept which is centred on the assumption that the smallest dose has the potential to cause a small increase in radiation risk to humans (National Research Council, 2006).

LAR data as presented in Tables 2.1 and 2.2, respectively, were utilised to estimate the cancer risks. Using the age of exposure and gender parameters, the *LAR* of cancer incidence (*LARi)* and cancer mortality (*LARm)* from organ doses were subsequently extrapolated for patients (age 20, 40 and 60 years) by BEIR VII models as presented in proportions via equations (3.8) and (3.9) below.

$$\mathrm{LAR}i = \left[\left(\frac{\mathrm{D_{org}}}{0.1}\,\mathrm{Gy}\right)\mathrm{LAR}if\right] \text{ in 100,000 patients} \qquad (3.8)$$

$$\mathrm{LAR}m = \left[\left(\frac{\mathrm{D_{org}}}{0.1}\,\mathrm{Gy}\right)\mathrm{LAR}mf\right] \text{ in 100,000 patients} \qquad (3.9)$$

where LAR_i and LAR_m represent the lifetime attributable risk of cancer incidence and mortality, respectively. The *LARif* and *LARmf* represent the BEIR VII organ-specific cancer incidence and mortality coefficients, normalised to age and gender, and D_{org} is the organ dose in gray (Gy).

The organ doses associated with each of the indication-based CT imaging examinations were estimated and used in the above cancer risk equations (3.8 and 3.9). To predict organ doses in the human body subjected to CT x-ray photons, two different methods are plausible. These include experimental measurement and computer simulation (Lee et al., 2012). In the case of the experimental dose measurements, physical phantoms (mostly) with capabilities to receive organ site-specific types of dosimeters are scanned with CT (Lee et al., 2011). However, this procedure is complex and time-consuming, and physical phantoms provide inadequate sampling of the disparities of age, gender, and body morphometries. Moreover, the procedure cannot, in some cases, accurately represent the average organ dose when high dose gradients exist, and also when the distributed body tissues (e.g. active bone marrow) are of concern (Lee et al., 2012; Lee et al., 2011).

Contrarily, computer simulation software programmes are good option when estimating organ doses across many facilities (Lee et al., 2012) as was the case in Ghana for each of the indications. The National Cancer Institute dosimetry system for CT (NCICT) (software version 2.1) was used in the organ dose estimations (Lee et al., 2015). The software is based on a comprehensive library of computational human phantoms (surrogate anatomy for patients) combined with Monte Carlo radiation simulation of reference CT scanners (Lee et al., 2015). It has been reported to be the most current, sophisticated and reliable way to obtain accurate values of organ dose under CT imaging (Lee et al., 2015; Lee et al., 2011). Although there are many available computer simulation software systems such as CT Dosimetry, CT-Expo, CTDOSE,

Radimetrics^{TM} for estimating organ doses, the computational phantoms within some of these existing software tools are limited to mathematical stylised phantoms which practically, may be different from the reference anatomy recommended by the ICRP (Lee et al., 2015). Moreover, most of these computer simulation systems are relatively old and do not have all the current CT scanner models in the software for dose estimations. Some studies (Lee et al., 2012; Liu et al., 2010) have reported some significant discrepancies in radiation doses between the actual and the estimated values when the correct scanner model and information are not selected in the software for estimation. However, the NCICT is known to provide a more realistic anatomy based on the ICRP reference phantoms and the most up-to-date bone marrow dosimetry with several convenient features compared to previous tools (Lee et al., 2015), hence, its usage in this study.

In this study, the $CTDI_{vol}$ values were displayed by all the scanners. The organ doses were normalised through the $CTDI_{vol}$ and patient- and scan-specific parameters by an algorithm. Mathematically, the algorithm is expressed in equation 3.10:

$$D(organ, age, gender, spectrum) = \sum_{Z=SS}^{Z=SE} DC(organ, age, gender, spectrum, Z)\, xCTDI_{vol} \quad (3.10)$$

where

D (organ, age, gender, spectrum) is the absorbed dose (mGy) for the organ of interest, the age and gender of a given scanned patient with an x-ray spectrum;

SS and SE are the respective *Scan Start* and *Scan End* distances (cm) from the top of the head (cranially) in patients;

DC (organ, age, gender, spectrum, Z) is the 5D matrix of organ dose coefficient (DC) (mGy/mGy) per 1-cm axial slice: organ dose (mGy) normalised to the $CTDI_{vol}$ (mGy) of the reference CT scanner used for the Monte Carlo calculations. Organ is the organ of

interest, age and gender are derived from a given patient, and spectrum is one of the six combinations of four tube potentials (80, 100, 120, and 140 kVp) and two filtrations (head and body) of a particular CT scan, and Z is the slice number ranging from the top of the head to the bottom of the patient's feet;

$CTDI_{vol}$ is from the particular scan for which organ doses are calculated (Lee et al., 2015).

Through the graphical user interface (GUI), the relevant parameters were entered into the software.

Figure 3.13 shows a NCICT software GUI which allows organ doses to be obtained based on the entered $CTDI_{vol}$ and patient- and scan-specific parameters.

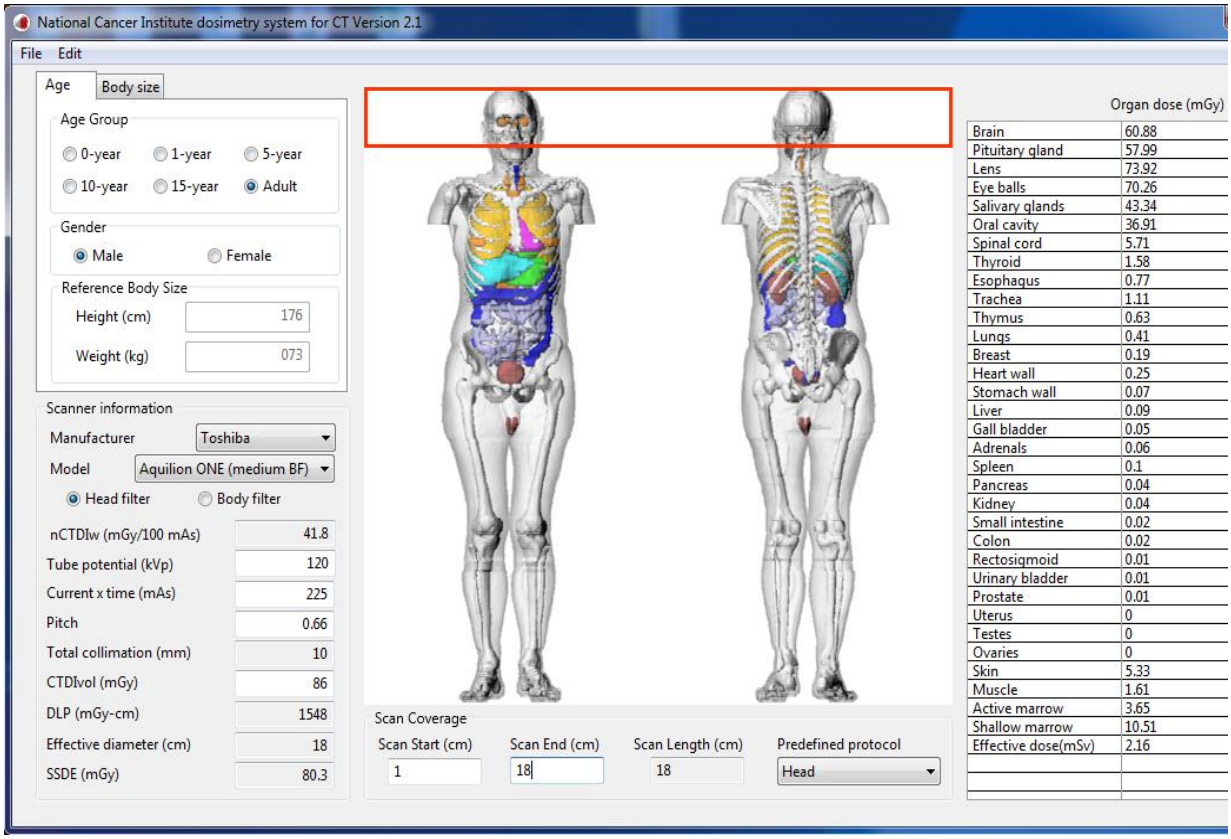


Figure 3.13: Graphical user interface (GUI) of the NCICT program showing an example of entered patient- and scan-specific parameters and estimated organ dose calculation for adult male head (brain tumour/SOL) scan.

Using the equations (3.8 and 3.9) and the estimated organ doses, the LAR_i and LAR_m for each organ were also estimated. The results of the organ dose and the *LARi* and *LARm* values are presented in Tables 4.52-4.56. The organs, whose doses were estimated, have been presented in Table 3.2.

Table 3.2: Indication-related organ whose doses were estimated

Anatomical region	Indication	Organs
Head	CVA, brain tumour, head injury/ trauma	Brain Pituitary gland Lens Eyeballs Salivary glands Oral cavity Spinal cord Thyroid
Chest	Lung tumour/cancer, Chest lesion with CKD, PE	Thyroid Oesophagus Trachea Thymus Lungs Breast Heart wall
Abdomino-pelvic	Abdomino-pelvic lesion, kidney stones, urothelial malignancy (CT-IVU)	Stomach wall Liver Gall bladder Adrenals Spleen Pancreas Kidney Small intestine Colon Rectosigmoid Urinary bladder Prostate Uterus Testes Ovaries Skin Muscle Active marrow Shallow marrow

Key: CVA= cerebrovascular accident, CKD =chronic kidney disease, PE= pulmonary embolism, CT-IVU =computed tomography intravenous urography.

3.8 Phase 6 Study: Optimisation

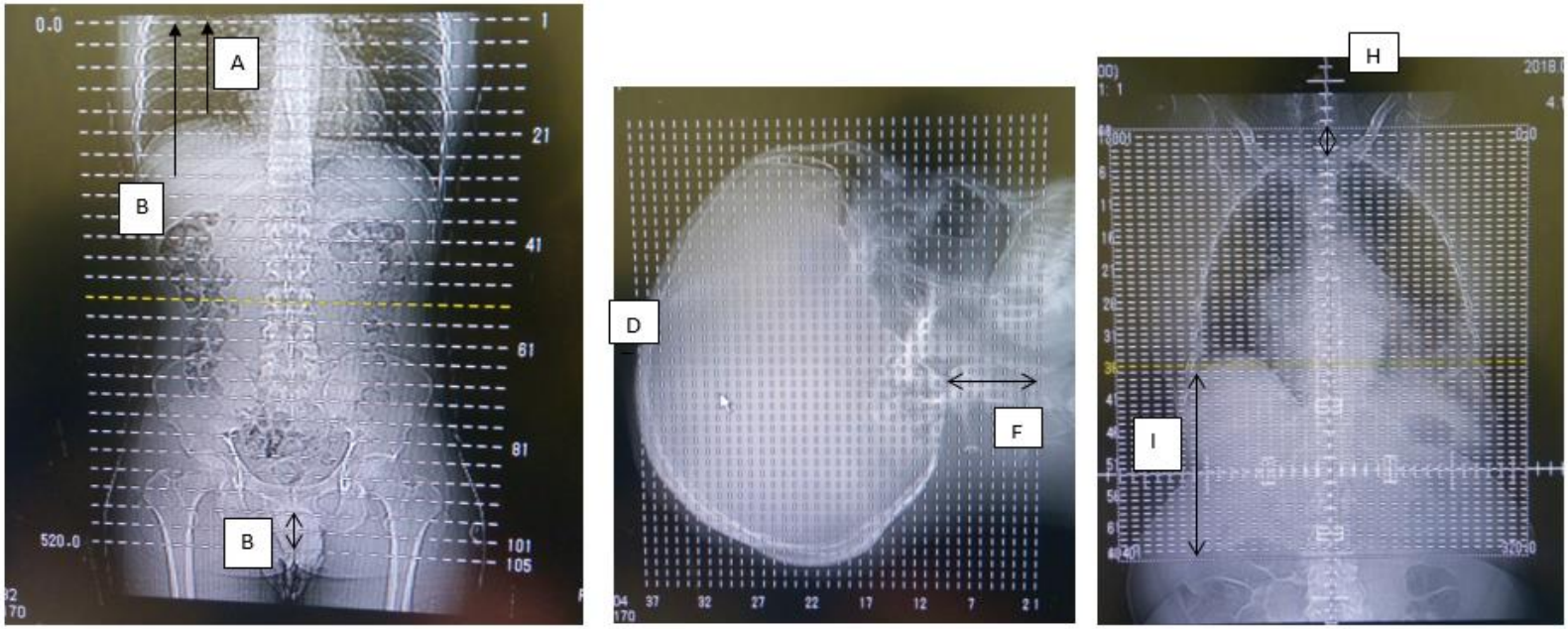
The procedures used in developing CT optimisation methods are outlined in Sections 3.8.1-3.8.2.5.

3.8.1 Optimisation Method 1: Management of Scan Length

Optimisation, through the management of scan lengths utilised in the facilities for CT imaging, was explored to improve the radiation protection of patients. The additional scan distances (along the z-axis) covered above (DAUT) and below (DBLT) the organ or anatomical region of interest for each indication was evaluated for optimisation options. The concept of evaluating the DAUT and DBLT is that, CT scanning exactly to the ends of the structure/organ of interest using a planner scanogram may lead to a cutting off of some essential part of the organ of interest. To prevent this and the associated risk of repeats and reporting uncertainties, there is a need to adequately cover the area/organ under examination by scanning slightly above or below the interested organ/region.

The criteria for characterising image coverage in CT have been defined and agreed upon in Europe for some specific adult and paediatric examinations (European Commission, 1999). However, these criteria are now over 23 years and do not reflect all the common indications in CT. Moreover, these criteria are mostly anatomy based. The European Commission (1999), in particular, states that the volume of investigation for head procedures should cover from the foramen magnum to the skull vertex. However, it does not provide recommendations for all specific indications of the head as they vary. In Phase 1, most of the CT facilities in Ghana lacked documented scan protocols for all the indications and the observed imaging requirements were numerically vague on the acceptable DAUT and DBLT. The lack of standardisation could lead to a great variation in practice and associated radiation doses.

In evaluating extra scan coverages, all patients' folders containing image information used for developing the DRLs were selected with their identification numbers and the images reconstructed. CT calibrated callipers at the CT workstations were used to undertake the DAUT and DBLT measurements, after reconstructing the acquired image slices into grid lines on scan planners. A template sheet used to collect the DAUT and DBLT data is presented in Appendix IX. To ensure accuracy in the measurements, the scanned PMMA CT head phantom length (of known length of 150 mm) used in the QC assessment was measured on the CT workstations. The measured length on the CT workstations was compared with original length for accuracy prior to taking the main measurement data. Each measurement was conducted twice, and the average values were used. Diagrams showing how the measurements of DAUT and DBLT were undertaking for each indication are shown in Figure 3.14. The DAUT measurements for head indications were measured from the skull vertex to the last slice line above the head (cranially) (Line D) and for the DBLT it was measured from base of skull (at foramen magnum) down the cervical to the last slice line caudally (Line F). For all chest indications, the DAUT was measured from the lung apex (first thoracic vertebra) to the last slice line cranially (Line H) and for the DBLT, it was measured from the lowest costophrenic angle to the last slice line caudally (Line I). Regarding abdomino-pelvic lesions/tumours, the DAUT was measured from the dome of diaphragm to the last slice line cranially (Line A). For the DBLT, it was measured from the symphysis pubis to the last slice line caudally (Line B). In the case of kidney stone and CT-IVU for urothelial malignancy, the DAUT was measured from 1 cm above the most cranial pole of the kidneys to where the last slice line ended upwards (Line C) and for the DBLT, it was measured from the symphysis pubis to the last slice line caudally (Line B).



INSRUCTIONS:

For **Abdomino-pelvic** cases that involve abdominopelvic lesions/tumours the DAUT was measured from the **dome of diaphragm** to where the last slice line ended upwards (cranially) (Line A in the diagram). For the **DBLT**, it was measured from the **symphysis pubis** to the last slice line downwards (caudally) (Line B).

For **Kidney stone, and CT IVU** ***for Urothelial malignancy the DAUT*** *was measured from* ***1 cm above the most cranial pole of the kidneys to where the last slice line ended upwards (Line C) and for the DBLT****, it was measured from the symphysis pubis to the last slice line downwards* ***(caudally) (Line B).***

For **Head** cases, the DAUT was measured from the **skull vertex to where the last slice line ended above the head** (cranially) (Line D) and for the DBLT it was measured from **bases of skull (at foramen magnum) down the cervical to the last slice line downwards (caudally)** (Line F).

For all **chest** cases including pulmonary angiogram, the **DAUT** was measured from **the lung apex (T1) to where the last slice line ended upwards (carnially)** (Line H) and for the **DBLT,** it was measured from the **lowest costophrenic angle (lung base) to the last slice line downwards (caudally) (Line I).**

Figure 3.14: The measurements of DAUT and DBLT for each indication

A Microsoft excel spreadsheet version 2013 was used to generate mean and standard deviation values for DAUT and DBUT that were used across the country for all the indications and the results presented in Table 4.57 of Chapter Four. To recommend an appropriate standard protocol to optimise and harmonise the extra scan length values and reduce unnecessary radiation for clinical application in Ghana, an experimental study using routine CVA/stroke indication as a case study was then undertaken. This CVA/stroke indication was selected because it was the most observed indication in this study.

3.8.1.1 Phantom-Based Optimisation Study

An anthropomorphic Alderson RANDO phantom was used to investigate the desirable scan coverage for CT CVA/stroke indication. The details are presented in Sections 3.8.1.1.1-3.8.1.1.4.

3.8.1.1.1 Materials

A Siemens CT Somatom Emotion scanner and an anthropomorphic Alderson RANDO phantom, which consists of a human skeleton embedded in plastic, were used in the experiment. The phantom has equivalent radiological properties to human tissues. Its physical characteristics were similar to an average male patient of weight, 73.5 kg, and height, 175 cm tall and without arms or legs. The phantom consists of 2.5 cm-thick plastic slices with pre-drilled holes into which TLDs can be inserted, and segmented into sections numbered from 0 at the cranial end to 35 at the caudal end. An ImageJ software version 1.52 and two radiologists were used to assess the image quality while Microsoft Excel version 2013 was used for data entering and processing for analysis. A diagram showing the anthropomorphic Alderson RANDO phantom and how it was positioned in a Siemens CT Somatom Emotion scanner for the optimisation study is presented in Figure 3.15.

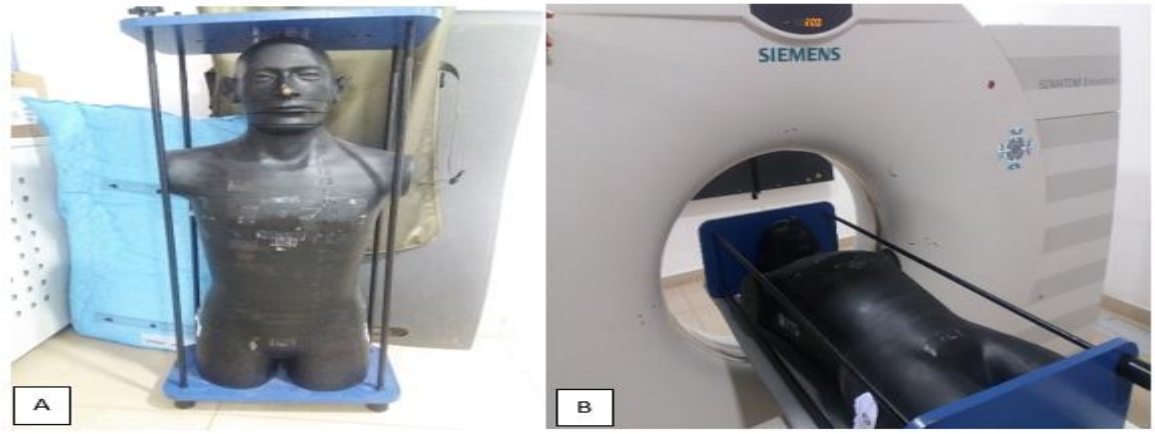


Figure 3.15: An anthropomorphic Alderson RANDO phantom as shown in Plate A, while Plate B shows the position of the phantom in a Siemens CT Somatom Emotion scanner.

3.8.1.1.2 Procedure

First, the standard protocol for routine CVA procedure was used to scan the phantom using a Siemens Somatom Emotion positioned for CVA procedure. A total of six different scan coverages (scan lengths) were used to acquire different sets of images. The imaging parameters used are presented in Table 3.3.

Table 3.3: Parameters used for performing the experimental study for scan coverage for routine CVA

Protocol/ image ID	kVp	Eff. mAs	Pitch	*Trot(s)*	*ST (mm)*	*Coll.*	SL *(mm)*	DAUT *(mm)*	DBLT *(mm)*
A	110	120	0.55	1.5	3	16 x 0.6	165	≈8	≈20
B	110	120	0.55	1.5	3	16 x 0.6	137	0	0
C	110	120	0.55	1.5	3	16 x 0.6	132	10*	0
D	110	120	0.55	1.5	3	16 x 0.6	157	10	10
E	110	120	0.55	1.5	3	16 x 0.6	142	0	5
F	110	120	0.55	1.5	3	16 x 0.6	147	5	5

*Key: * = below the vertex, kVp: peak kilovoltage, Eff. mAs: effective milliampere-second, Trot(s): rotation time, ST: scan thickness, Coll.: collimation, SL: Scan length, DAUT: distance above upper target, DBLT: distance below lower target. CVA: cerebrovascular accident.* **Note:** *upper and lower targets for CVA imaging were the skull vertex and foramen magnum, respectively.*

For study A, the scan coverage employed the mean DAUT and DBLT values used across the facilities to scan the phantom after a scanogram. With all factors remaining the same, the DAUT and DBLT values were adjusted to study the dose and image quality response. The second measurement (B) was undertaken by adjusting the scan length from exactly the vertex of the skull down to exactly the level of the foramen magnum at the base of the skull. The third measurement (C) was also undertaken 10 mm below the skull vertex and 0 mm below the base of the skull at the foramen magnum. The other measurements were taken; 10 mm above vertex and 10 mm below the base of the skull (D); no extra scan lengths above vertex and 5 mm extra scan lengths below the base of the skull (E), and 5 mm extra scan length above vertex and below the base of the skull (F). Six different scan coverages (scan lengths) were used to acquire different sets of images and, subsequently, the $CTDI_{vol}$, DLP values were obtained from the CT scanner's console. The scan coverages used in scanning the Alderson RANDO phantom are shown in Figure 3.16.

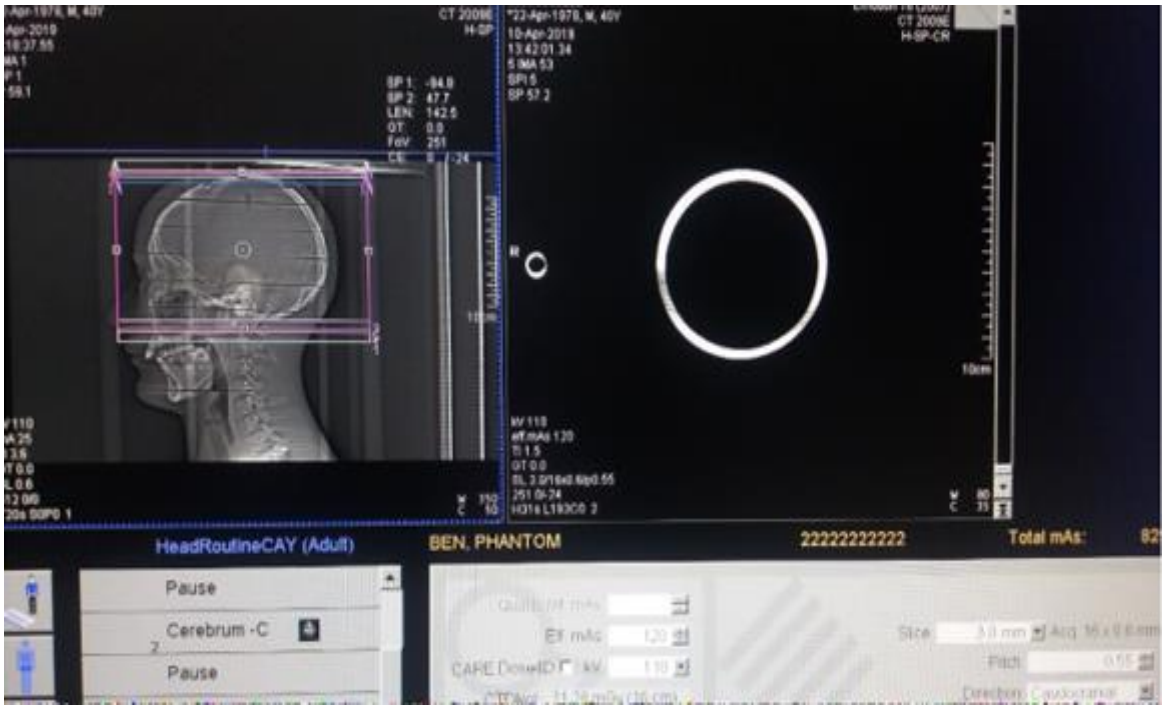


Figure 3.16: Scan coverages used in scanning the Alderson RANDO phantom.

3.8.1.1.3 Image Quality Assessment

Image quality in terms of SNR was calculated using equation (3.5) and the procedures described in Section 3.3.3.6 using ImageJ software version 1.52. Moreover, the images of each set of procedures were given to two senior radiologists to estimate the suitability and subjective image quality of all the suggested protocols for their intended tasks in clinical practice in Ghana. The two radiologists had 9-years and 5-years working experience in image reporting, respectively. A 5-point scale (1= poor to 5= very good) was used to rate the images on: coverage of the region of interest, image contrast resolution, acceptable spatial resolution, diagnostic image acceptability, visualization of anatomical structures of interest and image noise.

3.8.1.1.4 Data Analysis

An SPSS-based Intraclass Correlation Coefficients (ICC) was run to determine statistical agreement between the two raters in image quality scoring. A p-value of ≤ 0.05 was considered statistically significant in the ICC tests. The dose descriptor data for all the six protocols were descriptively compared using Microsoft Excel version 2013 and percentages of DLP dose reduction over the current practice (originally used across the facilities) were estimated. The results are presented in Table 4.58 of Chapter Four.

3.8.1.2 Patient-Based Optimisation Study

As the phantom could not absolutely mimic a real CVA condition, a clinical study using patients' data was conducted to evaluate the application of the phantom results in clinical practice. The average scan coverage used in the facilities was referred to as "Full range" while the best scan coverage protocol (*protocol C*) observed in the phantom study was referred to as "Reduced range". Details are presented in Sections 3.8.1.2.1 to 3.8.1.2.7.

3.8.1.2.1 Materials

Five CT scanners, including Toshiba Aquilion ONE, Philips Brilliance Extended, GE Optima 660, Siemens, Somatom Emotion and Hitachi Spuria together with their workstations with details presented in Table 3.4, were used in the patient-based study. These scanners were used because there was the need to have a representation of all the scanner models across the country in this study.

Table 3.4: CT equipment and scanning parameters

CT scanners	Scan parameters			
	Pitch	Tube voltage (kVp)	Tube loading (mAs)	Beam collimation (mm)
Toshiba Aquilion ONE	0.75	120	225	32. x 0.5
Philips Brilliance Extended	0.75	120	400	64 x 0.5
GE Optima 660	0.60	120	180	16 x 1.0
Siemens Somatom Emotion	0.55	130	250	6 x 1.0
Hitachi Spuria	0.75	120	263	16 x 1.25

kVp: peak kilovoltage, mAs: milliampere-second, CT: computed tomography

Other materials and people engaged in this study included:

I. PACS connected to each of the aforementioned scanners were also used to retrieve patients' clinical images.

II. NCICT software version 2.1 (A Monte Carlo-based software developed by the National Cancer Institute, USA).

III. ImageJ software version 1.52 (National Institute of Health, USA).

IV. Two radiologists

V. A Microsoft Excel version 2013.

3.8.1.2.2 Sample Size Determination

A sample size calculator was first used to determine the required sample size capable of producing statistically reliable responses when the "Full range" (used in the facilities) and "Reduced range" CT intervention values are compared. Charan and Biswas (2013) recommended equation (3.11) as a suitable means of estimating the required sample size for interventional studies involving two groups as the case for *Full range CT* and the *"Reduced range CT" scans.*

$$S = \frac{2D_{ev}^2\left(Z_{\alpha/2} + Z_{\beta}\right)^2}{d^2} \qquad (3.11)$$

where S is the sample size,

D_{ev} is standard deviation from previous studies of pilot study,

$Z_{\frac{\alpha}{2}}$ is standard normal variate for level of significance ($p < 0.05$).

Z_{β} is standard normal variate for statistical power

d^2 is the effect size.

At 5% type 1 error ($p < 0.05$), the $Z_{\frac{\alpha}{2}}$ was chosen as 1.96 since the majority of studies of this kind consider *p*-values significant below 0.05. From the DAUT and DBLT, the collective SD for CVA was 21.3 and this was used in the formula. The precision/absolute error of 5% was tolerable and the Z_{β} was chosen at 80% (0.84) as it is very reliable (Charan and Biswas, 2013). From the phantom study, effect size of 10% was considered an appreciable dose reduction. Hence, the sample size was calculated as:

$$S = \frac{2(23.1)^2(1.96+0.84)^2}{10^2} = 83.67$$

From the above, the least sample size that could be used for each group (*"Full range"* and *"Reduced range"* CT) was approximately 84. However, to account for a better statistical outcome, a sample size of 100 was used for each study group.

3.8.1.2.3 Inclusion and Exclusion Criteria

With the exception of non-CVA indicated CT procedures and patients under 18 years of age, all patients' images which had been undertaken for the evaluation of CVA within the study period (2017- 2019) in the facilities indicated in Table 3.4 were considered eligible for their inclusion in this study.

3.8.1.2.4 Procedure

Two groups of data, consisting of "Full range" and "Reduced range" were first created from the PACS and the CT workstations of the CT scanners. The data set in each group comprised the DAUT and DBLT. In the "Full range" group, the DAUT and DBLT of 100 original images were collected from all the five scanner facilities. The mean DAUT was 8.3±7.1 mm above the vertex and the mean DBLT was 20.2 ±11.3 mm. Subsequently, "Reduced range" data variables covering from 10 mm below the vertex and 0 mm the below

base of the skull at foramen magnum were reconstructed or reformatted from the original images using CT reconstruction tools. Each image set had both full range and reduced range values. The mean DAUT and DBLT parameters and pictorial representation of the scan coverages for full and reduced ranges are presented in Table 3.5, and Figures 3.17 to 3.19.

Table 3.5: The DAUT and DBLT used in the patient-based study

Protocol	Average coverage of skull for CVA		Average $CTDI_{vol}$(mGy)
	DAUT (mm)	DBLT (mm)	
Full range CT	8.3±7.1 mm above the vertex	20.2±11.3 mm below the base of skull (foramen magnum)	54.6
Reduced range CT	10* mm or 1 cm below or inferior to the vertex	0 mm below the base of the skull at (foramen magnum)	54.6

*DAUT = distance above upper target, DBLT = distance below lower target. * = below vertex, CVA = cerebrovascular accident, CT = computed tomography; $CTDI_{vol}$ = volume weighted CT Dose index*

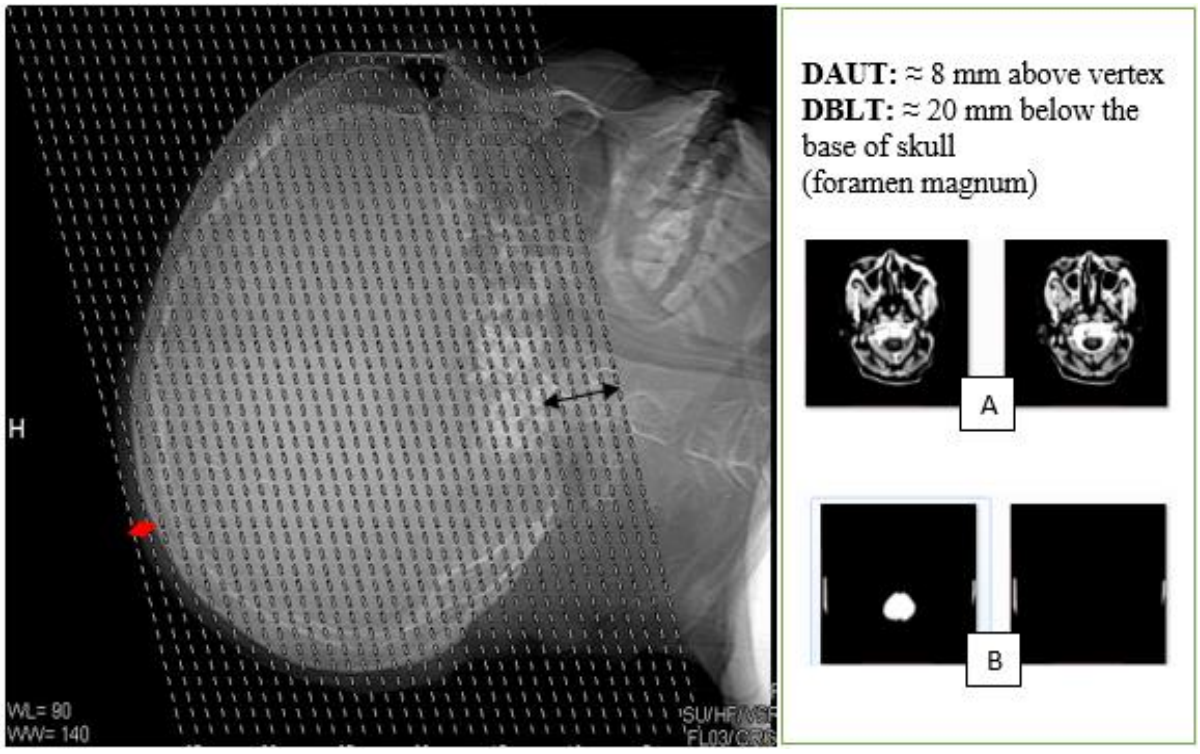


Figure 3.17: A typical scan coverage (grid areas) for a "Full range" CVA CT. Plate A shows the last two slices from the base of the skull (caudally) and Plate B shows the last two slices cranially which contain no information for CVA diagnosis. The red arrow shows a typical mean DAUT and the black arrow shows a typical mean DBLT used across the facilities.

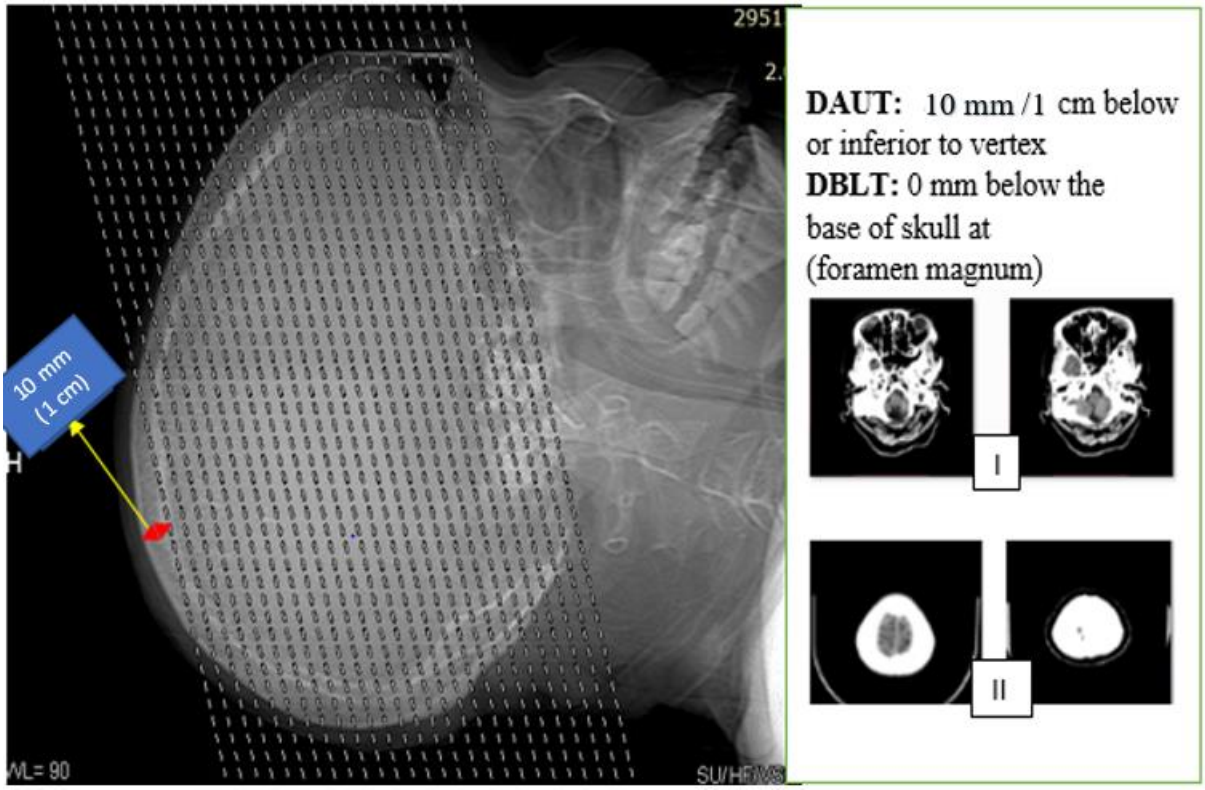


Figure 3.18: A typical scan coverage (grid areas) for a "Reduced range" CT for CVA. Plate I shows the last two slices from the skull base (caudally) and Plate II shows the last two slices cranially. The red arrow shows a 1 cm allowable distance from the vertex of the skull that can be used to optimise radiation in CVA examinations without compromising on image quality.

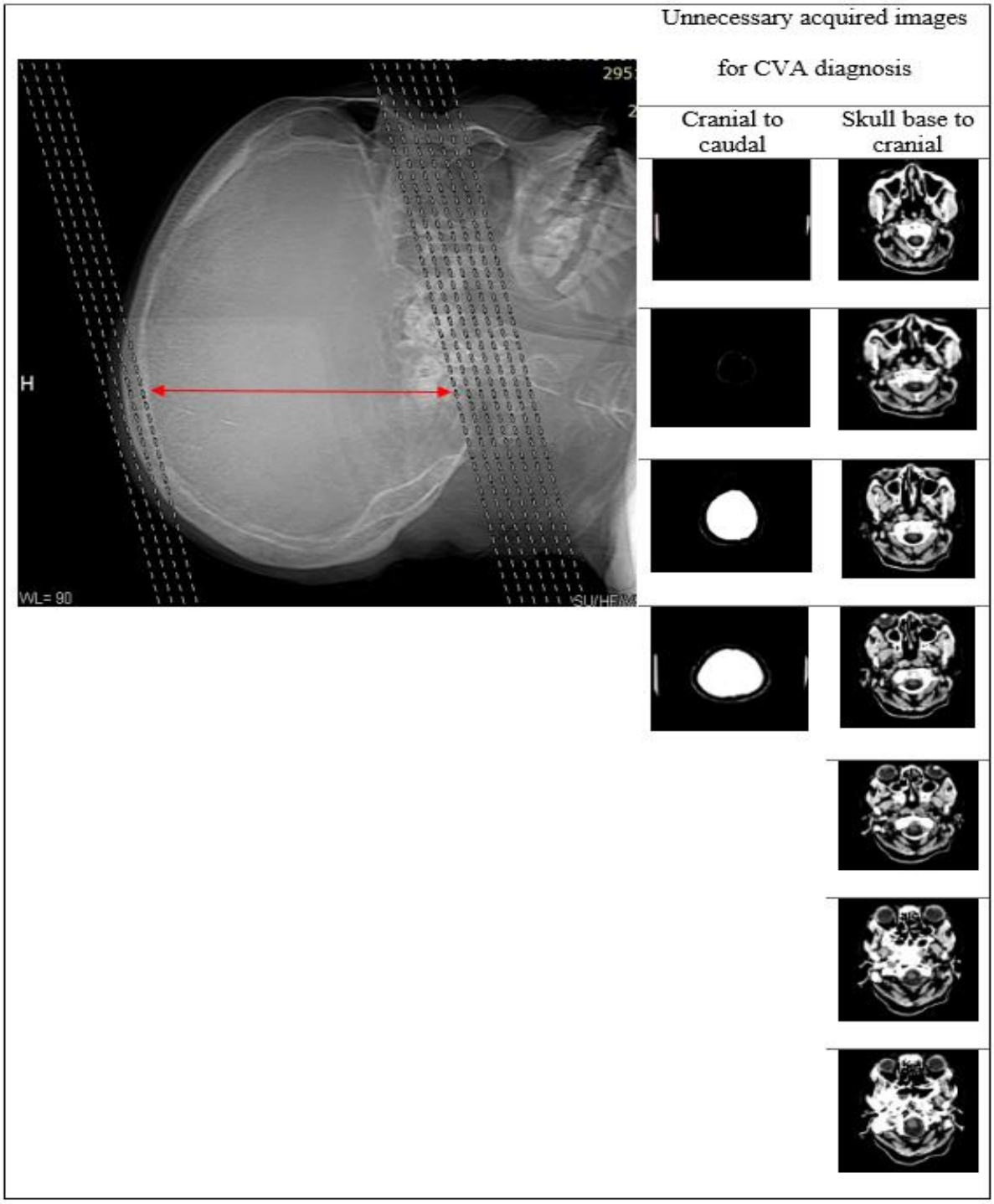


Figure 3.19: Unnecessary areas (grid lines) identified with Full range scan along z-axis and their corresponding unnecessary images for disgnosing CVA conditions are also displayed. Red arrow shows Reduced range CT area capable for CVA eaxaminations.

3.8.1.2.5 Radiation Dose Assessment

Following the reconstruction of the acquired images, the radiation dose descriptors (DLP, E_D and organ doses) for the Full and Reduced scan protocols were calculated using the NCICT software version 2.1 (National Cancer Institute, USA). The software has an interactive tool which allows for manual adjustment of the scan range to determine the aforementioned dose indices based on the scan parameters and the anthropometric information of the patients. With fixed scan parameters, the scan lengths for the Full and Reduced protocols of each patient data were reformatted and organ doses for brain, pituitary gland, eye lens, eyeballs, salivary glands, oral cavity, spinal cord and thyroid were assessed.

3.8.1.2.6 Image Quality Assessment

The image quality assessment procedures outlined in the phantom-based study were replicated in the patient-based study (Section 3.8.1.1.3) and the results are presented in Table 4.60. Moreover, radiologists reported on the pathologies (CVA-based and incidental findings) on the images of both Full and Reduced range protocols. The results on the conditions that were diagnosed on both the reduced and full range images are presented in Table 4.62.

3.8.1.2.7 Data Analysis

The data analysis procedure used in the phantom-based study (Section 3.8.1.1.4) was also employed here. In addition, the organ doses, DLP and E_D for both protocols were then compared. A Shapiro-Wilk test was used to test for normal distribution of the data. Based on the normality of the distribution of data (Appendix X), a parametric *T*-test was used to compare the Full-range and Reduced-range data variables. A *p*-value of ≤ 0.05 was considered statistically significant in all statistical analyses.

The MINITAB statistical tool version 19 was also used to model relationship between some organ doses (brain, salivary gland, eye lens, eyeballs, oral cavity, spinal cord, thyroid and pituitary glands) and some exposure parameters (such as $CTDI_{vol}$, slice thickness (T) and scan length).

The modelling process was centred on linear regression. To satisfy the assumptions of using linear regression, a large sample size > 20, continuous data variables and Shapiro-Wilk test of normality (as explained above for normality test) were used in the study and the data variables satisfied the normality rule as shown in Appendix X.

Grubbs' Test, a statistical tool for testing for outlies in MINITAB version 19 was used to ensure that there was a lack of strongly influential outliers in the data variables, as shown in Appendix XI. A Grubbs' Test *p*-value < 0.05 would suggest the presence of strongly influential outliers. However, all the *p*-values were > 0.05 at 95% significance level (Appendix XI).

Studies (Stoltzfus, 2011; Tabachnick and Fidell, 2007) have suggested that there should be an absence of multicollinearity in the independent variables for linear regression models as correlations or multiple correlations of enough magnitude have the ability to adversely affect regression estimate. This was achieved by using Variance Inflator Factors (VIF) to indicate the degree to which the standard error was inflated due to the levels of collinearity (Stoltzfus, 2011). Initial assessment showed that there were high VIF greater than 3 among some of the independent variables which showed moderately correlated independent variables (Appendix XII). Subsequently, those variables were eliminated to reduce the multicollinearity among the independent variables, prior to using the regression model.

3.8.2 Optimisation Method 2: The Role of AEC Utilisation

3.8.2.1 Overview

Follow up queries across the facilities scanning without AEC, as identified in this study revealed that these scanners had *default setting limitation* where the AECs were not activated for certain procedures. Also, some practitioners were not aware the AECs were off and due to limited knowledge about AEC operations they were not often checked. To effectively evaluate the impact of the AEC and make needed optimisation recommendations, an experimental study was undertaken in four facilities in Ghana scanning without AEC using an adult whole-body CT anthropomorphic phantom PBU-60.

3.8.2.2 Materials

The phantom and the CT scanner characteristics/specifications used in this experiment are shown in Tables 3.6 and 3.7, respectively.

Table 3.6: Characteristics of CT phantom PBU-60

Parameters	**Characteristics**
Phantom estimated weight	50 kilogram (kg)
Phantom estimated height	165 cm
Phantom estimated age	30 years (adult)
Manufacturer	KYOTO KAGAKU Co., LTD
Phantom composition:	Soft tissue/organs: Urethane based resin Synthetic bones: Epoxy resin Joint attachments: Epoxy, urethane with carbon fibre Screws: Polycarbonate

Table 3.7: Characteristics/specifications of CT scanners

CT ID	Manufacturer	Model	Scanning parameters	
			Fixed mAs	AEC
CT2	Siemens	Somatom Emotion	AEC: off Scan length: 46 cm kV: 100; Pitch: 1 Rotation time: 0.5 Fixed mAs: 240	AEC: CareDose4D Scan length: 46 cm kV: 100; Pitch: 1 Rotation time: 0.5, Ref. mAs 250 Mean effective mAs 166
CT8	GE	Lightspeed Pro 16	AEC: off Scan length: 46 cm kV: 120; Pitch: 1.38; Rotation time: 0.8 Fixed mAs: 170	AEC: AutomA 3D Scan length: 46 cm kV: 120; Pitch: 1.38; Rotation time: 0.8 Mean mAs: 105
CT14	Toshiba	Aquilion 16 TSX	AEC: off Scan length: 46 cm kV: 120; Pitch: 0.94; Rotation time: 0.75, Fixed mAs: 221	AEC: SureExposure 3D Scan length: 46 cm kV: 120; Pitch: 0.94; Rotation time: 0.75, Mean mAs: 137.7
CT19	Philips	Brilliance 64	AEC: off Scan length: 46 cm kV: 120; Pitch: 1.17; Rotation time: 1, Fixed mAs: 276	AEC: DoseRight Z-DOM, ACS Scan length: 46 cm kV: 120; Pitch: 1.17; Rotation time: 1, Mean mAs 191.8

AEC: automatic exposure control; kV: kilovoltage, mAs: milliampere-second, CT: computed tomography, ACS: Automatic Current Selection

3.8.2.3 Methods and Procedure

For each facility, the phantom was placed on the CT table and positioned for a routine AP CT examination. It was placed supine, and with the help of the laser beams, an isocentre position was achieved. The midsagittal plane coincided with the vertical lasers while the true coronal plane coincided with the horizontal lasers as shown in Figure 3.20. A scanogram was acquired from the top of higher hemidiaphragm to below the symphysis pubis. Subsequently, actual imaging, using the routine protocol of the AP region (as the case of non-contrast AP lesion) was undertaken with and without the activation of the AEC. The position of the lasers on the phantom and scan positions/coverage (46 cm) were kept constant for the scans.

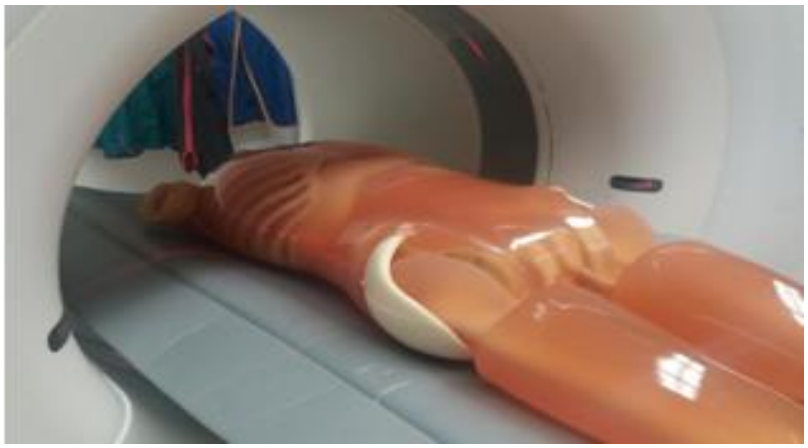


Figure 3.20: Positioning of PBU-60 phantom for AEC studies

The dose output descriptors for experiments with and without AEC were documented in a Microsoft Excel version 2013. The dose reduction was calculated from the DLP values using equation 3.12:

$$DR = \frac{DLP_{AEC\,\text{off}} - DLP_{AEC}}{DLP_{AEC\,\text{off}}} \times 100\% \qquad (3.12)$$

where

DR is dose reduction

$DLP_{AEC\ off}$ is measured dose length product without AEC

DLP_{AEC} is measured dose length product with AEC

3.8.2.4 Image Quality and Data Analysis

Image quality in terms of noise levels (using the standard deviation, SD, of CT number) and SNR were measured at proximal, middle and distal part of the phantom (at 577, 722 and 902 z-positions) using ImageJ version 1.52 software. First, ROIs of area 10 mm^2 were drawn at the specific places on image slices and the above-mentioned software programmes were used to determine the noise (SD) and the SNR. As already shown in Figure 3.12, the same measurement approach was used.

3.8.2.5 Data analysis

Data were then analysed using the Microsoft Excel version 2013 and SPSS version 23.0 (SPSS Inc., Chicago, IL USA). The dose descriptive data for all the protocols with fixed mAs and those with AEC were descriptively compared using Microsoft Excel version 2013 and percentages of DLP dose reduction over the current practice (originally used across the facilities) were estimated. In addition, based on the normal distribution of the data, a comparative analyses of the dose output (DLP) accruing from AEC and fixed mAs examinations were also compared with a *T*-test using SPSS. A *p*-value of ≤ 0.05 was considered statistically significant. The results are presented in Table 4.63.

3.9 Ethical Consideration and Data Handling

This study was conducted in adherence to the international research ethical guidelines and in compliance with the Helsinki declaration (World Medical Association Declaration of Helsinki, 2001). Prior to the study, ethical clearances (Appendices XIII- XV) were sought and approved by the Ethics Committee for Basic and Applied Sciences (ECBAS), University of Ghana (REF. No: ECBAS 041/17-18), the Ghana Health Service Ethics Review Committee (REF NO: GHS-ERC002/04/18), Korle Bu Teaching Hospital's Scientific and Technical Committee (KBTH-STC) and the Institutional Review Board (KBTH-IRB) (REF NO: KBTH-IRB/00092/2017). The Nuclear Regulatory Authority (NRA) of Ghana also granted permission and supported the study. Subsequently, permissions were sought and granted by all the Heads and Managers of institutions responsible for the CT scanners that were used in this study. Some of the permission letters are shown in Appendix XVI. All the CT facilities which finally took part in the study were coded and identified with alphabets to prevent public linkage of information to any of them.

Information sheets were used to educate all participants who provided questionnaire data prior to recruiting them. They were made aware that the research study carries very negligible risk and the outcome had the potential to help to establish indication-based DRL values and dose optimisation methods for CT examinations in Ghana for policy decisions and directions in the country. They were made aware that their participation in this research was voluntary, and they were at liberty to decline or withdraw from the research without providing an explanation at any time until the work is completed. In addition, they were informed that their personal details were not going to be used in the study and consequently, their identities were coded to ensure their confidentiality. All those who participated in the Phase 1 stage of the study finally consented to participate in the study before their involvement.

With respect to the patients' image folders retrieved from the CT Archives and workstations during the study period, the identities of patients were safeguarded by blocking the names during the data collection. The CT scanners display software programmes had "identity hide" tools for blocking patients' names and identities. The activation of the tools concealed patients' identities during the data collection and analysis process. The collected data sets were also stored on a computer and encrypted with a password to further ensure that confidentiality of information and details peculiar to the patients were also protected. All generated data sets were used for research purposes only and nothing else and would be kept for at least five years for future review if necessary. All the aforementioned were done to ensure patient's anonymity and confidentiality were considered during the study.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview

This Chapter presents the results and the discussion of the thesis and gives account of the six phases of the study. The results and discussions of Phase 1 covered the technical data on the CT infrastructure in the various facilities, common indications and definition of the basic diagnostic imaging requirements. Phase 2 addressed the CT scanner performance characteristics data. The outcomes of Phases 3 and 4 covered CT dose descriptors data, image quality assessment and DRLs estimations. Results and discussions on estimation of cancer risks associated with the doses and optimisation methods are presented under Phases 5 and 6, respectively.

4.2 PHASE 1: CT Technical Data, Common Indications and Imaging Requirements

As part of preliminary steps to achieve the objectives of the entire study, CT technical /infrastructure data, common indications and imaging requirements were first investigated (Phase 1 of the study). The results of Phase 1 are presented in two sections: the results on technical data on CT scanners and common indications are presented in Section 4.2.1, while those on basic diagnostic imaging requirements are presented in Section 4.2.2.

4.2.1 CT Technical Data and Common Indications

CT is a key component of modern healthcare in all countries. According to Statista, as of the year 2017, the distribution of CT scanners per one million inhabitants were 64 (Australia), 44 (United States of America), 35 (Germany) and 15.28 (Canada), respectively (Statista, 2017). However, 35 authorised CT scanners existed in Ghana at the time of the study. This was approximately one (1) CT scanner per 850,000 inhabitants or 1.18 scanners per one

million inhabitants (with an estimated population of 30 million inhabitants as indicated by the Ghana Statistical Services, 2019). Comparatively, this is 5.78% of the EU average of 20.4 CT scanners per 1 million population (Vanckavicienea et al., 2016).

Out of the 35 scanners in the country, responses on CT technical data, and common indications were received from the technical heads responsible for 31 CT scanners, representing 88.6% of the total number. The demographics of the technical heads are presented in Table 4.1.

Table 4.1: Demographics of study respondents (Technical Heads)

Demographics		Number	Percentage (%)
Gender	Male	23	74.2
	Female	8	25.8
Rank (Grade)	Chief Radiographer	3	9.7
	Deputy Chief Radiographer	3	9.7
	Principal Radiographer	16	51.6
	Senior Radiographer	7	22.6
	Principal Technical Officers	2	6.5

Most (*n*=16, 51.6%) of the technical heads were principal radiographers in their respective hospitals and majority (n=23, 74.2%) were males. This suggests a male dominated technical leadership at CT facilities in Ghana. A study (Steffens et al., 2019) has also noted that gender balance has been particularly scarce at leadership level with men mostly being in the majority.

The technical data on CT models, manufacturers, year of manufacture (YoM), year of installation (YoI) and number of detector rows/slices identified across the CT facilities are presented in Table 4.2.

Table 4.2: CT models, manufacturers, years of manufacture, installation and number of detector rows/slices (*N*=31)

Hospital	CT ID	Manufacturer	Model	YoM	YoI	Detector row/slice
A	CT 1	Toshiba	Aquilion One TSX-301A	2012	2012	320/640
B	CT 2	Siemens	Somatom Emotion 6	2006	2011	6
C	CT 3	GE	Brightspeed Elite	2011	2011	16
D	CT 4	Philips	Brilliance ICT	2015	2016	128
E	CT 5	Siemens	Somatom Perspective	2016	2016	16
F	CT 6	GE	VCT Lightspeed	2008	2009	64
G	CT 7	Siemens	Somatom Perspective	2016	2017	64
H	CT 8	GE	Lightspeed Pro 16	2011	2011	16
I	CT 9	GE	Brivo CT 385 series	2015	2016	16
	CT 10	Siemens	Somatom Emotion	2007	2008	6
J	CT 11	Toshiba	Aquilion GX	2012	2012	128
K	CT 12	Toshiba	Aquilion TSX-101A	2016	2016	16
L	CT 13	Siemens	Somatom Emotion	2010	2010	16
M	CT 14	Toshiba	Aquilion TSX-101A	2013	2013	16
	CT 15	Toshiba	Aquilion CXL TSX-101A	2015	2015	32
N	CT 16	Philips	MX 16	2015	2016	16
O	CT 17	Toshiba	Aquilion CXL TSX101A	2012	2015	32
P	CT 18	GE	Revolution Evo	2017	2017	64
Q	CT 19	Philips	Brilliance	2009	2010	4
R	CT 20	Hitachi	Supria	2015	2015	16
S	CT 21	Philips	Brilliance extended	2007	2010	64
T	CT 22	Picker International	PICKER PQ5000	1998	2017	1
U	CT 23	Siemens	Somatom Emotion	2009	2010	16
V	CT 24	GE	Brightspeed Edge[#]	1998[#]	2009[#]	8[#]
W	CT 25	Siemens	Somatom Emotion	2010	2011	16
X	CT 26	Siemens	Somatom Definition AS	2015	2016	64
Y	CT 27	Philips	Brilliance 16	2010	2016	16
Z	CT 28	Toshiba	Asteion	2009	2016	4
AA	CT 29	Toshiba	Aquilion TSX-101A	2015	2015	16
	CT 30	Toshiba	Aquilion TSX-101A	2012	2013	16
AB	CT 31	GE	Optima 660	2016	2016	64

Key: *YoM: year of manufacture, YoI: year of installation. CT: computed tomography. The sign* "#" *means that that machine was replaced with a 64 slice GE Revolution 5492001. It was manufactured and installed in 2018.*

Majority of the CT scanners as indicated in Table 4.2 were Toshiba (*n*=9, 29.0%) and Siemens (*n*=8, 26.0%) models. All recently installed public CT scanners by the Government of Ghana were Toshiba models, which contributed to the increased tally. The detector row and equipment slices ranged from 1 to 320 and 1 to 640, respectively, of which majority (*n*=14,

45.2%) were 16 slice scanners. The results indicated that 30 out of 31 scanners, representing 96.8%, were MDCT systems. Advanced MDCT scanners with higher detector configuration offer faster image acquisition speed, more patient body coverage, high spatial resolution, optimal image quality and optimised radiation dose levels (if properly utilised) (Gao et al., 2017). The year of manufacture ranged from 1998 to 2017 while installations were undertaken from 2008 to 2017. Only three facilities had two installed scanners, while the others had a single scanner. The mean age of the CT equipment was 7.3 ± 4.4 years old and 25.6% of them were 10 or more years old. According to a report (European Society of Radiology, 2014), scanners older than 10 years are no longer considered state-of-the art equipment and may not have the current technology for full patient benefits. Moreover, newer CT technologies offer 10–30% lower radiation exposure levels compared to systems installed 5 years ago (European Society of Radiology, 2014). There is, therefore, a need to upgrade older scanners (25.6%) in Ghana. Interestingly, one of the very old scanners (GE Brightspeed Edge manufactured in 1998 and installed in 2009) was being replaced with a 64 slice GE Revolution (manufactured in 2018) at the time of the study. This is a commendable action.

The scanners' ability to display dose descriptors (such as $CTDI_{vol}$ and DLP parameters), scan mode systems incorporated in the CT scanners, and the availability of AEC systems on the CT scanners are presented in Figure 4.1.

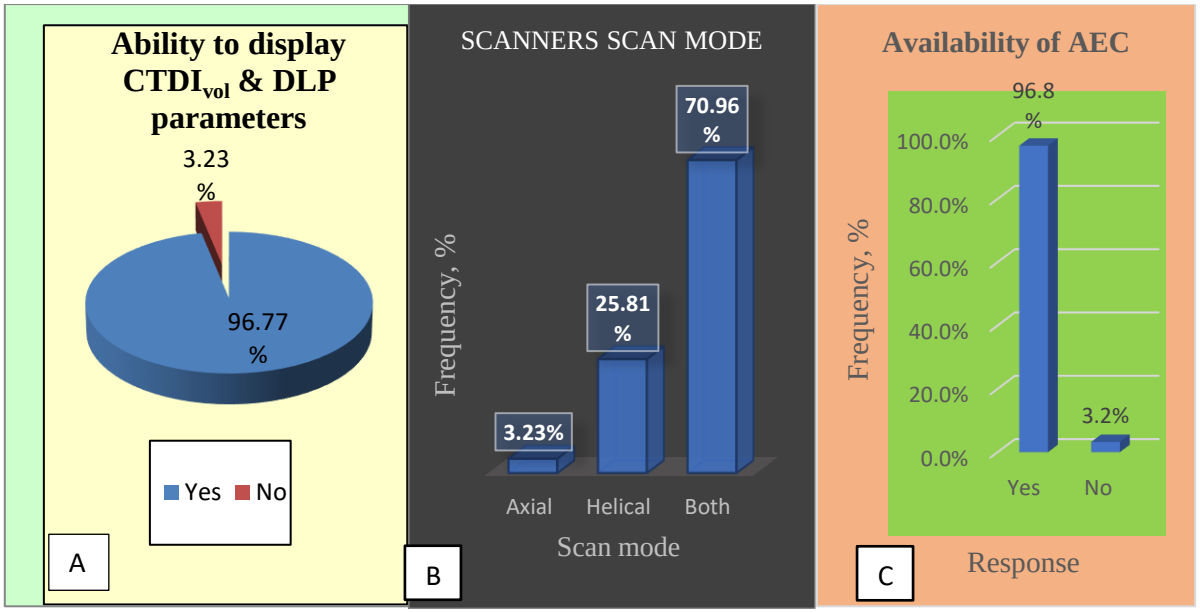


Figure 4.1: Equipment ability to display $CTDI_{vol}$ and DLP parameters (a); the scan mode systems incorporated in the CT scanners (b); availability of AEC systems on the CT scanners (c).

From Figure 4.1(a), 30 (96.77%) of the CT scanners could display $CTDI_{vol}$ and DLP parameters on the console, while 1 (3.23%) could not. Currently, it is an international requirement that all operational CT scanners should display dose descriptors such as $CTDI_{vol}$ and DLP on the CT console, post examination (ICRP, 2017; International Electrotechnical Commission, 2011; Institute of Physics and Engineering in Medicine, 2005). It was observed that one of the scanners lacked a self-display dose output configuration. Consequently, there is the need for the operator of this scanner to ensure compliance with the international mandatory requirement of console-displayed CT dose outputs. In Figure 4.1(b), although majority (n=22, 70.97%) of the scanners had the ability to scan in both helical and sequential modes, 8 (25.81%) and 1 (3.23%) of them were designed to scan in only helical and sequential modes, respectively. Unfortunately, 1 scanner (3.2%) was not incorporated with as AEC system. The AEC system's advantage of yielding significant reductions in patient doses while maintaining appropriate image quality could thus not be realised in this CT machine and needs to be replaced or upgraded (Higaki et al., 2019; Fillon et al., 2018).

The geographical distribution, ownership and functionality of the CT scanners across the country are presented in Table 4.3.

Table 4.3: Geographical location, ownership status and functionality of the CT scanners (*N*=31)

Location/ region	Ownership status				Functionability	
	Public	**Private**	**Quasi**	**Total**	**Yes**	**No**
GA	4(12.9%)	11(35.5%)	3(9.7%)	18(58.1%)	17(54.9%)	1(3.2%)
Ashanti	2(6.5%)	4(12.9%)	-	6(19.4%)	5(16.1%)	1(3.2%)
Northern	2(6.5%)	1(3.2%)	-	3(9.7%)	2 (6.5%)	1(3.3%)
Western	1(3.2%)	-	-	1(3.2%)	1(3.2%)	-
Eastern	1(3.2%)	-	-	1(3.2%)	1(3.2%)	-
BA	1(3.2%)	-	-	1(3.2%)	1(3.2%)	-
Central	1(3.2%)	-	-	1(3.2%)	1(3.2%)	-
Total	12(38.7%)	16(51.6%)	3(9.7%)	31(100%)	28(90.3%)	3(9.7%)

GA= Greater Accra; BA= Brong Ahafo; quasi: public-private partnership.

Out of the 31 CT scanners, the majority (*n*=16, 51.61%) were operated by the private sector, while 12 (38.7%) were operated in public health facilities, and 3 (9.68%) by quasi-governmental establishments (establishments controlled both by the government and private sectors). The CT scanners were not evenly distributed across the 10 regions of the country at the time of the study. In particular, most (18/31) CT scanners were operated in the Greater Accra Region inhabited by 16.3% of the national population (Ghana Statistical Services, 2019), and none installed in the Upper West, Upper East and the Volta Regions. The lack of CT scanners in these locations means that patients requiring CT services (even in emergency cases) would have to travel to other regions to access the service, which could compromise effective patient management. At the time of the study, 28 (90.32%) of the scanners were functional, while 3 (9.7%) were out of operation and could not be used in the DRLs study.

The categories of health professionals associated with the operation, quality and safety maintenance, and image reporting activities of the CT scanners are shown in Table 4.4.

Table 4.4: Number of CT scanning radiographers, reporting radiologists and attending medical physicists

Professional	Number	Ratio to population
Radiographers	107	1: 280,374
Radiologists	60	1: 500,000
Medical Physicists	10	1: 3,000,000

There were 107 radiographers operating the CT scanners, 60 reporting radiologists and 10 medical physicists in the diagnostic radiology responsible for CT scanners. Per the estimated population of Ghana as of 2019 (Ghana Statistical Services, 2019), the findings further suggest that the staff to populace ratios were 1: 280,374 for radiographers, 1: 500,000 for radiologists and 1: 3,000,000 for medical physicists. Compared to the situation in developed countries (Germany, USA, France) (Silvestrin, 2016), these numbers are very low, necessitating the need to address the staffing-gap situation. In particular, the professional distribution with respect to medical physicists is worse because of the lack of their recruitment by the public sector into the diagnostic radiology, although they are available for employment. Due to this limitation, many facilities mainly rely on the QC tests undertaken by the NRA for purposes of inspections, verifications of compliance with regulatory requirements, and issuance of authorisation to practice. This authorisation is renewed every 3 years. The inspection conducted every three years means that there is a lot of scope for something going wrong and not being fixed for a long time. This has the potential to compromise effective healthcare delivery. There is thus, an urgent need to employ the relevant health professionals in CT facilities to promote patient care, protection and safety during health delivery.

QA is an interdisciplinary management tool including policies that offer a means for guaranteeing that all activities, including CT imaging, are effectively planned, correctly performed and assessed to meet specifications. The availability of QA infrastructure at the various CT facilities is presented in Table 4.5.

Table 4.5: QA infrastructure availability at the CT facilities (*N*=31) in Ghana

Quality Assurance structures	**Responses**			
	Yes		No	
	n	%	*n*	%
Availability of QA or QC Committee	17	54.8	14	45.2
Availability of a documented protocol for CT scanning	15	48.4	16	51.6
Post-major repair QC assessment records	21	67.7	10	32.3
Do you have records of regular QC checks	20	64.5	11	35.5
Authorisation by NRA	31	100.0	0	0.0
Availability of established acceptance testing procedure	19	61.3	12	38.7
Availability of effective planned maintenance schedules	12	38.7	19	61.3
Equipment performance record keeping	29	93.5	2	6.5
Availability of radiation protection devices	31	100.0	0	0.0
Availability of systems for justifying CT exposures	31	100.0	0	0.0
Availability of adopted or established DRLs	0	0.0	31	100.0
Availability of scheduled optimisation programmes	20	64.5	11	35.5
Keeping of patient dose records	20	64.5	11	35.5
Availability of an established patient dose and image quality audit programmes	5	16.1	26	83.9
Planned schedules for frequent cleaning of equipment	10	32.3	21	67.7
Documented training program and records	5	16.1	26	83.9

Key; *QA: quality assurance, QC: quality control; NRA: Nuclear Regulatory Authority*. *DRLs: diagnostic reference levels, CT: computed tomography.*

QMS and quality programmes are the physical and non-physical structures required by radiology personnel to ensure patient satisfaction, protection and safety in radiology departments (Kruskal et al., 2009). The results indicated some CT facilities in Ghana lacked

the needed QA infrastructure. In particular, 14 (45.2%) of the facilities lacked essential infrastructure such as QA/QC Committees, while a documented protocol for CT scanning was absent in 16 (51.6%) of them. A study (Ofori et al., 2013) has equally observed this situation in the general x-ray facilities in Ghana. According to the IAEA (IAEA, 2012), the QA/QC Committees have the primary function to keep lines of communication amongst all groups with QA, QC and QI responsibilities. These include the maintenance of acceptable standards of quality and periodical review or audit of practices for effectiveness and compliance with quality standards. Therefore, the absence of operational tools like documented scanning protocols and appropriate committees to ensure functional QA, QC and QI could have severe consequences on the radiation protection culture (Ofori et al., 2013).

A study (Schandorf and Tetteh, 1998) reported that established acceptance testing procedures, commissioning, regular QC tests and post-major repair records are important international indices for assessing equipment performance after an installation and over a period of time. However, in this study, regular and post-major repair QC assessment records were missing in 10 (32.3%) and 11 (35.5%) of the facilities, respectively, while established acceptance testing procedures were lacking in 12 (38.7%) facilities. A similar situation was reported in Tanzania, where only 6% of the facilities had records of all QC (Ngoye et al., 2015).

Although it is commendable that all facilities had received authorisation from the NRA and had radiation protection devices and systems for justifying CT exposures, it was also worrying that some facilities lacked effective planned maintenance schedules (n=19, 61.3%), equipment performance records (n=2, 6.5%), and scheduled dose optimisation programmes (n=1, 35.5%), respectively. Patients' dose record keeping, and establishment of patient dose and image quality programmes are important optimisation processes. However, these programmes were missing in majority (n=26, 83.9%) of the facilities, respectively. Furthermore, planned schedules for frequent cleaning of equipment and documented training

programme and records were available in only 10 (32.3%) and 5 (16.1%) facilities. These need to be improved.

Figure 4.3 presents the breakdown of the regularity of the routine QC among the facilities (*n*=20) that indicated their involvement in regular QC testing.

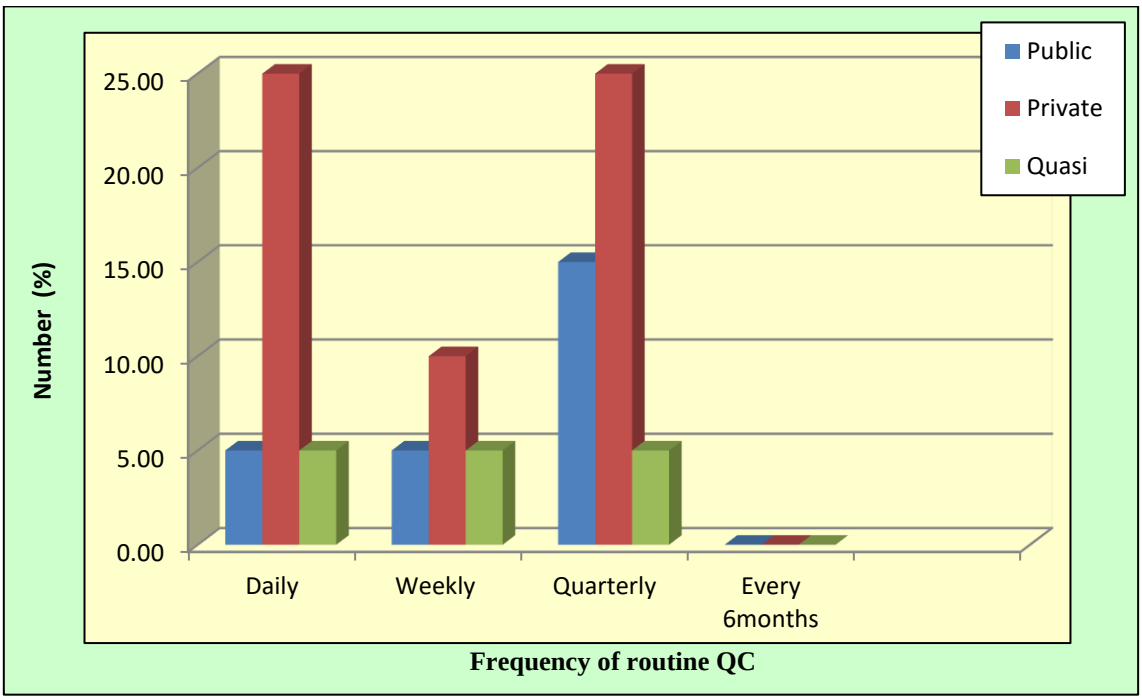


Figure 4.2: Regularity of routine Quality control (QC) (*N*=20)

Daily and weekly QC assessments were undertaken in two public sector facilities, while quarterly assessments were done in 3 (60.0%) others. In the private sector category, QC assessments were conducted daily (*n*=5, 41.7%), weekly (*n*=5, 41.7%), and quarterly (*n*=3, 16.7%), while same were done daily, weekly and quarterly in each (33.33%) of the 3 quasi-government facilities. The lack of regular QC tests across all the CT facilities could be attributed to the inadequate numbers of medical physicists in the facilities. This lack of systems to ensure effective QC tests and record keeping across the CT facilities does not promote quality service delivery (Korir et al., 2013). The availability of basic QI structures in the CT facilities in Ghana is presented in Table 4.6.

Table 4.6: Basic quality improvement (QI) structures in the CT facilities (*N*=31) in Ghana

QI structures	Availability			
	Yes		No	
	n	**%**	***N***	**%**
Do you have institutional leadership and support toward QI?	31	100	-	-
Do you have regular meetings involving all the stakeholders to communicate QC results?	5	16.1	26	83.9
Has your facility establish a culture of quality in your practice?	3	9.7	28	90.3
Has your facility established an improvement team?	5	16.1	26	83.9
Do you have a QI protocol or manual	3	9.7	28	90.3
Do you have a system that engages all the professional groups in the department on QI?	6	19.4	25	80.6
Do you have a system that regularly receives and analyses feedback from customers and stakeholders?	10	32.3	21	67.7
Do you have surveillances system for monitoring QI indicators?	3	9.7	28	90.3
Does your facility have a system to reward hard work associated with QI?	18	58.1	13	41.9
Do you have an educational programme on QI?	5	16.1	26	83.9

QI: quality improvement, QC: quality control

Apart from available institutional leadership and support toward QI (100%), and QI reward systems (58.1%), over 67% of facilities lacked all the pertinent structures that constitute effective QI systems. Over 90% of the facilities lacked the protocol or manual and surveillance systems for monitoring QI indicators. This lack of effective QI infrastructures is a concern for the imaging services in the country which may have dire consequences on improved care. This is because the goal of QI systems, in particular, is to do the needful in a timely fashion for every patient every time and to ensure that a particular level of quality performance is improved (Kruskal et al., 2011). The availability of Quality Management Teams, established culture of quality and regular meetings involving all the stakeholders for purposes of communicating QC results for instance, were only available in 5 (16.1%), 3 (9.7%) and 5 (16.1%) of the facilities, respectively. However, it is known that a well-functioning, cohesive team, stakeholder relations

and a culture that recognises quality are crucial for the effective implementation and operation of a quality radiation protection and safety program in any facility (Ngoye et al, 2015; UNSCEAR; 2012).

The data on CT policy driven infrastructure and their availability are shown in Table 4.7.

Table 4.7: Policy infrastructure and their availability in Ghana

Policy infrastructure	Availability			
	Yes		No	
	n	***%***	***N***	***%***
Policy on CT authorisation for use in Ghana	31	100	-	-
Policy driving CT infrastructure and distribution	-	-	31	100
Policy on operation and maintenance	-	-	31	100
Policy and availability of quality management systems	-	-	31	100
Policy on purchasing, construction and installations	-	-	31	100
Policy on decommission of a CT facility			31	100
Policy on education and training	31	100	-	-
Policy and availability of diagnostic reference levels	-	-	31	100
Policy on CT referrer guidelines	-	-	31	100
Policy on recommended frequency for QC tests	-	-	31	100
Standardised policy on AEC application	-	-	31	100
Policy on patient dose optimisation, image quality and audit programmes	-	-	31	100
Policy on acceptance testing and record keeping	-	-	31	100
Policy on human resources in CT facilities	-	-	31	100
Policy on CT maintenance systems	-	-	31	100

QC: quality control, AEC: automatic exposure control

CT infrastructure is generally driven by policies in respect of directing purchasing, installation, commissioning and operation of CT facilities to ensure a sustainable service to the population (Kruskal et al., 2011). However, Table 4.7 showed the lack of many structured policies, with the exception of CT authorisation, and education and training of staff. A study

(Qureshi, 2019) has cautioned that the lack of practice-driven structured policies could limit economic growth and development as well as improved care.

Table 4.8 shows the duration (down time) taken to repair broken down CT equipment operated in the various categories of sectors.

Table 4.8: Duration to repair broken down equipment (down time)

Organisation Sector	Duration
Public	1 day -2 years
Private	1 hour -1 month
Quasi	1 day - 3 months

A fault is a key index for determining the down time of CT imaging equipment. Depending on the type, broken-down CT equipment in the public hospitals were repaired between a day to 2 years. On the contrary, shorter down times of an hour to one month, and a day to 3 months were required in the private and quasi-government hospitals, respectively. Many health institutions have applied planning and scheduling to their maintenance functions to enhance the use of their equipment, decrease unplanned downtime and more efficiently manage their maintenance budgets. However, effective planned maintenance schedules, which were missing in 61.3% of the facilities, could be the cause for long down times in the public facilities in particular. A study (Korir et al., 2013) had also found in Kenya that only 22% of the health centres had reports of semi-annual preventive maintenance. As a result, equipment faults are likely not to be detected on time, and when a breakdown occurs, it could take a long time to have the equipment fixed. The lack of parts supply, after sales service and training of local human resource to perform maintenance has long been noted as part of the major problem (ICRP, 2007). The absence of formal organisational structures for effective planned maintenance systems for CT facilities in Ghana, QMS and management culture have clinical,

radiation protection and financial implications due to the long downtimes. The Information on the equipment down time was crucial in determining when a broken-down equipment could be waited upon to be fixed and included in this DRL study.

Schematic data on whether or not CT facilities benchmark their dose information with internationally established indication-based DRLs, and agreement levels of respondents on the need for the establishment indication-based DRLs in Ghana are presented in Figure. 4.3.

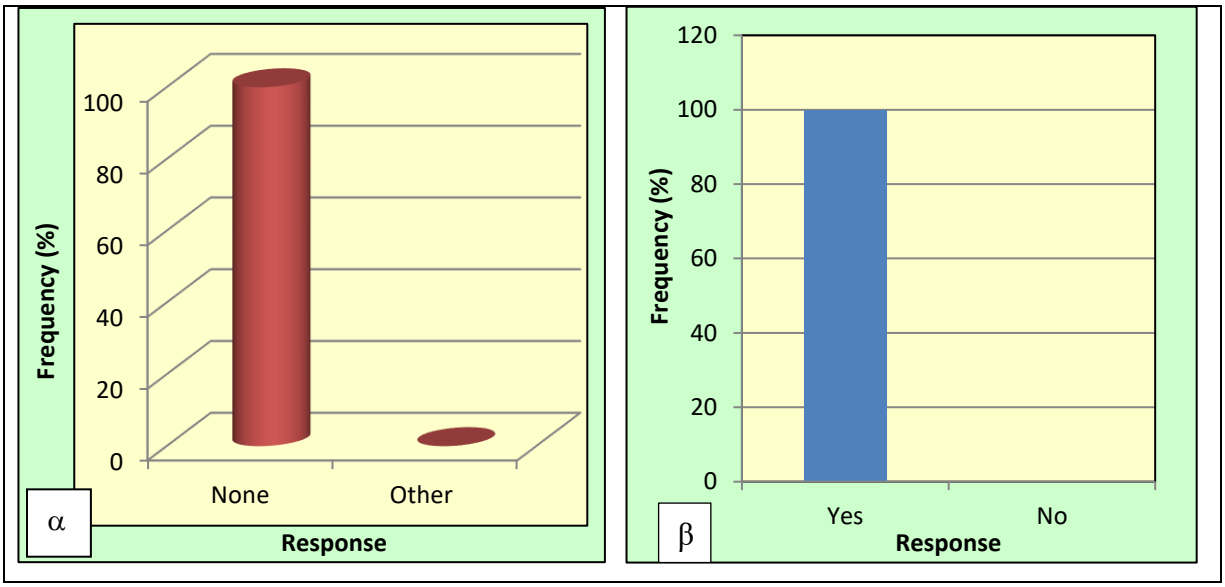


Figure 4.3: Responses on (A) whether or not CT facilities benchmark their dose information with internationally established indication-based DRLs and (B) respondents agreement levels on the need for the establishment indication-based DRLs in Ghana.

A DRL is a QA/QC tool used as a trigger to find imaging centres using remarkably high radiation doses in a particular examination, for which optimisation measures are needed (ICRP, 2017; IAEA, 2013). It needs to be established or adopted so that dose outputs from facilities could be benchmarked (ICRP, 2007) for effective management practices. Figure 4.3 shows that CT facilities in Ghana do not compare their dose parameters with any indication-based DRLs. However, all the respondents agreed on the need for the establishment and consequent practice of indication-based DRLs in Ghana.

The various examination indices (number and percentage) performed each year across the facilities are presented in Table 4.9 and Figure 4.4.

Table 4.9: CT examinations undertaken in a year

Location	Examinations									
(Region)	**Head**	**Neck**	**Chest**	**Abdomen**	**Pelvic**	**AP**	**L/S**	**Ext**	**Special**	**Total**
GA	66462	1873	11204	7737	3174	21713	1313	636	8398	122510
Ashanti	25387	1133	3073	1009	872	10364	773	297	2242	45150
Northern	6434	621	1460	201	310	1565	342	556	192	11680
Western	3391	278	705	239	71	819	210	38	88	5840
Eastern	3559	262	652	278	147	1321	196	13	117	6545
BA	3899	260	169	141	141	821	157	26	78	5690
Central	4385	385	611	398	277	864	185	75	164	7345
Total	113517	4812	17874	10003	4990	37467	3177	1640	11280	**204,760**

GA= Greater Accra; BA= Brong Ahafo; Ext= Extremities; L/S= Lumbar spine, AP= abdominopelvic.

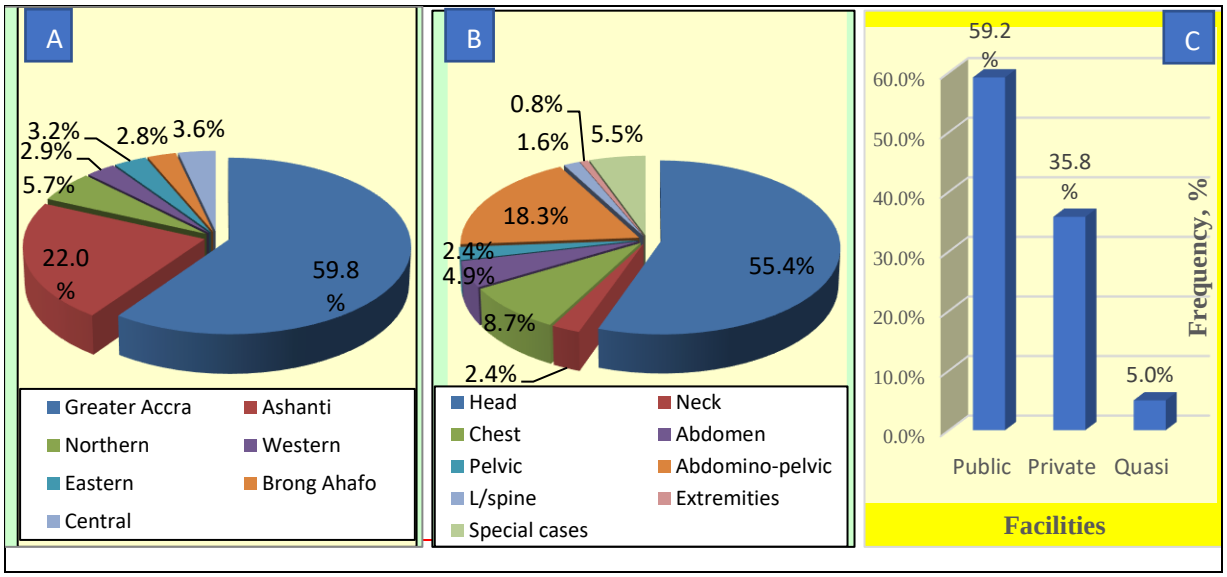


Figure 4.4: Percentage distribution of CT examinations per region (Plate A), anatomical part (Plate B) and hospital type (C).

Table 4.9 and Figure 4.4 show that 204,760 CT examinations were performed in a year, of which head (n=113,517, 55.4%), AP (n=37,467, 18.4%) and chest (n=17874, 8.7%) were the most prevalent examinations. These three types of examinations accounted for 82.4% of the CT procedures conducted in Ghana in a year. The frequency of these procedures is generally consistent with the worldwide trend (Jaffe et al., 2010). The extremities (n=1640, 0.8%) were the least prevalent CT procedures. The Greater Accra and Ashanti Regions contributed 59.8% and 22.0% of the CT examinations, respectively, because of the larger number of installed CT scanners in the two Regions. Majority of CT examinations were undertaken in the public (n=121,279, 59.2%) and private (n =73,366, 35.8%) imaging facilities. While only 5.0% were reportedly performed in quasi hospital organisations. The total number of CT examinations performed in a particular year translates into a lower national annual average of 6.8 CT procedures per 1000 people compared to 226.6, 94.4 and 85 CT procedures per 1000 people in the USA, Canada and UK, respectively (OECD, 2019; Statista, 2017). However, Kenya has a national annual number of 3 CT procedures per 1000 inhabitants, which is about twice less than the Ghanaian annual average (Korir et al., 2016).

The results of the analysis of the various common indications for adult CT examinations as well as their scanning protocol similarity index are presented in Table 4.10.

Table 4.10: Identified common CT indications for adult head, chest and abdomino-pelvic regions

Indication per anatomical region	Number (*n*)	Percentage (%)	Scanning protocol similarity index	Prioritised indications for DRLs
Head region				
CVA/Stroke	37234	32.8	A	✓
Head injury/trauma	25314	22.3	B	✓
Headaches with suspicion of SOL/tumour	17482	15.4	C	✓
Sinusitis	2724	2.4	D	
Dizziness	1135	1.0	C	
Loss of consciousness	1249	1.1	C	
Psychiatric disorder	3406	3.0	C	
Others	24974	22.0	-	
Chest region				
Cough with suspicion of lung cancer/tumour	5720	32	E	✓
Suspicion of chest lesion with chronic kidney disease (CKD)	1752	9.8	F	✓
Tuberculosis (TB)	1662	9.3	E	
Chronic obstructive pulmonary disease (COPD)	429	2.4	E	
Pulmonary embolism (PE)	2681	15	G	✓
Pneumonia	518	2.9	E	
Pleural effusion	500	2.8	E	
Lung abscess	894	5	E	
Interstitial lung disease	894	5	E	
Haemoptysis	375	2.1	E	
Others	2449	13.7	-	
Abdomino-pelvic regions (include abdomen, pelvis, both)				
Suspicion of AP lesion/abscess	14584	27.8	H	✓
Kidney stones (plain)	9705	18.5	I	✓
Liver metastasis	5403	10.3	J	
Urothelial malignancy	7974	15.2	K	✓
Bowel obstruction	1626	3.1	H	
AP distension	2990	5.7	H	
Prostate cancer	2361	4.5	L	
Bladder mass	1312	2.5	L	
Others	6505	12.4	-	

Key: AP: Abdomino-pelvic. CVA: cerebrovascular accident. ***Note:*** *Indications with similar scanning protocol index (eg. C, E, H, L alphabets) were scanned with very common protocol such as collimation, number of sequences, contrast usage or not, scan length etc. Indication with exclusive alphabet (eg. A, B, D, F, G, I, J and K) used a unique scan scanning protocol. DRLs: diagnostic reference levels.*

Many publications (ICRP, 2017; European Society of Radiology, 2017; Vocks and Frija, 2016; Lajunen, 2015) have recommended baseline DRLs for common diagnostic procedures and indications which contribute significantly to the population dose. CVA/stroke, a brain cell death condition, resulting from poor blood flow to the brain, and the second leading cause of death worldwide (WHO, 2019), was identified as the most common (*n*=37234, 32.8%) indication for head CT imaging. Sanuade et al. (2019), indicated that it was 2.6% prevalent in Ghana. Other common indications included head injury (*n*=25314, 22.3%) and headaches with suspicion of SOL or tumour (*n*=17482, 15.4%). Indications such as sinusitis, dizziness and loss of consciousness were less common. Scanning protocols for the former three indications as well as sinusitis differed from the rest. However, scanning protocols for dizziness and psychiatric disorder were similar to those of headaches with suspicion of SOL/tumour. Based on the frequency and protocol dynamics, CVA/Stroke, head injury/trauma, and headaches with suspicion of SOL/tumour were prioritised for DRLs in the head region.

In the chest category, as indicated in Table 4.10, cough with suspicions of lung cancer/tumour, chest lesion with CKD, TB, COPD, PE, pneumonia, pleural effusion, lung abscess and interstitial lung diseases were identified as the common indications for adult patient CT examination of the chest region. However, cough with suspicion of chest lung cancer/tumour (*n*=5720, 32%), suspicion of chest lesion with CKD (*n*=1752, 9.8%) and PE (*n*=2681, 15%) were the prioritised indications for DRLs in the chest region because of their prevalence and differences in the scanning protocol.

For the abdomen and pelvis region, the most common indications identified for adult patient CT examinations were suspicion of AP lesion/abscess (*n*=14584, 27.8%), kidney stones (*n*=9705, 18.5%) and urothelial malignancy (*n*=7974, 15.2%). Based on their frequency, they were prioritised for DRLs development. The prioritised indications across the body regions were similar to those suggested in literature (Vocks and Frija, 2016).

4.2.2 Definition of Basic Imaging Requirements for Indications

From the initial results (Table 4.5), it was found that most of the facilities did not have written down working protocols for imaging. Hence, in order to select the appropriate technical dose descriptors for the various indications, the basic diagnostic imaging requirements were investigated, and the concept defined. In particular, this was needful for selecting the appropriate images (without including the unnecessary ones) and their associated dose descriptors for the DRL development. The findings of the basic diagnostic imaging requirements for each of the prioritised indications are summarised and presented in the Tables 4.11-4.13. The demographic characteristics of the respondent are presented in Figure 4.5.

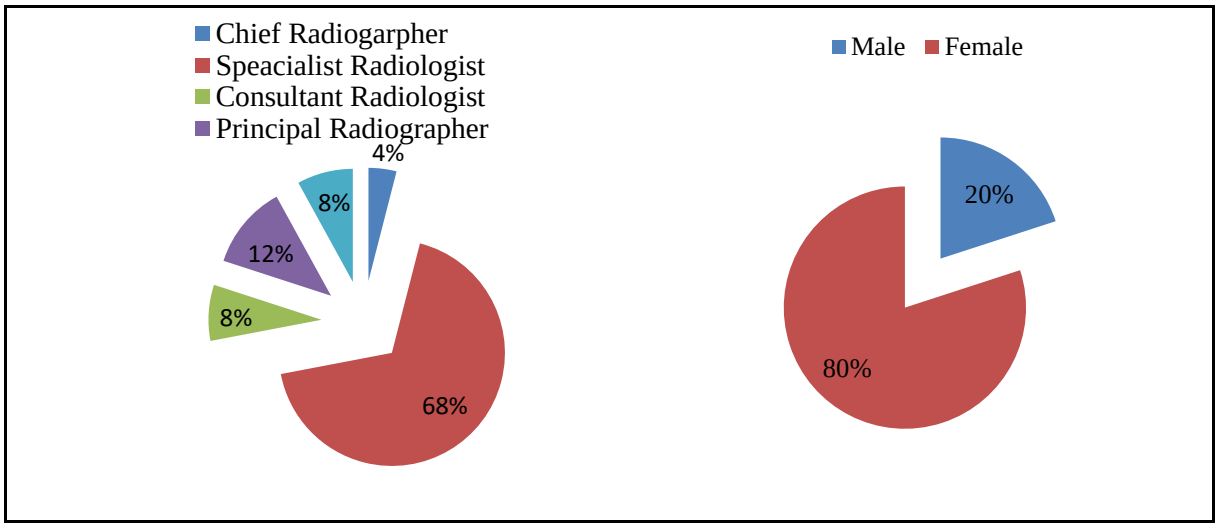


Figure 4.5: Grade of the respondents

Figure 4.5 shows that the majority of the respondents were male (*n*=20, 80%), and specialist radiologists (*n*=17, 68%) who are qualified in image interpretations. Therefore, their involvement provided crucial determinants for basic clinical diagnostic imaging requirements in this study. The basic diagnostic imaging requirements for CVA/stroke, head injury and brain tumour/SOL procedures in Ghana are presented in Table 4.11.

Table 4.11: Basic diagnostic imaging requirements for CVA/stroke, head injury and brain tumour/SOL procedures in Ghana *(Number of respondents =25).*

Diagnostic imaging requirements		CVA/stroke		Head injury		Brain tumour/SOL	
		Response		Response		Response	
		Yes	No	Yes	No	Yes	No
		n (%)	*n (%)*	*n (%)*	*n (%)*	*n (%)*	*n (%)*
Scan coverage:	Scan should cover from just below the base of the skull to the vertex	25 (100%)	-	-	12 (48%)	25 (100%)	-
	Scan should cover from C3 to the vertex if the base of the skull injury is suspected	-	-	13 (52%)	-	-	-
Scan series:	None contrast	25 (100%)	-	25 (100%)	-	-	-
	Once (only IV contrast phase)	-	-	-	-	2 (8%)	23 (92%)
	Twice (both non-contrast and contrast phases)	-	-	-	-	23 (92%)	2 (8%)
Image quality should be acceptable to the reporting radiologists and should meet national/international standards		25 (100%)	-	25 (100%)	-	25(100%)	-
Slice thickness-	5 mm-10 mm	16 (64%)	9 (36%)	16 (64%)	9 (36%)	17 (68%)	8 (36%)
	<5 mm	9 (36%)	16 (64%)	9 (36%)	16 (64%)	8 (32%)	17 (62%)
Scan mode:	Helical only	-	-	-	-	-	-
	Axial only	-	-	-	-	-	-
	Both	25 (25%)	-	25 (25%)	-	25 (25%)	-
Scan Technique:	Low dose	-	-				-
	Optimised dose	25(100%)	-	25 (25%)		25(25%)	
	High dose	-	-				-
AEC usage:	Yes	25 (25%)	-	25 (25%)		25(25%)	
	No	-	-				-

Key: *C3= Third Cervical vertebrae; CVA=cerebrovascular accident; SOL =space occupying lesion; AEC= automatic exposure control system, IV =intravenous, n= frequency.*

From Table 4.11, the basic diagnostic imaging requirements for CVA/stroke examinations in Ghana are that, the scan should cover regions just below the base of skull to the vertex, no contrast media is needed, and the scan should be performed once, while the quality of the images should be acceptable to the reporting radiologists and meet national and international requirements. Many (*n*=16, 64%) of the facilities preferred a scan thickness of 5-10 mm for CVA/stroke examinations while few (*n*=9; 36%) preferred scan thickness of less than 5 mm. In addition, the scan could be either helical or sequential (axial) and the technique should be optimised dose with AEC activated.

For a head injury/trauma, about half (*n*=12, 48%) of the facilities required a scan coverage of regions just below the base of the skull to the vertex while the majority (*n*=13, 52) indicated that the scan should cover from the third cervical vertebra (C3) to the vertex. Moreover, just one optimised plain scan is required, which could be in either helical or axial modes. In addition, scan thicknesses of 5-10 mm were preferred by many (*n*=16, 64%) facilities while few preferred scan thicknesses of less than 5 mm. It was also necessary that images were generated with AEC and the image quality acceptable to the reporting radiologists and meet national/international standards.

With CT brain tumour/SOL examinations, all the facilities preferred the scans to cover from just below the base of skull to the vertex and the majority (*n*=23, 92%) required a dual scan (both non-contrast and contrast phases) while few, (*n*=2, 8%), required one-phase scan (only IV contrast). All the respondents required acceptable resultant image qualities by the reporting radiologists that met national/international standards. Scan thicknesses of 5-10 mm were required by many (*n*=17, 68%), and few (*n*=8, 32%), required scans thicknesses of less than 5 mm. Either helical or axial scanning was acceptable to all facilities, except that the scanning technique had to be optimised and utilising AEC systems.

The basic diagnostic imaging requirements for CT lung tumour, chest lesion with CKD and PE procedures in Ghana are presented in Table 4.12.

Table 4.12: Basic diagnostic imaging requirements for lung tumour, chest lesion with CKD and PE CT procedures in Ghana (*Number of respondents: lung tumour = 23; Chest lesion with CKD = 23, PE = 10).*

Diagnostic imaging requirements		Lung tumour		CL CKD		PE	
		Yes	No	Yes	No	Yes	No
		n (%)	*n (%)*	*n (%)*	*n (%)*	*n (%)*	*n (%)*
Scan coverage:	Scan should cover from just above lung apices to below lung bases	23(100%)	-	23(100%)	-	10(100%)	-
Scan series:	Once (only non- contrast phase)	-	-	23(100%)	-	-	-
	Once (only IV routine contrast phase)	2(9%)	-	-	-	-	-
	Once (only IV contrast "*angiogram*" phase)	-	-	-	-	3(30%)	7(70%)
	Twice (both non-contrast and contrast "*angiogram*" phases	-	-	-	-	7(70%)	3(30%)
	Twice (both non-contrast and contrast phases)	20(87%)	-	-	-	-	-
	Twice (IV contrast scan of the lung filed and scan of the liver)	1(4%)	-	-	-	-	-
Image quality should be acceptable to the reporting radiologists and should meet national/international standards		23(100%)	-	23(100%)	-	23(100%)	-
Slice thickness	< 5 mm	3(13%)	-	3(13%)	-	10(100%)	-
	5 mm-10 mm	20(87%)	-	20(87%)	-	-	
Scan mode:	Helical only	23(100%)	-	23(100%)	-	10(100%)	-
	Axial only	-	-	-	-	-	-
	Both	-	-	-	-	-	-
Scan technique:	Low dose	-	-	-	-	-	-
	Optimised dose	23(100%)	-	23(100%)	-	10(100%)	-
	High dose	-	-	-	-	-	-
AEC usage:	Yes	23(100%)	-	23(100%)		10(100%)	-
	No	-	-	-	-	-	-

Key: *Chest lesion with CKD= CL CKD, AEC= automatic exposure control system, IV= intravenous, f=frequency.*

Table 4.12 shows that all respondents (100%) specified that lung tumour CT scans should cover regions just above lung apices to below lung bases. Few centres preferred only IV contrast-phase, while 1 (4%) required IV contrast scan of the lung filed and scan of the liver (2 sequences). Majority (*n*=20, 87%), of the facilities required both non-contrast and contrast phases (2 sequences). Scan thicknesses of 5 to 10 mm were required by the majority (*n*=20, 87%), and few (*n*=3, 13%) facilities preferred scan thicknesses of less than 5 mm. All the imaging facilities wanted acceptable image qualities that met national/international requirements. Additionally, all facilities also needed lung tumour CT images to be acquired in helical mode utilising AEC systems.

It was evident that a CT scan for a 'chest lesion with CKD' examination had to cover from just above lung apices to below lung bases, with only a single non-contrast phase and scanned in helical mode. The basic requirement for most (*n*=20, 87%) facilities was scan thickness of 5 -10 mm, and less than 5 mm for a few (*n*=3, 13%). The elementary requirements for all the CT imaging facilities included dose optimisation, utilisation of AEC systems, and acceptable image qualities that meet national/international standards.

It was also evident that the diagnostic imaging requirements for CT PE examinations included scanning of lung apices to below lung bases (*n*=10, 100%). Seven (70%) of the facilities undertaking such examinations required a two-sequence scan (both non-contrast and contrast angiogram phases), and only the angiogram phase by a few (*n*=3, 30%). Scan thicknesses of ≤ 5 mm with helical mode were considered necessary by all. In addition, AEC application, as well as dose optimisation, was required. All the facilities also required image qualities to be acceptable to the reporting radiologists and meet national/international standards.

The basic diagnostic imaging requirements for abdomino-pelvic lesion, kidney stone and urothelial malignancy indication (CT-IVU) examinations in Ghana are presented in Table 4.12.

Table 4.13: Basic diagnostic imaging requirements for abdomino-pelvic lesion, kidney stone and urothelial malignancy indication (CT-IVU) examinations in Ghana (Number of respondents: abdomino-pelvic lesion =24, kidney stone =24, urothelial malignancy =19).

Diagnostic imaging requirements		AP lesion		Kidney stone		UM (IVU)	
		Yes	No	Yes	Yes	No	Yes
		n (%)	*n (%)*	*n (%)*	*n (%)*	*n (%)*	*n (%)*
Scan coverage:	Scan should cover from just top of higher hemidiaphragm to below the ischium or symphysis pubis	24(100%)	-	24(100%)	-	19(100%)	-
Scan series:	Once (Non-contrast phase)	-	-	24(100%)	-	-	-
	Once (*only contrast phase; "oral with IV"*)	2(8%)	22(92%)				
	Twice (both non-contrast and contrast phases)	22(92%)	2(8%)	-	-	-	-
	*3-4 phases (*pre-contrast* and *2-3 other post IV contrast phases* including *nephrographic, corticomedullary** and *excretory* phases*)*	-	-	-	-	17(89%)	2(11%)
	2 phases (slip bolus technique involving *nephrographic* and *excretory* phases)	-	-	-		2(11%)	17(89%)
Image quality should be acceptable to the reporting radiologists and should meet national/international standards		24(100%)	-	24(100%)	-	19(100%)	-
Slice thickness:	≤ 5 mm	12(50%)	12(50%)	13(54%)	11(46%)	19(100%)	-
	7-10 mm	12(50%)	12(50%)	11(46%)	13(53%)	-	19(100%)
Scan mode:	Helical only	24(100%)	-	24(100%)	-	19(100%)	-
	Axial only	-	-	-	-	-	-
	Both	-	-	-	-	-	-
Scan technique:	Low dose	-	-	-	-	-	-
	Optimised dose	24(100%)	-	24(100%)	-	19(100%)	-
	High dose	-	-	-	-	-	-
AEC usage:	Yes	24(100%)	-	24(100%)	-	19(100%)	-
	No	-	-	-	-	-	-

Key: *IV represents intravenous; UM=Urothelial malignancy; CT-IVU= computed tomography intravenous urography, AP = Abdomino-pelvic lesion; AEC= automatic exposure control system, n =frequency.*

From Table 4.13, one of the basic diagnostic imaging requirements for AP lesion is that the scan should cover from just top of higher hemidiaphragm to below the symphysis pubis. The majority (*n*=22, 92%) of the centres preferred both contrast and non-contrast phases while only a few (n=2, 8%) needed one phase scan (contrast phase involving oral and intravenous, IV). Helical scanning and AEC applications are key requirements. Also, the protocol involved the use of optimised dose and image quality acceptable to the reporting radiologists and meeting other national and international requirements. Half of the facilities required 7-10 mm scan thickness while the rest preferred ≤ 5 mm cuts.

For a CT of kidney stone indication, a non-contrast scan covering from the top of the higher hemidiaphragm to below the ischium or symphysis pubis was a basic diagnostic imaging requirement by all the facilities. Scan thickness ≤ 5 mm was a basic requirement for 13 (54%) centres, while scan thickness of 7-10 mm was required by 11 (46%) centres. Other requirements included helical mode scanning and utilisation of AEC systems. As observed for CT imaging of other body regions, all the facilities required dose optimisation and acceptable image qualities that meet national/international standards.

Urothelial malignancy indication examination that falls under CT-IVU required scanning regions from the top of higher hemidiaphragm to below the symphysis pubis. The majority (*n* =17, 89%) of the centres preferred 3 to 4 scan phases (pre-contrast and 2-3 other post IV contrast phases including nephrographic, corticomedullary and excretory phases). However, as a basic requirement, few (*n* = 2, 11%) centres required only two phases (split bolus technique involving nephrographic and excretory phases). Also, all the centres preferred scan thickness of ≤ 5 mm, helical scanning, optimised dose and AEC applications, and image quality acceptable to the reporting radiologists and meeting national and international requirements. The above basic diagnostic requirements were relied upon to select the appropriate data for the DRLs.

4.3 PHASE 2: Performance Characteristics Data on CT Scanners

No major scanner deficiencies were found from the various QC and dose delivery validation tests undertaken. The various deviations were within the acceptable limits as suggested by many international bodies (Shefer et al., 2013; IAEA, 2012; AAPM, 2008; Institute of Physics and Engineering in Medicine, 2005; European Commission, 1999; AAPM, 1992). Details of the results are presented in Tables 4.14-4.21. Table 4.14 shows the comparison of measured and console displayed $CTDI_{vol}$ values for head phantom (16 mm diameter).

Table 4.14: Comparison of measured and console displayed $CTDI_{vol}$ values for head phantom

CT(ID)	1st Measurement				2nd Measurement			
	kVp	Measured $CTDI_{vol}$ (mGy)	Displayed $CTDI_{vol}$ (mGy)	% Deviation ($CTDI_{vol}$)	kVp	Measured $CTDI_{vol}$ (mGy)	Displayed $CTDI_{vol}$ (mGy)	% Deviation ($CTDI_{vol}$)
CT 01	100	48.1	48.5	-0.8	120	55.4	56.0	-1.1
CT 02	110	35.7	35.9	-0.6	130	61.1	60.3	1.3
CT 03	100	37.6	36.1	4.0	120	69.4	68.2	1.7
CT 04	120	36.9	34.8	5.7	140	54.0	51.3	5.0
CT 05	100	32.3	34.1	-5.6	120	49.3	50.8	-3.0
CT 06	100	33.2	34.5	-3.9	120	52.6	51.9	1.3
CT 07	110	26.1	23.53	9.9	130	37.4	35.5	5.1
CT 08	100	41.7	40.3	3.4	120	65.2	64.3	1.4
CT 09	100	25.7	25.4	1.2	120	39.3	38.1	3.1
CT 10	110	40.1	39.4	1.7	130	61.3	62.1	-1.3
CT 12	100	45.0	43.9	2.4	120	68.2	66.8	2.1
CT 14	100	37.9	37.4	1.3	120	67.6	69.4	-2.7
CT 15	100	45.6	45.9	-0.7	120	67.7	69.3	-2.4
CT 17	100	31.1	30.1	3.2	120	47.8	48.3	-1.0
CT 18	120	14.1	13.1	7.1	140	23.3	21.4	8.2
CT 19	120	67.8	67.0	1.2	140	48.6	47.2	2.9
CT 20	100	42.3	41.4	2.1	120	63.3	65.0	-2.7
CT 21	100	28.7	29.2	-1.7	120	40.2	38.1	5.2
CT 23	110	33.6	32.3	3.9	130	55.6	54.8	1.4
CT 24	100	14.3	13.2	7.7	120	25.9	26.3	-1.5
CT 26	110	30.6	31.5	-2.9	130	47.4	46.7	1.5
CT 28	100	26.6	26.0	2.3	120	39.9	40.1	-0.5
CT 29	100	33.29	34.1	-2.4	120	51.4	52.6	-2.3
CT 30	120	18.59	20.17	-8.5	135	125.9	127.3	-1.1
CT 31	120	84.72	83.1	1.9	140	87.6	86.1	1.7

$CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, kVp=peak kilovoltage, CT (ID): computed tomography identity.

The $CTDI_{vol}$ delivery accuracy tests involving the head phantom showed that the discrepancies between measured and console displayed $CTDI_{vol}$ values were all within the acceptable deviation limit of 20% of the displayed manufacturer's specifications (IAEA, 2012, AAPM, 2008). The first measurements recorded a deviation range from -8.5% to 9.9%, while the second measurements ranged from -2.7% to 8.2%. These results suggest that the scanners were delivering acceptable $CTDI_{vol}$ readings on head projections on the console.

The inter-comparison results of the measured and console displayed $CTDI_{vol}$ values for the body phantom (32 mm diameter) are presented in Table 4.15.

Table 4.15: Comparison of measured and displayed $CTDI_{vol}$ values for body phantom

CT(ID)	1st Measurement				2nd Measurement			
	kVp	Measured $CTDI_{vol}$ (mGy)	Displayed $CTDI_{vol}$ (mGy)	% Deviation ($CTDI_{vol}$)	kVp	Measured $CTDI_{vol}$ (mGy)	Displayed $CTDI_{vol}$ (mGy)	% Deviation ($CTDI_{vol}$)
CT 01	110	17.8	17.2	3.4	130	27.5	26.7	2.9
CT 02	110	7.9	8.0	-1.3	130	10.9	11.2	-2.8
CT 03	100	15.7	16.1	-2.5	120	18.9	19.0	-0.5
CT 04	120	19.5	17.8	8.7	140	22.1	21.3	3.6
CT 05	100	12.6	12.7	-0.8	130	18.8	18.2	3.2
CT 06	100	15.3	14.3	6.5	120	19.4	20.2	-4.1
CT 07	110	11.9	11.3	5.0	130	17.2	15.9	7.6
CT 08	100	26.2	26.9	-2.7	120	28.7	28.1	2.1
CT 09	100	9.0	9.4	-4.4	120	15.4	16.0	-3.9
CT 10	110	10.6	11.1	-4.7	130	16.4	15.5	5.5
CT 12	100	19.1	18.9	1.0	120	23.5	23.4	0.4
CT 14	100	25.6	25.0	2.3	120	27.4	27.6	-0.7
CT 15	100	14.1	14.3	-1.4	120	17.9	18.1	-1.1
CT 17	100	16.9	17.5	-3.6	120	20.1	21.4	-6.5
CT 18	120	11.9	11.2	5.9	140	17.7	17.9	-1.1
CT 19	120	16.5	16	3.0	140	24.3	23.9	1.6
CT 20	100	11.3	11.5	-1.8	120	17.4	18.7	-7.5
CT 21	100	7.9	8.3	-5.1	120	11.3	10.7	5.3
CT 23	110	10.9	10.6	2.8	130	16.6	15.3	7.8
CT 24	100	7.9	7.2	8.9	120	14.5	14.8	-2.1
CT 26	110	9.8	9.0	8.2	130	16.0	15.7	1.9
CT 28	100	26.6	26.2	1.5	120	23.4	24.2	-3.4
CT 29	100	17.3	18.2	-5.2	120	26.3	27.0	-2.7
CT 30	120	31.4	34.1	-8.5	135	32.0	33.7	-5.3
CT 31	120	15.9	14.9	6.3	140	23.6	24.0	-1.7

$CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, kVp=peak kilovoltage, CT (ID): computed tomography identity.

From the $CTDI_{vol}$ dose delivery accuracy test using body phantom (32 mm diameter), the measured and the console displayed values were within the acceptable deviation limit ($\leq \pm$ 20% of the displayed manufacturer's specifications) as recommended by IAEA (2012) and AAPM (2008). The minimum observed deviations for the first measurements ranged from -8.5% to 8.9%, while the second measurements ranged from -7.5% to 7.8%. The findings indicated a satisfactory dose delivery accuracy for body projections which was important in the utilisation of dose descriptors in the DRL study.

The results of the $CTDI_{vol}$ dose delivery reproducibility tests are also presented in Table 4.16.

Table 4.16: $CTDI_{vol}$ dose delivery reproducibility for both head and body phantoms

CT(ID)	Head phantom					Body phantom				
	kVp	Measured $CTDI_{vol}$ (mGy)				kVp	Measured $CTDI_{vol}$ (mGy)			
		1	2	3	*CoV (%)*		1	2	3	*CoV (%)*
CT 01	100	48.1	48.1	48.2	0.12	110	17.8	17.6	17.7	0.56
CT 02	110	35.7	35.7	35.7	0.00	110	7.9	7.9	7.9	0.00
CT 03	100	37.6	37.5	37.6	0.15	100	15.7	15.6	15.7	0.37
CT 04	120	36.9	36.8	36.8	0.16	120	19.5	19.6	19.4	0.51
CT 05	100	32.3	32.4	32.3	0.18	100	12.6	12.4	12.5	0.80
CT 06	100	33.2	33.2	33.1	0.17	100	15.3	15.3	15.3	0.00
CT 07	110	26.1	26.1	26.1	0.00	110	11.9	11.9	11.9	0.00
CT 08	100	41.7	41.6	41.6	0.14	100	26.2	26.3	26.3	0.22
CT 09	100	25.7	25.7	25.6	0.22	100	9.0	9.1	9.1	0.64
CT 10	110	40.1	40.2	40.1	0.14	110	10.6	10.5	10.6	0.55
CT 12	100	45.0	45.1	45.0	0.13	100	19.1	19.1	19.2	0.30
CT 14	100	37.9	37.9	37.9	0.00	100	25.6	25.5	25.5	0.23
CT 15	100	45.6	45.5	45.6	0.13	100	14.1	14.2	14.1	0.41
CT 17	100	31.1	31.1	31.2	0.19	100	16.9	16.9	16.9	0.00
CT 18	120	14.1	14.2	14.2	0.41	120	11.9	11.9	11.9	0.00
CT 19	120	67.8	67.7	67.8	0.09	120	16.5	16.6	16.5	0.35
CT 20	100	42.3	42.4	42.3	0.14	100	11.3	11.4	11.3	0.51
CT 21	100	28.7	28.7	28.6	0.20	100	7.9	7.9	7.9	0.00
CT 23	110	33.6	33.6	33.7	0.17	110	10.9	10.9	10.9	0.00
CT 24	100	14.3	14.4	14.3	0.40	100	7.9	7.9	7.9	0.00
CT 26	110	30.6	30.6	30.6	0.00	110	9.8	9.7	9.7	0.59
CT 28	100	26.6	26.6	26.6	0.00	100	26.6	26.8	26.7	0.37
CT 29	100	33.29	33.29	33.29	0.00	100	17.3	17.3	17.3	0.00
CT 30	120	18.59	18.59	18.59	0.00	120	31.4	31.5	31.4	0.18
CT 31	120	84.72	84.73	84.72	0.01	120	15.9	15.9	15.9	0.00

$CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product; CoV: coefficient of variation, kVp: peak kilovoltage, CT (ID): computed tomography identity.

In general, dose delivery reproducibility provides information on the ability of a scanner to consistently generate similar dose outputs over time under the same conditions (AAPM, 2008). The variations in dose output observed (Table 4.16) over three different exposures under same conditions were within the acceptable limit of ≤ ± 5% or within a coefficient of variation (C_OV) of ≤ 0.05 (AAPM,1992). Hence, all the scanners passed the dose delivery reproducibility tests and were reliable for generating dose outputs for the DRL study.

Table 4.17 shows results of the geometric efficiency (GE) assessments undertaken at the study sites.

Table 4.17: Measured geometric efficiency values for CT scanners

CT(ID)	1st Measurement		2nd Measurement	
	kVp	Measured Geometric Efficiency (%)	kVp	Measured Geometric Efficiency (%)
CT 01	100	87.9	120	86.3
CT 02	110	88.6	130	87.8
CT 03	100	83.2	120	85.2
CT 04	120	100	140	100
CT 05	100	76.3	120	79.2
CT 06	100	80.4	120	87.9
CT 07	120	82.0	140	75.2
CT 08	100	70.8	120	73.1
CT 09	100	100.0	120	76.0
CT 10	110	79.5	135	80.4
CT 12	100	76.7	120	78.2
CT 14	100	75.2	120	77.3
CT 15	100	87.3	120	88.8
CT 17	100	71.7	120	81.8
CT 18	120	87.3	140	95.6
CT 19	120	71.4	140	73.4
CT 20	100	88.7	120	88.6
CT 21	100	87.2	120	89.1
CT 23	110	78.3	130	84.1
CT 24	100	80.5	120	96.0
CT 26	110	90.4	130	97.5
CT 28	100	80.1	120	80.3
CT 29	100	71.0	120	83.3
CT 30	120	74.0	135	71.8
CT 31	120	72.4	140	100

kVp=peak kilovoltage, CT (ID): computed tomography identity.

The geometric efficiency (GE) of a detector system is the percentage of the radiation quanta incident on the detector in a given interval. The recommended GE acceptable limit is >70% (Shefer et al., 2013, IAEA, 2012; AAPM, 2008). In this study, the minimum and maximum recorded GEs were 70.8% and 100%, respectively, for two measurements across the facilities. Therefore, all the scanners were performing satisfactorily in this regard.

The outcomes of the tube voltage accuracy testing at the various CT facilities are shown in Table 4.18.

Table 4.18: Measured kVp accuracy values for CT scanners

CT Centre (ID)	1st Measurement			2nd Measurement		
	I kVp	M kVp	% Deviation	I kVp	M kVp	% Deviation
CT 01	100	97.9	2.1	120	122.2	-1.8
CT 02	110	111.9	-1.7	130	132.1	-1.6
CT 03	100	101.3	-1.3	120	116.5	3.0
CT 04	120	117.6	2.0	140	136.3	2.7
CT 05	100	101.0	-1.0	120	122.0	-1.6
CT 06	100	101.7	-1.7	120	121.1	-0.9
CT 07	120	117.5	2.1	140	138.1	1.4
CT 08	100	101.6	-1.6	120	117.2	2.4
CT 09	100	99.9	0.1	120	119.8	0.2
CT 10	110	107.5	2.3	135	134.1	0.7
CT 12	100	99.1	0.9	120	118.3	1.4
CT 14	100	102.8	-2.7	120	119.6	0.3
CT 15	100	102.5	-2.4	120	122.1	-1.7
CT 17	100	102.0	-2.0	120	117.4	2.2
CT 18	120	118.6	1.2	140	137.1	2.1
CT 19	120	119.9	0.1	140	139.7	0.2
CT 20	100	102.8	-2.7	120	118.7	1.1
CT 21	100	97.8	2.2	120	123.3	-2.7
CT 23	110	111.8	-1.6	130	126.3	2.9
CT 24	100	102.6	-2.5	120	116.8	2.7
CT 26	110	111.7	-1.5	130	132.5	-1.9
CT 28	100	101.5	-1.5	120	118.5	1.3
CT 29	100	102.4	-2.3	120	121.7	-1.4
CT 30	120	121.3	-1.1	135	137.8	-2.0
CT 31	120	121.6	-1.3	140	138.8	0.9

kVp=peak kilovoltage. I kVp = Indicated kVp; M kVp = Measured kVp; % = percentage; CT (ID): computed tomography identity.

Tube voltage accuracy testing was undertaken to ensure optimal tube potential for each x-ray exposure and that the peak energy of the output beam did not differ significantly to ensure an acceptable image is produced. All the scanners (Table 4.18) recorded acceptable tube voltage accuracy deviations consistent with the IAEA and AAPM recommended limit of ± 5% nominal value (IAEA, 2012; AAPM, 2008). The minimum and maximum obtained deviations for the first tube voltage measurements were -2.7% and 2.3%, while the minimum and maximum deviations for the second measurements were 2.7% and 3.0%, respectively. The results further indicated that all the scanners optimally displayed values which were integral to a successful DRL development.

Table 4.19 shows the measured half value layer (HVL) values for the various CT scanners.

Table 4.19: Measured HVL values for CT scanners

CT (ID)	kVp	Measured HVL (mmAl)	Acceptable deviation value
CT 01	130	7.85	≥ 2.5 mm Al for kV >100
CT 02	130	7.65	≥ 2.5 mm Al for kV >100
CT 03	120	7.51	≥ 2.5 mm Al for kV >100
CT 04	140	8.81	≥ 2.5 mm Al for kV >100
CT 05	120	7.34	≥ 2.5 mm Al for kV >100
CT 06	120	7.32	≥ 2.5 mm Al for kV >100
CT 07	140	8.79	≥ 2.5 mm Al for kV >100
CT 08	120	7.51	≥ 2.5 mm Al for kV >100
CT 09	120	7.57	≥ 2.5 mm Al for kV >100
CT 10	135	7.83	≥ 2.5 mm Al for kV >100
CT 12	120	7.45	≥ 2.5 mm Al for kV >100
CT 14	120	7.61	≥ 2.5 mm Al for kV >100
CT 15	120	7.62	≥ 2.5 mm Al for kV >100
CT 17	120	7.53	≥ 2.5 mm Al for kV >100
CT 18	140	8.87	≥ 2.5 mm Al for kV >100
CT 19	140	8.84	≥ 2.5 mm Al for kV >100
CT 20	120	7.54	≥ 2.5 mm Al for kV >100
CT 21	120	7.51	≥ 2.5 mm Al for kV >100
CT 23	130	7.98	≥ 2.5 mm Al for kV >100
CT 24	120	7.61	≥ 2.5 mm Al for kV >100
CT 26	130	8.83	≥ 2.5 mm Al for kV >100
CT 28	120	7.64	≥ 2.5 mm Al for kV >100
CT 29	120	7.54	≥ 2.5 mm Al for kV >100
CT 30	135	8.78	≥ 2.5 mm Al for kV >100
CT 31	140	8.85	≥ 2.5 mm Al for kV >100

kVp: peak kilovoltage, HVL: half value layer; CT (ID): computed tomography identity.

Table 4.19 shows that the measured HVLs in aluminium thickness (mm Al) equivalent were all acceptable according to the United States Food and Drug Administration (2017) recommendations, which requires ≥ 2.5 mm Al for kVp >100. The minimum and maximum HVLs were 7.32 mm Al at 120 kV and 8.79 mm Al at 140 kV, respectively. The acceptable outcome is important because low filtration gives unnecessary radiation to patients while higher filtration leads to beam hardening minimising skin dose (AL-Jasim et al., 2017).

The measured CT number for water in Hounsfield Unit (HU) and image noise in the various CT scanners are presented in Table 4.20.

Table 4.20: Measured CT number for water and image noise in scanners

CT number and acceptable deviation				Image noise and acceptable deviation		
CT (ID)	Measured water CT number (HU)	Acceptable deviation limit (HU)	Remarks	Noise level	Acceptable limit	Remarks
CT 01	1.65	≤ ±4	Pass	5.920	≤ ±10% baseline value	Pass
CT 02	1.00	≤ ±4	Pass	6.956	≤ ±10% baseline value	Pass
CT 03	0.00	≤ ±4	Pass	4.945	≤ ±10% baseline value	Pass
CT 04	0.00	≤ ±4	Pass	5.130	≤ ±10% baseline value	Pass
CT 05	2.00	≤ ±4	Pass	6.001	≤ ±10% baseline value	Pass
CT 06	2.50	≤ ±4	Pass	6.105	≤ ±10% baseline value	Pass
CT 07	0.00	≤ ±4	Pass	3.231	≤ ±10% baseline value	Pass
CT 08	0.00	≤ ±4	Pass	5.988	≤ ±10% baseline value	Pass
CT 09	0.70	≤ ±4	Pass	5.911	≤ ±10% baseline value	Pass
CT 10	0.00	≤ ±4	Pass	6.337	≤ ±10% baseline value	Pass
CT 12	1.45	≤ ±4	Pass	5.989	≤ ±10% baseline value	Pass
CT 14	4.00	≤ ±4	Pass	8.710	≤ ±10% baseline value	Pass
CT 15	4.00	≤ ±4	Pass	9.830	≤ ±10% baseline value	Pass
CT 17	0.50	≤ ±4	Pass	8.960	≤ ±10% baseline value	Pass
CT 18	0.80	≤ ±4	Pass	8.800	≤ ±10% baseline value	Pass
CT 19	1.03	≤ ±4	Pass	9.660	≤ ±10% baseline value	Pass
CT 20	0.00	≤ ±4	Pass	9.800	≤ ±10% baseline value	Pass
CT 21	0.97	≤ ±4	Pass	6.880	≤ ±10% baseline value	Pass
CT 23	4.00	≤ ±4	Pass	7.830	≤ ±10% baseline value	Pass
CT 24	0.50	≤ ±4	Pass	4.990	≤ ±10% baseline value	Pass
CT 26	4.00	≤ ±4	Pass	6.780	≤ ±10% baseline value	Pass
CT 28	2.00	≤ ±4	Pass	8.560	≤ ±10% baseline value	Pass
CT 29	2.00	≤ ±4	Pass	9.230	≤ ±10% baseline value	Pass
CT 30	1.00	≤ ±4	Pass	7.400	≤ ±10% baseline value	Pass
CT 31	0.00	≤ ±4	Pass	5.330	≤ ±10% baseline value	Pass

HU: Hounsfield Unit; CT (ID): computed tomography identity.

The attenuation coefficient of radiation within a tissue is used during CT reconstruction to produce a grayscale image (DenOtter and Schubert, 2019). Based on a linear transformation of the original linear attenuation coefficient, the HU scale is calculated as gray tones to project image details (DenOtter and Schubert, 2019). The HU values are associated as CT number scale and are checked regularly during normal QC tests of the CT system. To test for the HU display of the scanners, the CT number in water was evaluated for each of them which according to the literature is 0 HU (Pan, 2009). However, there is an acceptable limit of ± 4 HU from which optimally functional scanners should be able to display x-ray attenuation information (AAPM, 2008). The minimum (0.0 HU) and maximum (4.0 HU) measured values from Table 4.20 suggest that all scanners passed the CT number (water) tests.

Image noise in CT imaging is "the degree of uncertainty in measuring attenuation of an x-ray beam passing through a patient" (Zarb et al., 2010, p. 3). Excessive image noise can degrade image quality; hence, it has to be corrected whenever detected (Zarb et al., 2010). The image noise levels ranging from 3.2 to 9.8 observed across the scanners were all within the tolerable limit of $\leq \pm 10\%$ baseline value as recommended by the IAEA (IAEA, 2012), and thus suggest optimal CT noise levels in images produced by the scanners.

The results of the image uniformity (homogeneity) analyses performed at the various CT facilities are presented in Table 4.21.

Table 4.21: Image uniformity (homogeneity) findings at different locations

CT ID	12 o'clock	15 o'clock	18 o'clock	21 o'clock	Centre HU	Diff C 12	Diff C15	Diff C18	Diff C 21
CT 01	2.189	2.321	1.053	1.679	1.35	0.839	0.971	-0.297	0.329
CT 02	2.047	1.587	0.909	1.872	1.407	0.84	0.181	-0.498	0.465
CT 03	2.159	1.909	1.443	1.719	1.197	0.962	0.713	0.247	0.522
CT 04	2.473	1.874	1.537	2.295	1.138	1.335	0.736	0.399	1.157
CT 05	2.143	2.209	1.459	2.318	0.683	1.460	1.526	0.776	1.635
CT 06	3.364	3.130	3.108	2.604	1.120	2.244	2.010	1.989	1.484
CT 07	1.785	1.377	0.820	1.405	0.871	0.914	0.507	-0.050	0.535
CT 08	2.129	1.965	0.869	1.515	1.466	0.663	0.499	-0.597	0.050
CT 09	2.907	2.967	2.690	2.840	1.200	1.707	1.767	1.49	1.639
CT 10	2.392	1.953	1.587	2.221	1.078	1.314	0.875	0.509	1.143
CT 12	1.788	1.864	1.344	2.021	1.255	0.534	0.609	0.09	0.766
CT 14	1.977	1.58	1.385	1.624	1.301	0.676	0.278	0.084	0.323
CT 15	2.641	2.223	1.619	1.770	1.270	1.371	0.955	0.348	0.500
CT 17	2.461	2.008	0.995	2.045	1.114	1.347	0.894	-0.12	0.93
CT 18	2.541	1.483	1.61	1.587	1.319	1.222	0.165	0.291	0.269
CT 19	2.452	1.726	1.289	2.05	1.448	1.004	0.278	-0.159	0.601
CT 20	2.309	1.851	1.025	1.639	1.097	1.212	0.753	-0.072	0.541
CT 21	2.430	2.109	1.275	1.574	1.255	1.174	0.854	0.02	0.318
CT 23	2.391	2.144	1.404	1.953	1.181	1.211	0.963	0.223	0.772
CT 24	1.869	1.963	1.601	1.566	1.267	0.602	0.696	0.334	0.298
CT 26	2.159	2.164	1.144	1.778	0.942	1.217	1.222	0.202	0.836
CT 28	2.687	2.815	2.064	2.642	0.822	1.866	1.994	1.242	1.820
CT 29	2.433	2.143	1.624	1.983	1.277	1.156	0.866	0.347	0.706
CT 30	2.403	2.488	1.350	2.501	1.246	1.157	1.243	0.105	1.255
CT 31	1.737	1.927	1.174	2.008	1.136	0.802	0.791	0.038	0.872

HU: Hounsfield Unit; CT (ID): computed tomography identity.

The image homogeneity test results (Table 4.21), describe how uniform a homogenous material appears, and indicated that the scanners operated within the IAEA tolerable recommended limits of ±10 HU for a head and body phantom (IAEA, 2012). In particular, the deviations of uniformities at all the five ROIs (12 o'clock, 15 o'clock, 18 o'clock, 21 o'clock and the centre) of the respective images were all within the ±10 HU of the central ROI (HU).

4.4 PHASES 3 & 4: CT Dose and Image Quality Assessment and Estimation of DRLs

This section presents the results of the sample demographics, scan parameters, and DRL values for various indications as well as the developed tool for dose monitoring, following a successful data validation. The age, gender and weight of the patients are shown in Table 4.22.

Table 4.22: Demographic characteristics of patients' data

Indication	Age (years)	Weight (kg)	Gender	
	Mean (Range)	*Mean (Range)*	*Male*	*Female*
CVA or stroke	60.7±15.0(18-96)	71.4±8.9(50-90)	239(42.8%)	261(52.2%)
Head trauma/Injury	41.7±18.2(18-97)	72.6±9.9(50-90)	332(66.4%)	168(33.6%)
Brain tumour/ SOL	44.4±17.5(18-92)	73.3±9.7(50-90)	227(45.4%)	273(54.6%)
Lung tumour/cancer	54.0±16.7(18-93)	74.4±8.7(50-90)	236(51.3%)	224(48.7%)
Chest lesion with CKD	52.1±16.2(18-87)	74.1±8.9(50-90)	226(49.1%)	234(50.9%)
Abdominopelvic lesion	51.6±16.1(18-96)	76.6±9.5(50-90)	228(47.5%)	252(52.5%)
Kidney stones	49.9±16.2(18-94)	74.8±9.4(50-90)	249(51.9%)	231(48.1%)
Urothelial malignancy	45.9±15.7(18-89)	73.4±8.4(50-90)	226(59.5%)	154(40.5%)
Pulmonary embolism	58.8±14.1(23-88)	74.4±9.4(55-90)	86(43.0%)	114(57.0%)
Overall	50.5±17.4(18-97)	73.8±9.3(50-90)	2049(51.7%)	1911(48.3%)

CVA: cerebrovascular accident, SOL: space occupying lesion, CKD: chronic kidney disease; kg: kilogram

The CT dose descriptor and image quality data were collected from 25 scanners following the exclusion of non-functional, specially dedicated and technically challenged (inability to display dose descriptors) CT scanners (Figure 3.3). This number represented 71.4% of the CT scanners in Ghana. The ICRP has recommended NDRL surveys to include at least 30-50% of facilities, where all the facilities could not be used (ICRP, 2017). The large number of CTs used in this study gives a representative sample. In total, 3,960 patient data sets were used to develop the indication-based DRLs. Majority (2,049, 51.7%) of the study samples were males. The overall mean age and weight of participants were 50.5 ± 17.4 years and 73.8 ± 9.3 kg, respectively, which was similar to a reference mean weight of an adult population (ICRP, 2017). The scan parameters and factors used for generating the dose output data for the respective indications are presented in Table 4.23.

Table 4.23: Descriptive statistics of scanning parameters used to acquire images

Indication	Scan parameters (mean ± SD)								
	Tube voltage kVp	Tube loading mAs	Pitch	Trot (s)	Slice thickness (mm)	No. of slices per series	Scan length (mm)	No. of series*	Phantom Diameter (cm)
CVA/stoke	121.8 ± 7.4	238.0 ± 80.6	0.75 ± 0.2	0.97 ± 0.3	4.30 ± 1.1	51.4 ± 61.9	161.9 ± 24.0	1	16
HT/I	120.3 ± 6.4	229.4 ± 73.5	0.72 ± 0.2	0.96 ± 0.4	4.40 ± 1.1	61.2 ± 71.1	197.1 ± 40.0	1	16
BT/S	121.0 ± 7.8	238.2 ± 83.1	0.74 ± 0.2	1.01 ±1.5	4.40 ± 1.1	53.1 ± 66.4	164.5 ± 21.0	2	16
LT/C	119.0 ± 7.4	114.0 ± 76.8	1.16 ± 0.2	0.71 ±0.3	5.50 ± 2.5	93.2 ± 125.0	313.4 ± 43.0	1-2	32
CLCKD	119.0 ± 7.3	114.0 ± 74.7	1.15 ± 0.2	0.70 ± 0.3	5.50 ± 2.5	91.7 ± 123.0	310.2 ± 43.0	1	32
APL	118.7 ± 7.5	137.0 ± 91.4	1.11 ± 0.3	0.76 ± 0.3	5.40 ± 2.6	162.0 ± 208.0	459.9 ± 43.0	1-2	32
KS	118.0 ± 8.3	138.4 ± 98.4	1.12 ± 0.3	0.80 ± 0.3	5.30 ± 2.5	152.0 ± 187.0	455.1 ± 41.0	1	32
UM	118.0 ± 8.5	114.0 ± 82.0	1.09 ± 0.3	0.71 ± 0.4	5.10 ± 2.4	165.4 ± 200.0	461.2 ± 56.0	2-4	32
PE	117.8 ± 4.0	167.5 ± 92.9	1.20 ± 0.3	0.64 ± 0.2	2.20 ± 1.7	294.6 ± 216.0	303.7 ± 41.0	1-2	32

*HT/I=Head trauma/Injury; BT/S=Brain tumour/SOL; LT/C= Lung tumour/cancer; CLCKD=Chest lesion with CKD; APL=Abdomino-pelvic lesion, KS=Kidney stones; UM=Urothelial malignancy, PE=Pulmonary angiogram, SD=standard deviation, kVp=peak kilovoltage, mAs=milliampere-second, Trot=rotation time. *For a number of series, the scout or scanogram sequences and monitoring phases (e.g. in the cases of PE) were not included as it is the situation for all established DRLs.*

For the CVA/stroke indications, the mean tube voltage was 121.8 ± 7.4 kVp while the tube loading, pitch and gantry rotation time (*Trot*) were 238.0 ± 80.6 mAs, 0.75 ± 0.2, and 0.97 ± 0.3 s, respectively. The average scan slice thickness used was 4.3 ± 1.1 mm and an average of 51.4 ± 61.9 images were acquired over an average scan range of 161.9 ± 24 mm.

The mean scan parameters used in the case of head trauma or injury were 120.3 ± 6.4 (kVp), 229.4 ± 73.5 (mAs), 0.72 ± 0.20 (pitch), 4.40 ± 1.10 mm (slice thickness) and 197.1 ± 40.0 mm (scan length). Both CVA/stroke and head injury procedures were scanned using a single sequence while brain tumour/SOL procedures were scanned twice. The scan parameters of brain tumour/SOL were closely similar to CVA/stroke indications except the number of scan sequences. A 16 cm phantom was utilised for generating dose outputs for all head related indications such as head injury, CVA/stroke and brain tumour/SOL while a larger mean scan length was utilised in the former indication compared to the rest. Hence, a correspondingly larger DLP was envisaged in the dose output.

The mean scan parameters for lung tumour/cancer imaging were 119.0 ± 7.4 kVp, 114.0 ± 76.8 mAs, 1.16 ± 0.2 (pitch), 5.5 ± 2.5 mm (slice thickness) and 313.4 ± 43.0 mm (scan length). Lung tumour/cancer and chest lesion with CKD parameters were similar except that scan sequences for the latter was 1, and the former was 1-2.

Moreover, the mean scan parameters for AP lesion, kidney stones and urothelial malignancy (CT-IVU) were closely related except that kidney stone procedures were scanned in a single sequence mode while AP lesion and CT-IVU procedures were scanned using 1-2 and 2-4 sequences, respectively.

PE scans were also generated with parameters which included voltage (117.8 ± 4.0 kVp), tube loading (167.5 ± 92.9 mAs), pitch (1.20 ± 0.3), slice thickness (2.2 ± 1.7 mm), scan length (303.7 ± 41.0 mm) and scan sequence of 1-2. All the body procedures were undertaken with a 32-cm diameter phantom in conformity with the international norm (AAPM, 2008).

The descriptive statistics of scanning mode, contrast and AEC utilisation are described in Table 4.24.

Table 4.24: Descriptive statistics of scanning mode and contrast and AEC utilisation

Indication	Contrast		Scanning mode		AEC	
	Used	*Unused*	*Helical*	*Axial*	*Used*	*Unused*
CVA/stroke	-	500 (100%)	344 (68.8%)	156 (32.2%)	241(48.2%)	259 (51.8%)
HT/I	-	500 (100%)	389 (77.8%)	111 (22.2%)	219 (43.8%)	281(56.2%)
BT/S	500 (100%)	-	340 (68.0%)	160 (32.0%)	190 (38.9%)	310 (62.0%)
LT/C	500 (100%)	-	460 (100%)	-	440 (95.7%)	20 (4.3%)
CLCKD	-	500 (100%)	640 (100%)	-	440 (95.7%)	20 (4.3%)
APL	480 (100%)	-	480 (100%)	-	400 (83.3%)	80 (16.7%)
KS	480 (100%)	-	480 (100%)	-	400 (83.3%)	80 (16.7%)
UM	380 (100%)	-	380 (100%)	-	380 (100%)	-
PE	200 (100%)	-	200 (100%)	-	200 (100%)	-

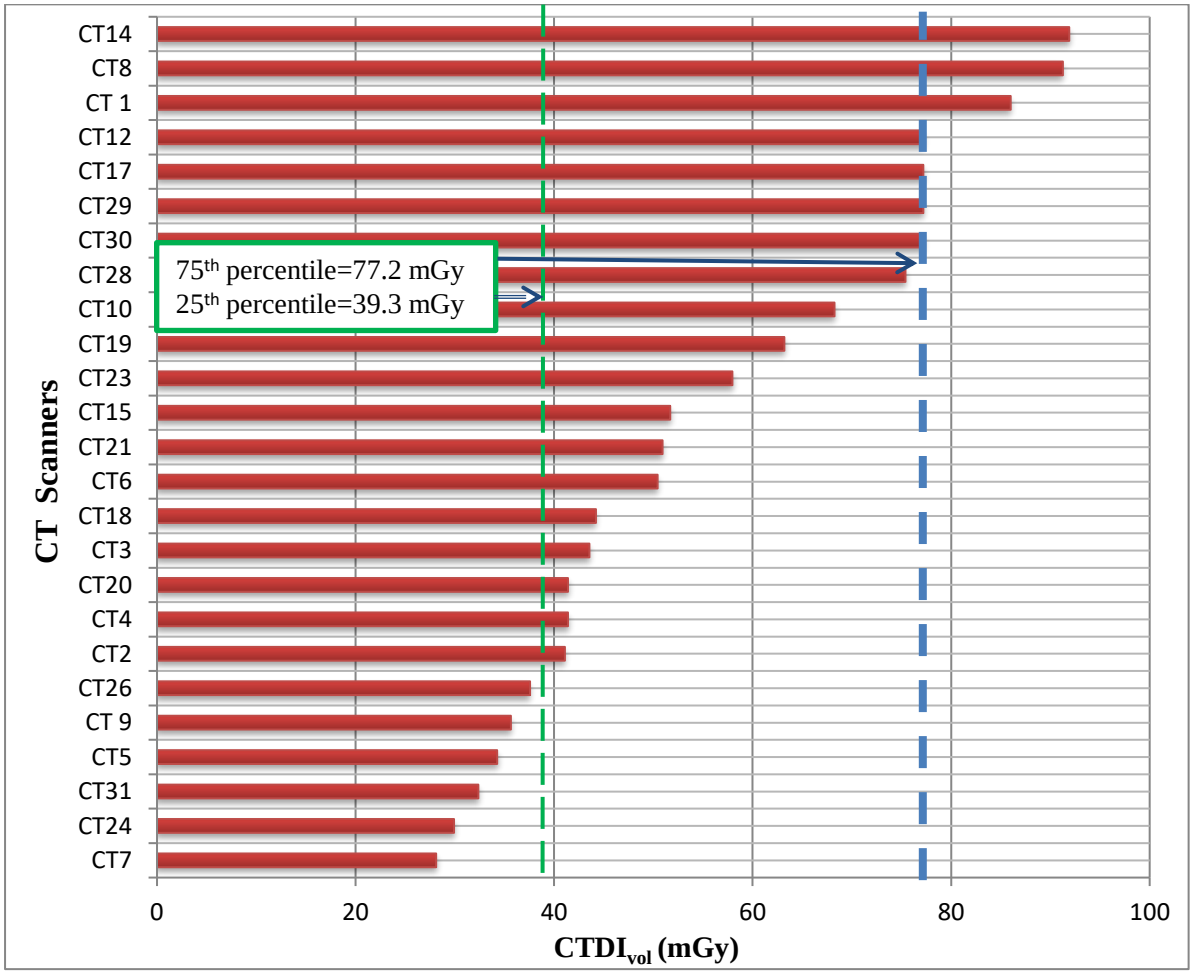
HT/I=Head trauma/Injury; BT/S=Brain tumour/SOL; LT/C=Lung tumour/cancer; CLCKD=Chest lesion with CKD; APL= Abdomino-pelvic lesion, KS=Kidney stones UM= Urothelial malignancy, PE= Pulmonary angiogram.

Table 4.24 indicates that contrast agents were not used in routine CVA/stroke, head injury, chest lesion with CKD and kidney stone examinations. They were, however, used for the rest of the indications. Moreover, for CVA/stroke, head injury and brain tumour/SOL indications, it was found that 156 (32.2%), 111 (22.2%), 160 (32.0%), were scanned in axial mode. However, the rest (representing the majority) were all scanned in helical mode. AEC systems were not utilised in some indication-based procedures during scanning, *albeit* few in the body examinations. According to Higaki et al., (2019) and Merzan et al., (2017), such examinations may not benefit from the radiation dose reduction advantages of AEC configurations and hence, would require dose optimisation in those CT facilities.

Following a successful data validation, where all dose descriptors were in statistical control (within the upper and lower control limits) (Appendix VIII), the DRL values for each indication were projected. The descriptive statistics and projected DRL values for CT CVA indications with respect to $CTDI_{vol}$ are presented in Table 4.25 and Figure. 4.6, respectively, while those of DLP are shown in Table 4.26 and Figure 4.7. A comparison of developed DRL values ($CTDI_{vol}$ and DLP) for CVA with international values is shown in Table 4.27.

Table 4.25: Descriptive statistics of representative $CTDI_{vol}$ values for CVA CT

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. Median $CTDI_{vol}$ (mGy)	Max. Median $CTDI_{vol}$ (mGy)	SD
25	50.9	28.1	91.9	20.1

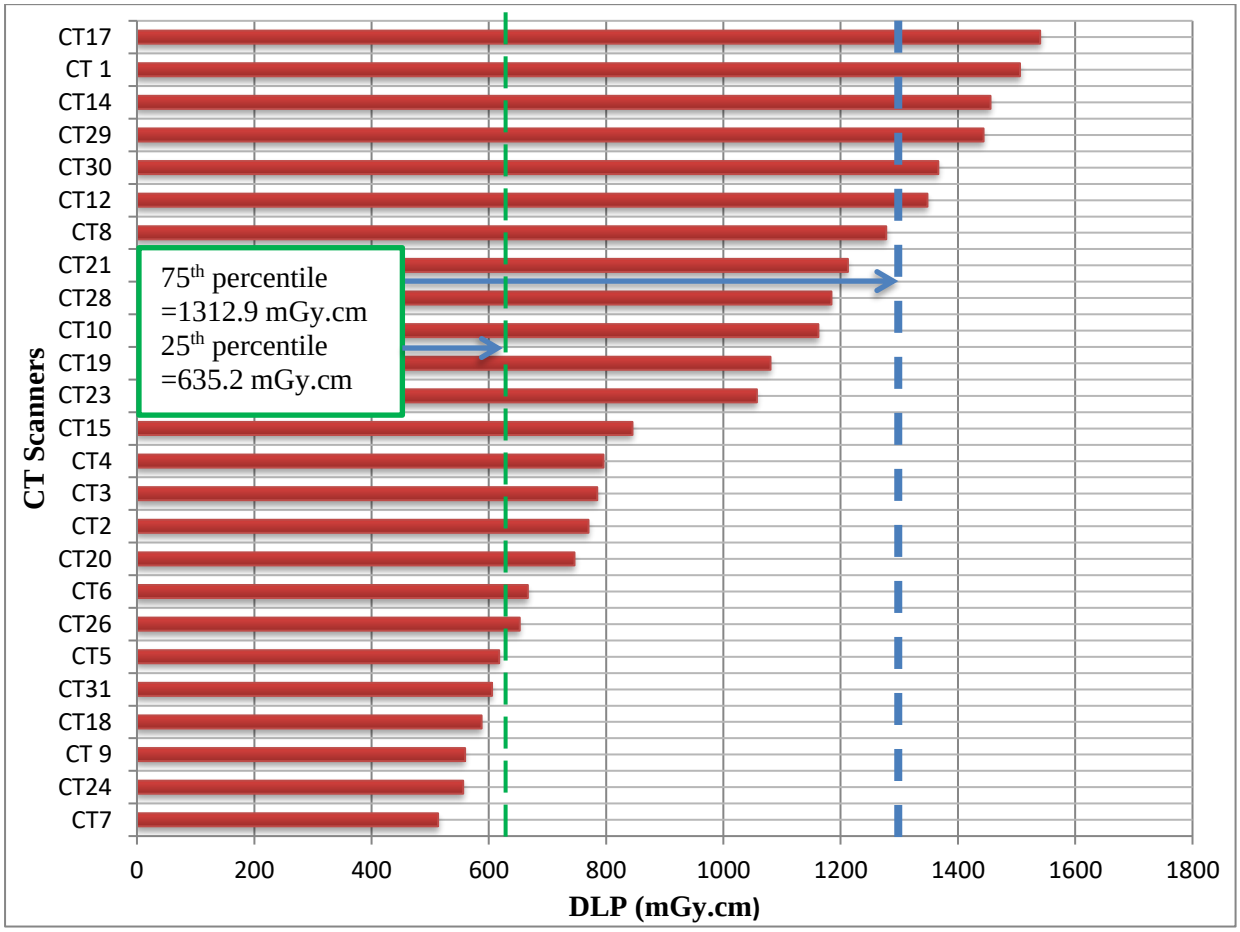


AD= Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.6: Distribution of representative $CTDI_{vol}$ values for CVA CT.

Table 4.26: Descriptive statistics of representative DLP values for CVA CT

Total scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
25	845.0	513.4	1540.2	350.2



The DLP values are from 1 sequence (Non-contrast examination). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.7: Distribution of representative DLP values for CVA CT

Table 4.27: A comparison of CVA indication-based DRL values with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	77	1313*	8.7± 2.1
Public Health England, (2016), UK	80	970*	-
Treier et al., (2010), CH	65	1000*	-

**=Single sequence procedure; CH represents Switzerland and UK represents the United Kingdom. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

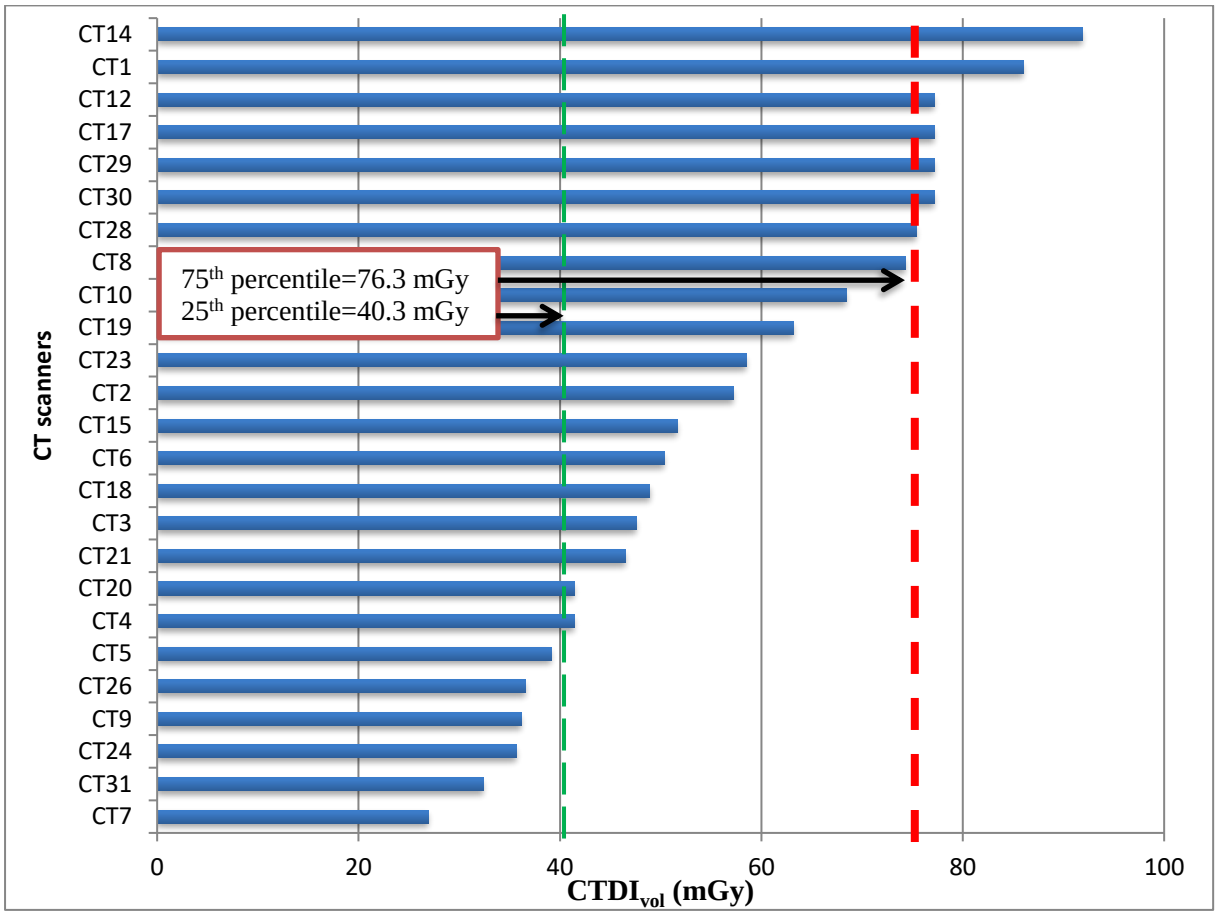
In accordance with the Rose criterion (model) (Bushberg et al., 2011), the image quality test results (SNR = 8.7± 2.1) indicated that images from which dose descriptors were used for CVA DRLs, were within the clinical requirements needed to distinguish image features at 100% certainty. The calculated 75^{th} and 25^{th} percentiles for CVA CT indications have been displayed in blue and green dashed lines, respectively, in both Figures 4.6 and 4.7. The results indicated that the minimum and maximum median $CTDI_{vol}$ values across the facilities varied by a factor of 3.3. The proposed NDRL for CVA with respect to $CTDI_{vol}$ was approximately 77 mGy. The achievable $CTDI_{vol}$ which is the 50^{th} percentile of the calculated doses was approximately 51 mGy. The projected NDRL for CVA with respect to DLP was approximately 1313 mGy.cm and the achievable DLP dose was approximately 845 mGy.cm.

Compared to internationally established values, it was observed that Ghana's NDRL values for CVA ($CTDI_{vol}$ = 77 mGy; DLP = 1313 mGy.cm) were higher than those reported by Treier et al. (2010) in Switzerland, although SNR values were not reported in the latter results. Comparatively, the UK $CTDI_{vol}$ value (80 mGy) was higher but with an interestingly lower DLP (970 mGy.cm). Since DLP is a product of $CTDI_{vol}$ and scan length, it may be projected that longer scan lengths are used in Ghana compared to their UK counterparts, if all other factors remain the same.

The descriptive statistics and projected DRL values for head trauma/injury CT with respect to $CTDI_{vol}$ are presented in Table 4.28 and Figure 4.8, respectively, while that of DLP are shown in Table 4.29 and Figure 4.9. A comparison of developed DRL values ($CTDI_{vol}$ and DLP) for head trauma/injury with international values is shown in Table 4.30.

Table 4.28: Descriptive statistics of representative $CTDI_{vol}$ values for head trauma/injury CT

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
25	51.7	27.0	91.9	18.8

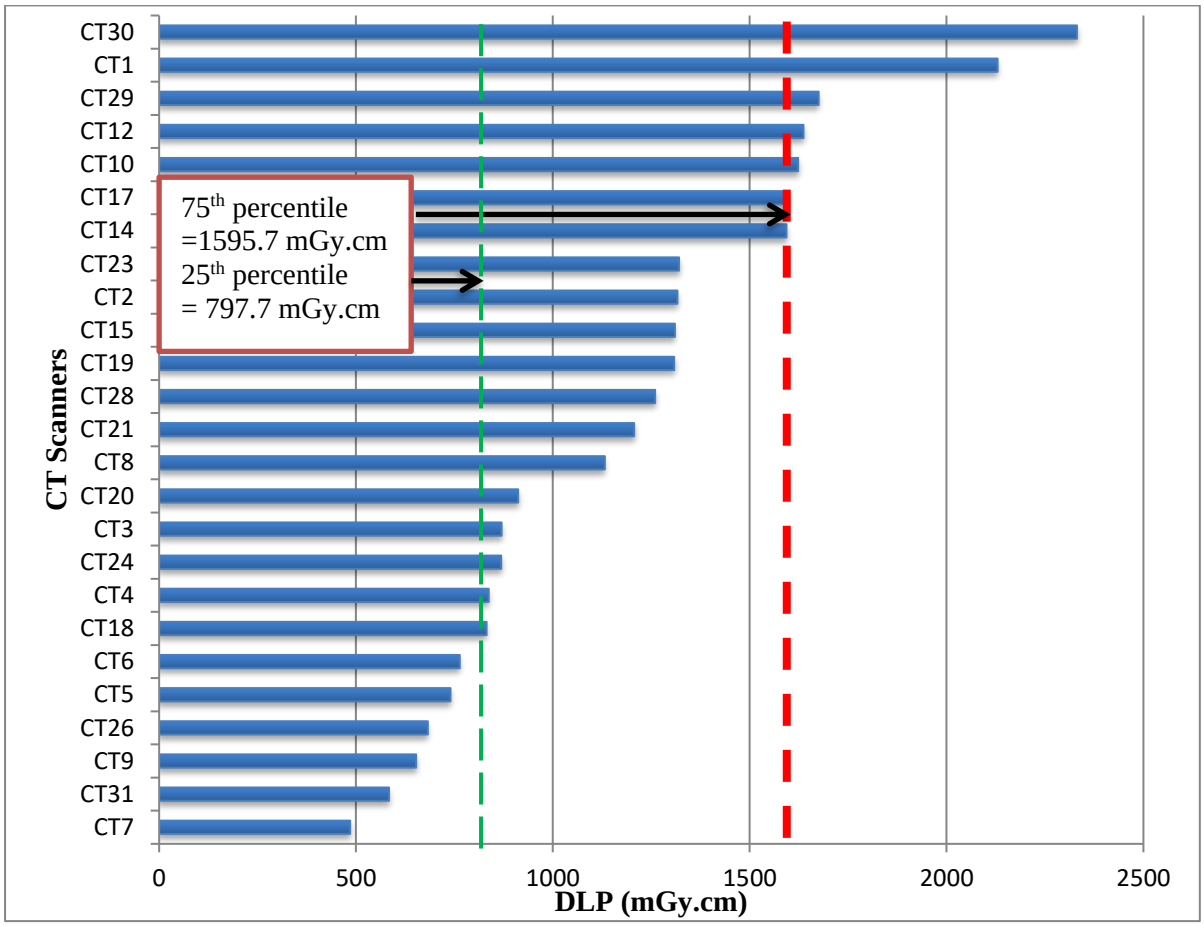


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.8: Distribution of representative $CTDI_{vol}$ values for head trauma or injury CT

Table 4.29: Descriptive statistics of representative DLP values for head trauma/injury CT

Total scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
25	1206.5	485.2	2331.2	480.3



The DLP values are from 1 sequence (Non-contrast examination). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4. 9: Distribution of representative DLP values for head trauma/injury CT

Table 4.30: A comparison of indication-based DRL values for head trauma/injury CT, with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	77	1596*	7.1 ± 1.3
Widmark, (2018), NO	60	950*	-

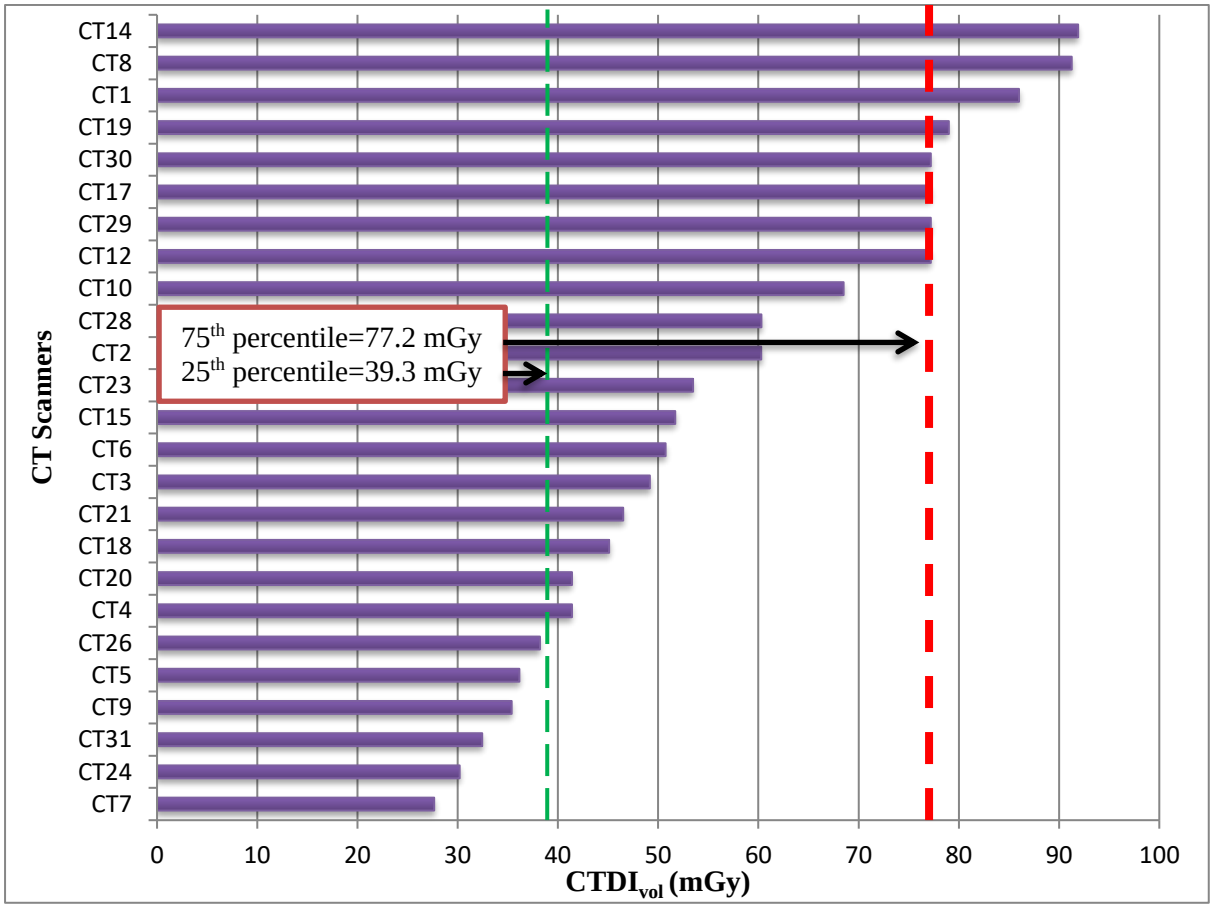
**=Single sequence procedure; NO represents Norway. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

The CT dose levels used for head trauma/injury examinations varied across the facilities in Ghana. The minimum and maximum median $CTDI_{vol}$ values varied by 3.4-fold. The mean SNR of 7.1 ± 1.3 indicated that head trauma/injury images were of acceptable image quality. The calculated 75^{th} and 25^{th} ($CTDI_{vol}$ and DLP) percentiles for CT of head trauma/injury are displayed in red and green dashed lines, respectively, in Figures 4.8 and 4.9. The findings indicated that the projected national $CTDI_{vol}$ DRL for CT of head trauma/injury was approximately 76 mGy, while the achievable dose was approximately 52 mGy. The corresponding projected DLP DRL was approximately 1596 mGy.cm, while the achievable DLP DRL was also approximately 1207 mGy.cm. Comparatively, this study's DRLs for head trauma were higher than the projected NDRLs ($CTDI_{vol}$ = 60 mGy; DLP= 950 mGy.cm) in Norway (Widmark, 2018).

Table 4.31 and Figure 4.10 show the descriptive statistics and projected $CTDI_{vol}$ DRL values for CT of brain tumour/SOL indication, while the descriptive statistics and projected DLP DRL values for the same indication are also presented in Table 4.32 and Figure 4.11. A comparison of these developed DRLs with international values are shown in Table 4.33.

Table 4.31: Descriptive statistics of representative $CTDI_{vol}$ values for brain tumour/SOL CT indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
25	51.7	27.7	91.9	20.6

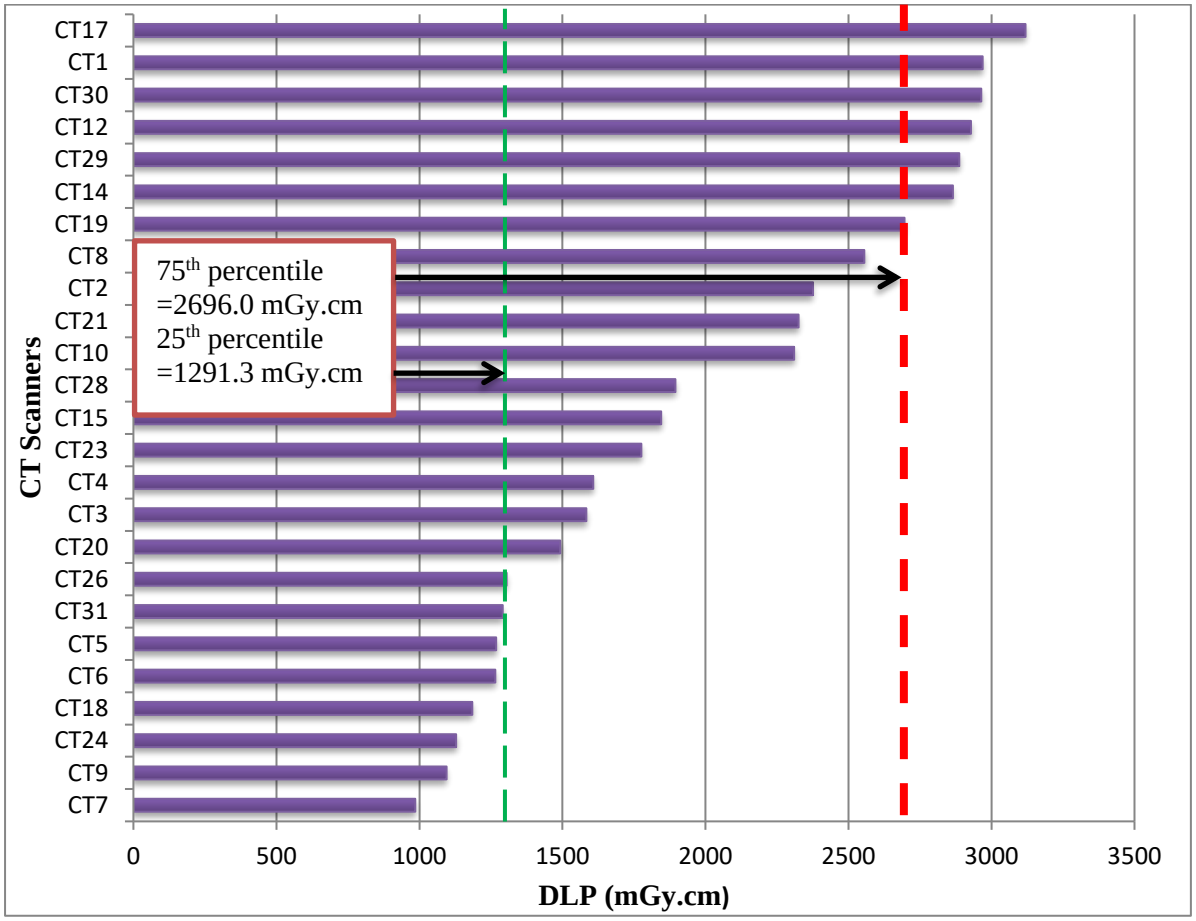


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.10: Distribution of representative $CTDI_{vol}$ values for brain tumour/SOL CT indication

Table 4.32: Descriptive statistics of representative DLP values for brain tumour/SOL CT indication

Total scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
25	1845.2	985.4	3119.0	726.2



The DLP values are from 1-2 sequences (Pre- and post-contrast examinations). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.11: Distribution of representative DLP values for brain tumour/SOL CT indication

Table 4.33: A comparison of indication-based DRL values for brain tumour/SOL CT, with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	77	2696+	6.7 ± 1.5
Treier et al., (2010), CH	65	1000*	-

**=Single sequence procedure*; + =1-2 *sequences (pre- and post-contrast examinations). CH represents Switzerland. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

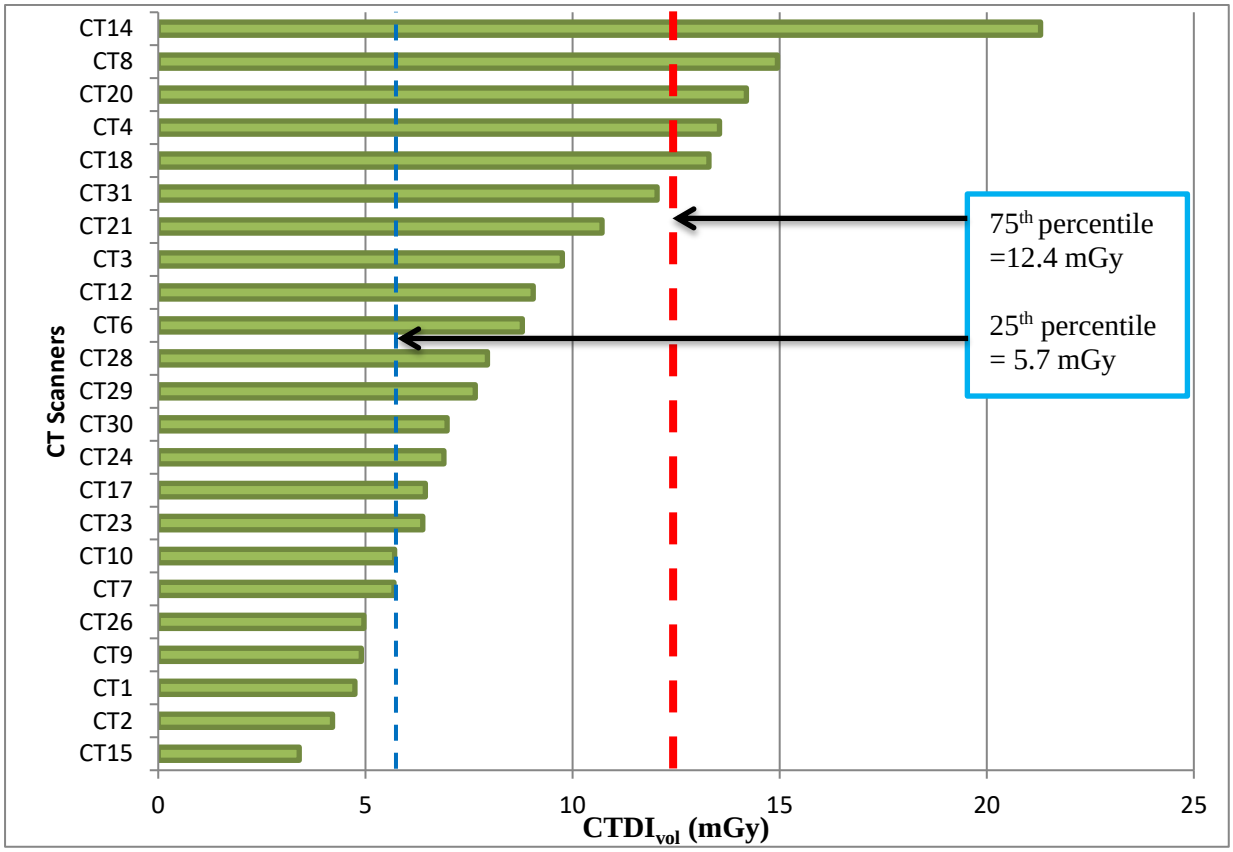
As seen in Figures 4.10 and 4.11, the red and green dashed lines represent the calculated 75^{th} and 25^{th} ($CTDI_{vol}$ and DLP) percentiles for brain tumour/SOL indication CT, respectively. Image quality in terms of SNR for brain tumour/SOL CT indication was 6.7 ± 1.5, which was considered good for diagnostic purposes. The observed dose variation in $CTDI_{vol}$ values (minimum and the maximum) was 3.3-fold. The projected NDRL for brain tumour/SOL CT with respect to $CTDI_{vol}$ was therefore approximately 77 mGy, while the calculated achievable dictation $CTDI_{vol}$ dose was approximately 52 mGy. Moreover, the projected NDRL for brain tumour/SOL CT with respect to DLP and the calculated achievable DLP dose were approximately 2696 mGy.cm and 1845 mGy.cm, respectively.

Comparatively, the projected brain tumour/SOL DRL values from this study were higher than the established values ($CTDI_{vol}$ = 65 mGy; DLP = 1000 mGy.cm) in Switzerland as reported by Treier et al., (2010). A critical factor effecting the large variation in DRL values across the two studies was the scan sequences. Particularly, it was observed that radiographers in Ghana used 1-2 sequences (pre- and post-contrast), while their Swiss counterparts used a single sequence (post-contrast) to diagnose brain tumour/SOL conditions. It may be important for medical professionals in Ghana to explore the possibility of using a single sequence in brain tumour/SOL conditions since it is practicable in Switzerland. Its implementation may further optimise patient's radiation levels.

The projected $CTDI_{vol}$ DRLs ($CTDI_{vol}$) for lung tumour/cancer CT indication as well as the respective descriptive statistics are presented in Table 4.34 and Figure 4.12. The corresponding descriptive statistics and projected DLP DRLs are also presented in Table 4.35 and Figure 4.13. A comparison of these developed DRL for lung tumour/cancer CT indication with international values is shown in Table 4.36.

Table 4.34: Descriptive statistics of representative $CTDI_{vol}$ values for lung tumour/cancer CT indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
23	7.7	3.4	21.3	4.4

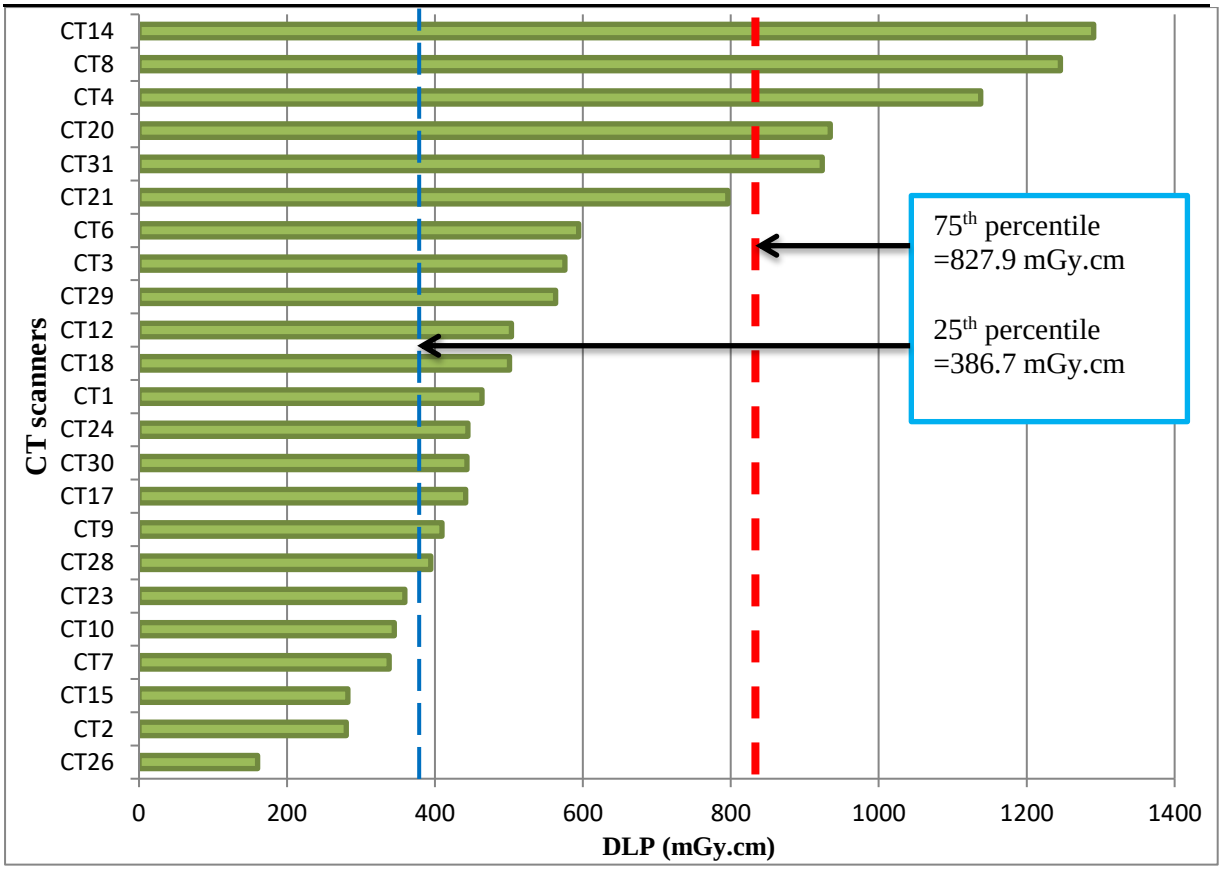


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4. 12: Distribution of representative $CTDI_{vol}$ values for lung tumour/cancer CT indication

Table 4.35: Descriptive statistics of DLP values for lung tumour/cancer CT indication

Total Scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. Median DLP (mGy.cm)	SD
23	463.7	160.4	1290.6	310.5



The DLP values are from 1-2 sequences (Pre- and post-contrast examinations). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.13: Distribution of DLP values for lung tumour/cancer CT indication

Table 4.36: A comparison of indication-based DRL values for lung tumour/cancer CT, with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	12	828+	11.3 ± 3
Widmark, (2018), NO	9	350*	-
Public Health England, (2016), UK	12	610?	-
Danish Health Authority, (2015), DK	16	620?	-
Radiation and Nuclear Safety Authority, (2013), (FI)	11	430*	-

**=Single sequence procedure; + =1-2 sequences (pre- and post-contrast), ? =undeclared number of sequences. NO represents Norway, UK represents United Kingdom, DK represents Denmark, FI represents Finland. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product*

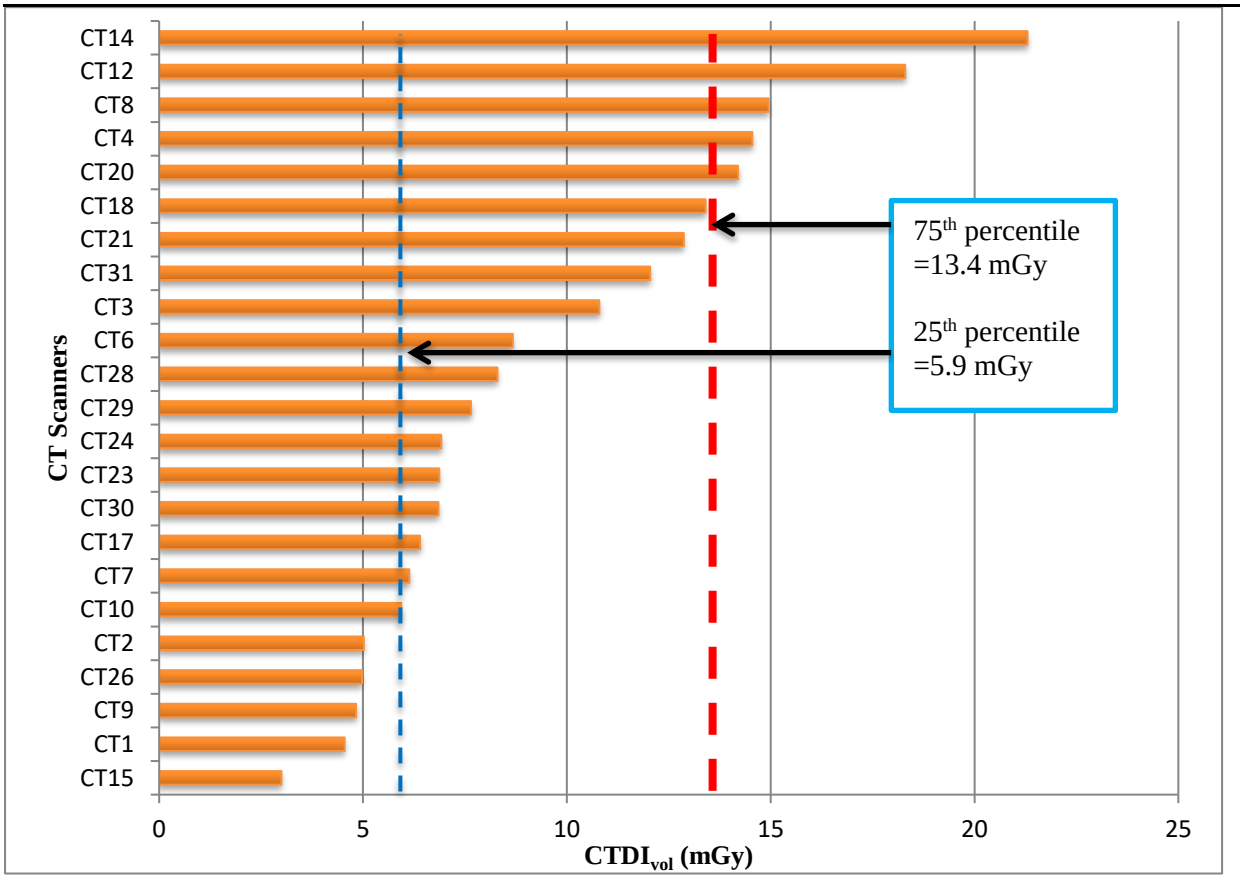
A mean SNR value of 11.3 ± 3 was observed across the images whose dose descriptors were used in developing DRL values for lung tumour/cancer. The result indicated a good objective image quality following successful subjective comments by radiographers. The dose levels used for diagnosing lung tumour/cancer across the facilities were wide-ranging. In particular, the $CTDI_{vol}$ values between the minimum and maximum varied by a factor of 6.2. The red and blue dashed lines in Figures 4.12 and 4.13 show the respective 75^{th} and 25^{th} ($CTDI_{vol}$ and DLP) percentiles for lung tumour/cancer CT indications. The suggested NDRL for lung tumour/cancer CT indication with respect to $CTDI_{vol}$ was approximately 12 mGy, while the observed achievable $CTDI_{vol}$ dose across the facilities was approximately 8 mGy. The corresponding projected DLP was approximately 828 mGy.cm and the observed achievable DLP was approximately 464 mGy.cm.

Compared with available literature, this study's DRLs were higher than the projected Norwegian NDRL values ($CTDI_{vol}$ = 9 mGy; DLP = 350 mGy.cm) (Widmark, 2018) and and Finish DRLs ($CTDI_{vol}$ = 11 mGy; DLP = 430 mGy.cm) (Radiation and Nuclear Safety Authority, 2013), respectively. The $CTDI_{vol}$ DRL was similar to the established national value (12 mGy) in the UK, but less than the 16 mGy reported in Denmark (Danish Health Authority, 2015). However, the projected DLP value in this study was higher than all its counterparts. In Ghana, the diagnostic imaging requirement for tumour/cancer largely required a two-sequence (pre- and post-contrast) procedure with few facilities scanning with a single sequence (Table 4.12). On the contrary, the Norway and Finland DRLs were based on a single sequence values due to their practice norm. However, the number of scan sequence from which the DLP values were established for the UK and Denmark was unclear as available literature was silent on it.

For lung lesion with CKD indications, the descriptive statistics and projected DRL values are presented in terms of $CTDI_{vol}$ (Table 4.37 and Figure 4.14) and DLP (Table 4.38 and Figure 4.15), respectively.

Table 4.37: Descriptive statistics of representative $CTDI_{vol}$ values for CT of chest lesion with CKD indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
23	7.7	3.0	21.3	4.9

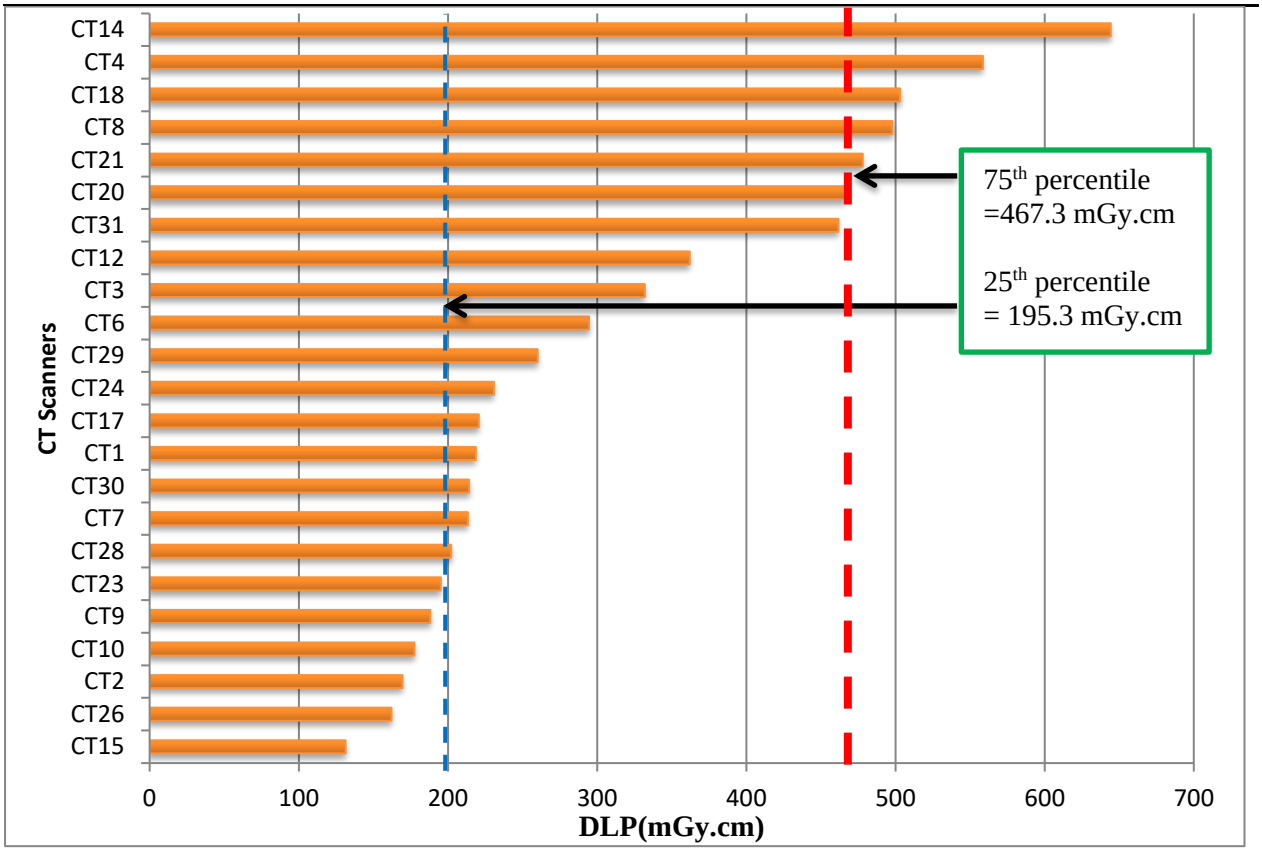


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.14: Distribution of representative $CTDI_{vol}$ values for CT of chest lesion with CKD indication

Table 4.38: Descriptive statistics of DLP (mGy.cm) values for CT of chest lesion with CKD

Total Scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
23	230.8	131.4	644.4	150.7



The DLP values are from 1 sequence (Non-contrast examination). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.15: Distribution of DLP values for CT of chest lesion with CKD indication

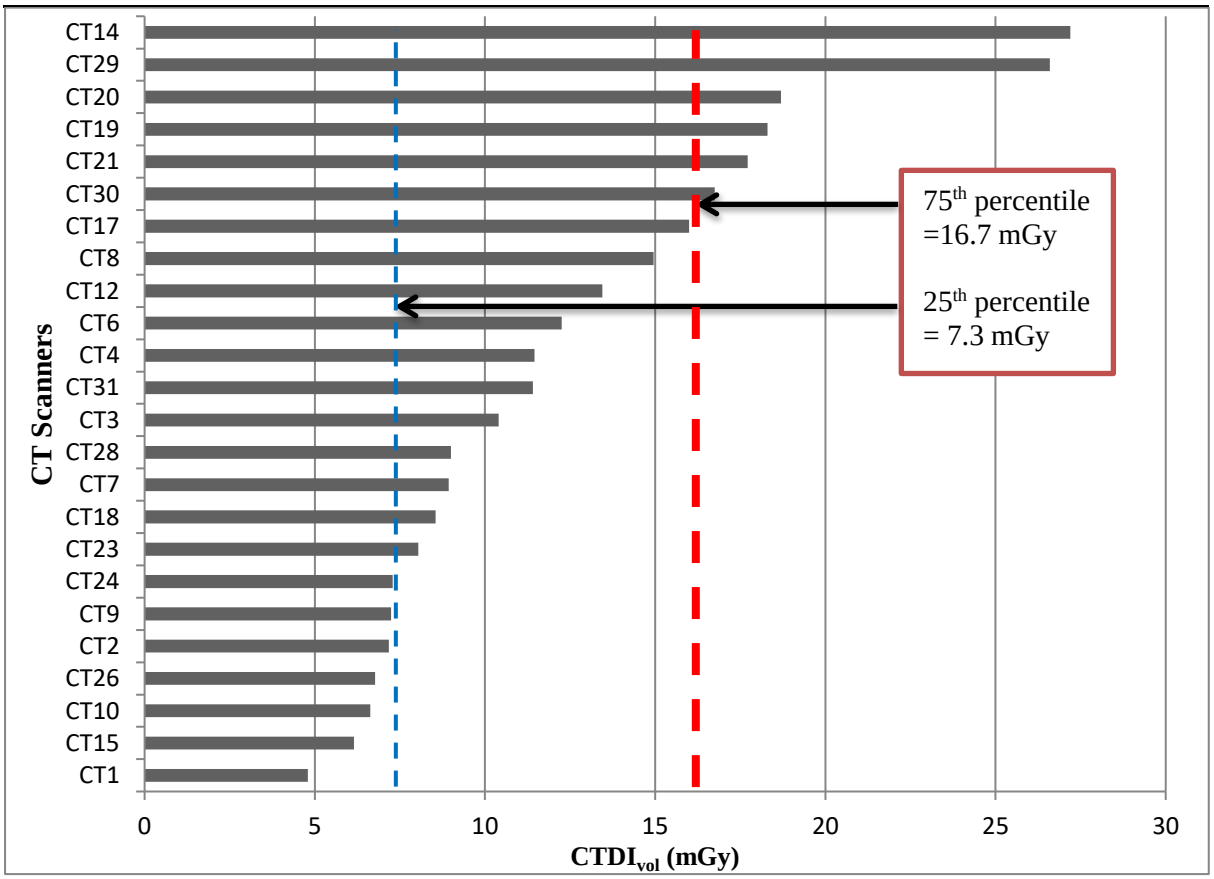
Available literature (Patschan et al., 2018) indicates that patients suffering from kidney diseases such as CKD do not often undergo CT with iodinated contrast agents because it could increase serum creatinine and potentially cause nephropathy. The observed median dose levels ($CTDI_{vol}$) used for this indication using non-contrast imaging varied by a factor of 7. The proposed national $CTDI_{vol}$ DRL was approximately 13 mGy, while the observed $CTDI_{vol}$ achievable dose (50^{th} percentile) across the facilities for CT of lung lesion with CKD indication was approximately 7.7 mGy. The projected associated DLP value was approximately 467

mGy.cm, while the achievable DLP dose was also approximately 231 mGy.cm. The mean SNR associated with the indication-specific images was 11.8 ± 2.2 which implied that the DRLs were derived from dose descriptors whose image characteristics were within an acceptable level (Bushberg et al., 2011). Moreover, no internationally established DRL value was found for chest lesion with CKD. Hence, this was the first time it has been projected.

The descriptive statistics and DRL values for AP lesion are presented in Table 4.39 and Figure 4.16. for $CTDI_{vol}$ descriptors and in Table 4.40 and Figure 4.17 for DLP descriptors. A comparison of developed DRL values with international values is shown in Table 4.41.

Table 4.39: Descriptive statistics of $CTDI_{vol}$ (mGy) values for CT of AP lesion indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
24	10.9	4.8	27.2	6.1

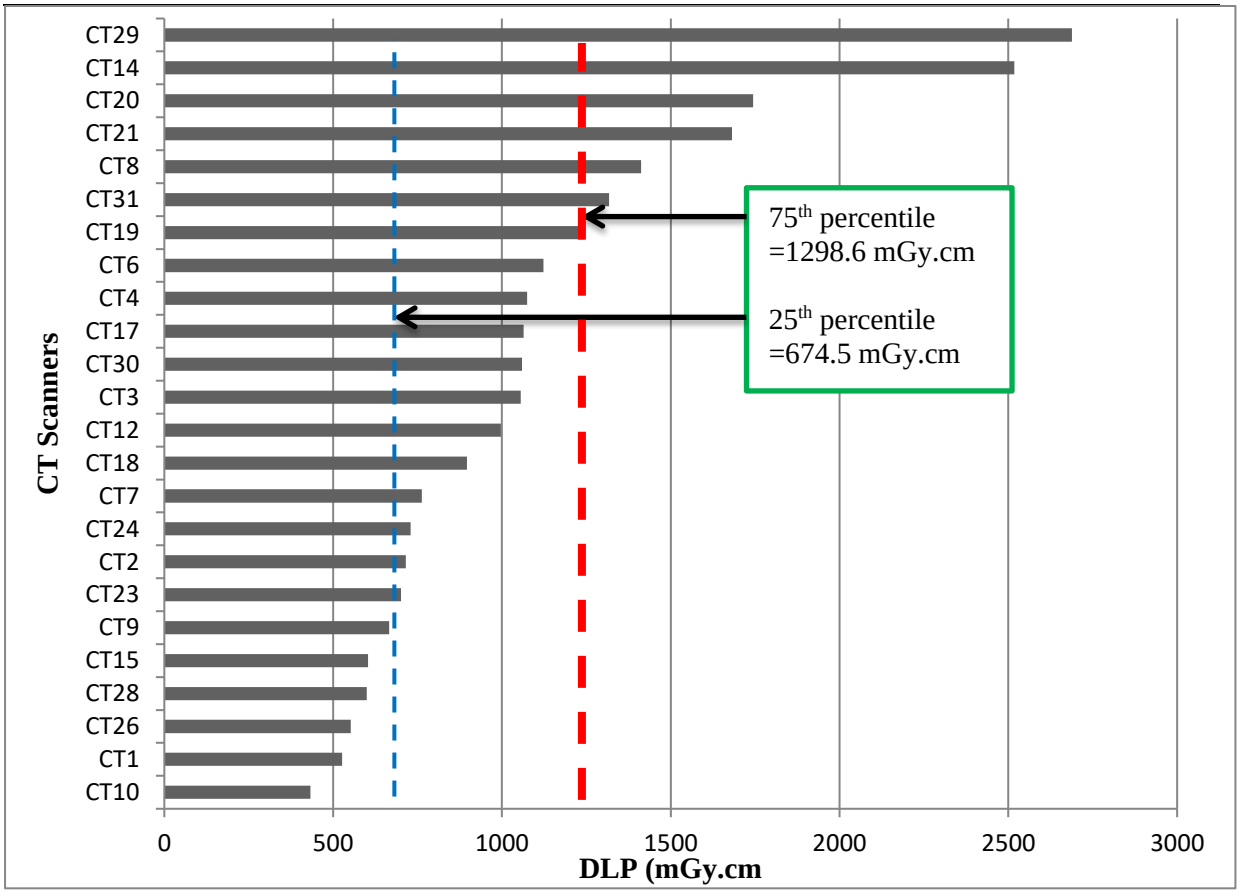


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.16: Distribution of representative $CTDI_{vol}$ values for CT of AP lesion indication

Table 4.40: Descriptive statistics of representative DLP values for CT of AP lesion indication

Total Scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
24	1026.4	432.5	2688.8	583.4



The DLP values are from 1-2 sequences (Pre- and post-contrast examinations). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.17: Distribution of DLP values for CT of AP lesion indication

Table 4.41: A comparison of indication-based DRL values for CT of AP lesion, with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	17	1299+	11.8 ± 2.2
Widmark, (2018), NO	11	800+	-
Public Health England, (2016), UK	15	745?	-
Treier et al., (2010), CH	15	650*	-
Wachabauer et al., (2017), AU	-	650*	-

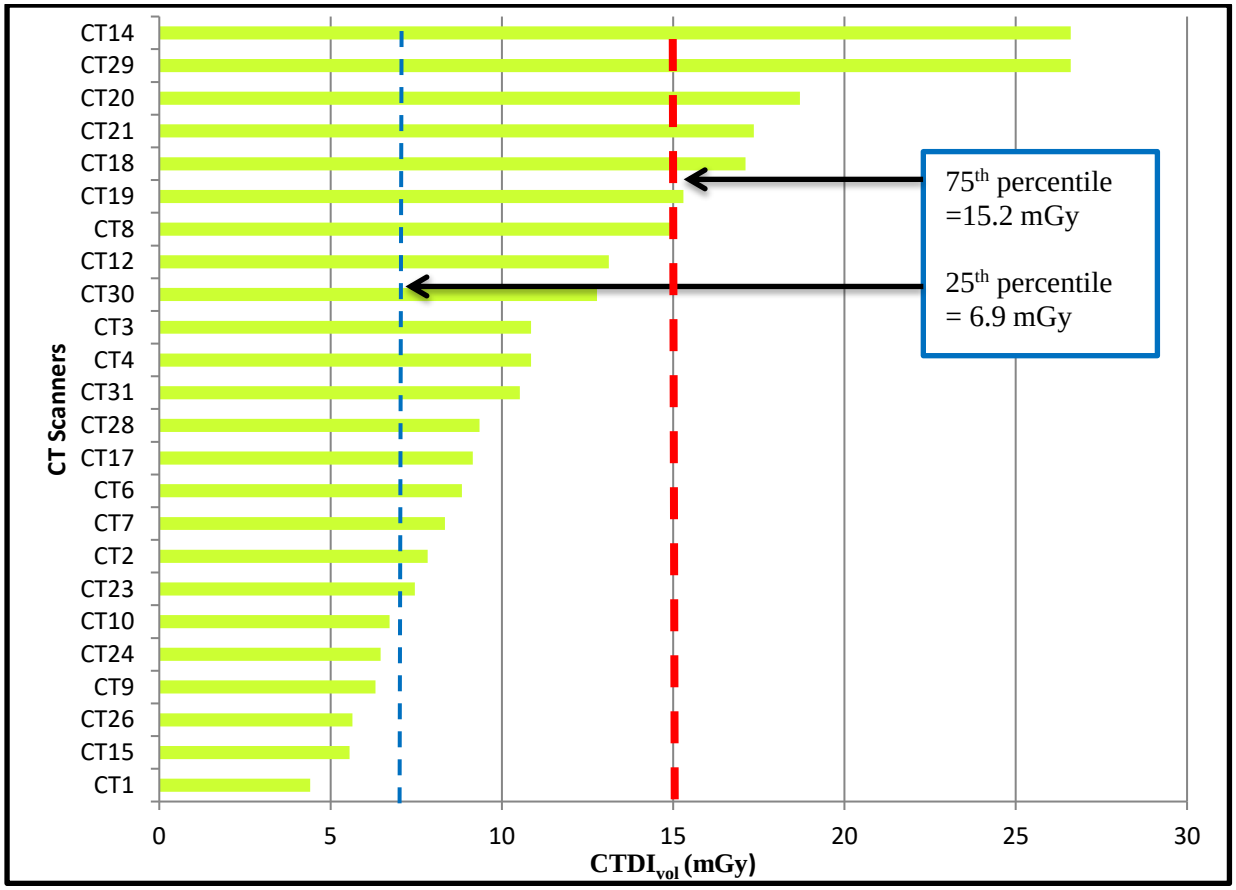
**=Single sequence procedure; + =1-2 sequences (pre- and post-contrast),? =undeclared number of sequences. NO represents Norway, UK represents United Kingdom, CH represents Switzerland and AU represents the Australia. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

For AP lesion, the observed CT dose levels ($CTDI_{vol}$) between the minimum and maximum median values across the facilities varied by 5.7-fold. The estimated 75^{th} and 25^{th} ($CTDI_{vol}$ and DLP) percentiles for CT of AP lesions are respectively displayed in red and blue dashed lines in Figures 4.16 and 4.17. The projected national $CTDI_{vol}$ DRL and calculated $CTDI_{vol}$ achievable dose values for CT of AP lesion were approximately 17 mGy and 11 mGy, respectively. The corresponding national DLP DRL and calculated DLP achievable doses for CT of AP lesion were approximately 1299 mGy.cm and 1026 mGy.cm, respectively. A good image quality (mean SNR = 11.8 ± 2.2) was observed across the images. The projected DRL values were higher than those reported in literature by Widmark, (2018), Public Health England, (2016), Treier et al., (2010) and Wachabauer et al., (2017). Particularly, the DLP values reported by Treier et al., (2010), and Wachabauer et al., (2017) were about half of values projected in this study. The scan diagnostic imaging requirement where some radiographers in Ghana used a pre- and post-contrast protocol, while radiographers in some other countries utilised a single sequence procedure for AP lesion CT imaging could be one of the factors leading to the wide variation between the projected and literature values.

Table 4.42 and Figure 4.18 present the descriptive statistics and projected $CTDI_{vol}$ DRLs for kidney stone indication, respectively, while the same for the DLP DRLs are also presented in Table 4.43 and Figure 4.19. A comparison of developed DRLs for kidney stone with international values is shown in Table 4.44.

Table 4.42: Descriptive statistics of $CTDI_{vol}$ values for CT of kidney stone indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median CTDIvol (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
24	9.9	4.4	26.6	6.1

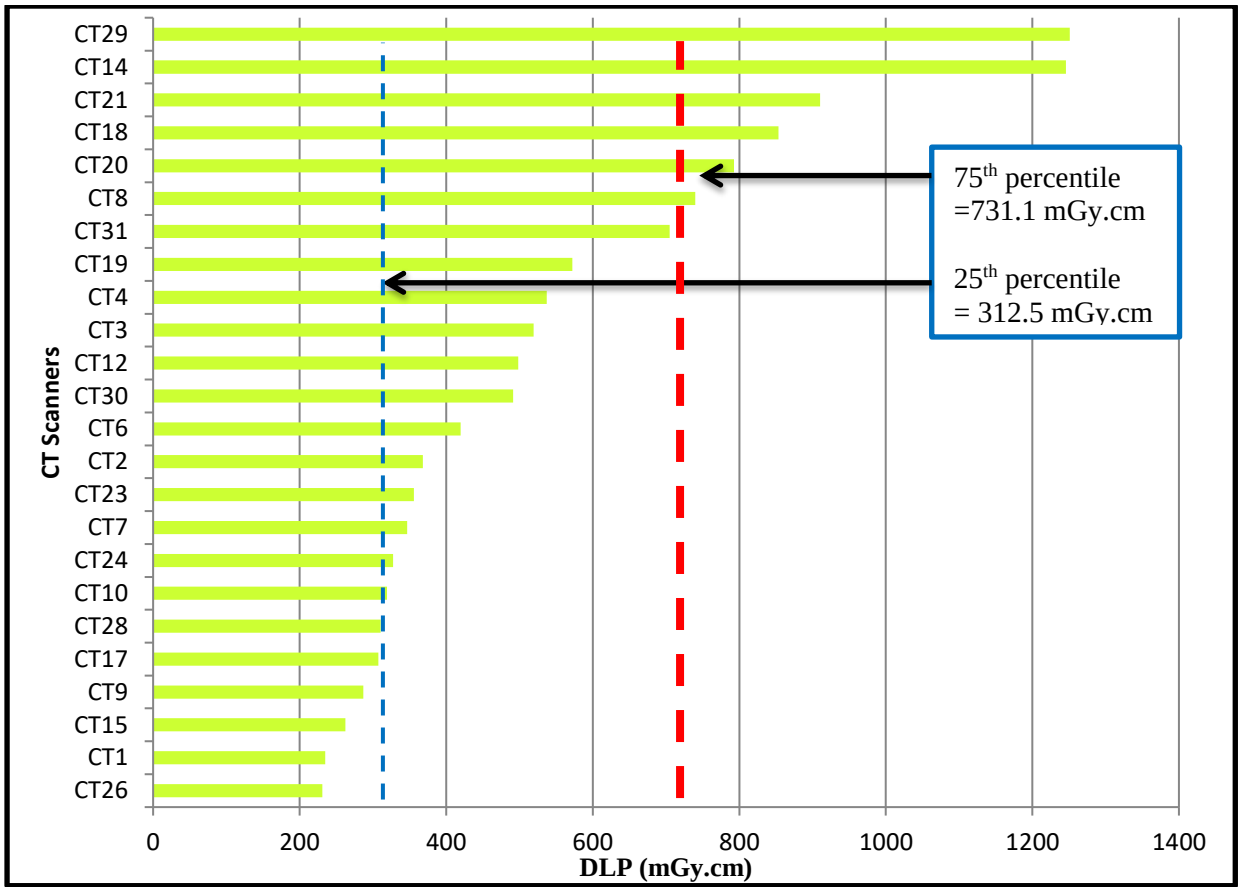


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.18: Distribution of $CTDI_{vol}$ values for CT of values for kidney stone indication

Table 4.43: Descriptive statistics of representative DLP values for CT of kidney stone indication

Total Scanners	AD	DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
24		455.4	231.2	1251.2	296.4



The DLP values are from 1 sequence (Non-contrast examination). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.19: Distribution of DLP values for CT of kidney stone indication

Table 4.44: A comparison of indication-based DRL values for CT of kidney stone indication with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	15	731*	6.7 ± 1.4
Public Health England, 2016 (UK)	10	460*	-
Lajunen (2015 (FI)	7	330*	-
Wachabauer et al., 2017 (AU)	-	329*	-

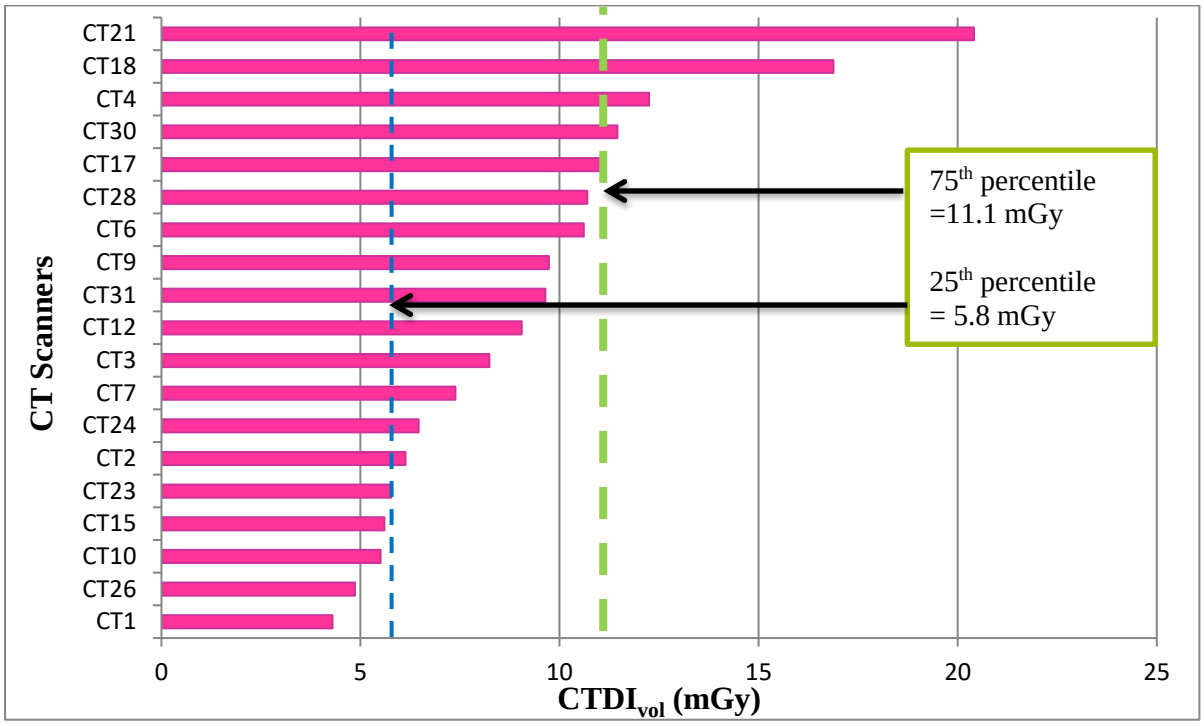
**=Single sequence procedure; UK represents United Kingdom, FI represents Finland and AU represents the Australia. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

The projected 75th and 25th ($CTDI_{vol}$ and DLP) percentiles for CT of kidney stone have been displayed in red and blue dashed lines, respectively, in Figures 4.18 and 4.19. The median dose values ($CTDI_{vol}$) varied by a factor of 6, although they were all of acceptable image quality with a mean SNR of 6.7 ± 1.4. The suggested national $CTDI_{vol}$ DRL and the calculated $CTDI_{vol}$ achievable doses for CT of kidney stone are approximately 15 mGy and 10 mGy, respectively. Accordingly, the proposed national DLP DRL is approximately 731 mGy.cm. Additionally, the achievable DLP dose was approximately 455 mGy.cm. Values reported in the literature were generated from a single sequence as done in this study. However, the DRL values were higher than those reported by Public Health England (2016) ($CTDI_{vol}$ = 10 mGy; DLP = 460 mGy.cm), Lajunen (2015) ($CTDI_{vol}$ = 7 mGy; DLP = 330 mGy.cm), and Wachabauer et al. (2017) (DLP = 329 mGy.cm) respectively.

The descriptive statistics and projected DRL values for urothelial malignancy (CT-IVU) indication with respect to $CTDI_{vol}$ are presented in Table 4.45 and Figure 4.20 respectively, while those of DLP are shown in Table 4.29 and Figure 4.9. A comparison of developed DRL values ($CTDI_{vol}$ and DLP) for urothelial malignancy (CT-IVU) indications with international values are shown in Table 4.47.

Table 4.45: Descriptive statistics of representative $CTDI_{vol}$ values for CT of urothelial malignancy indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
19	9.1	4.3	20.4	4.2

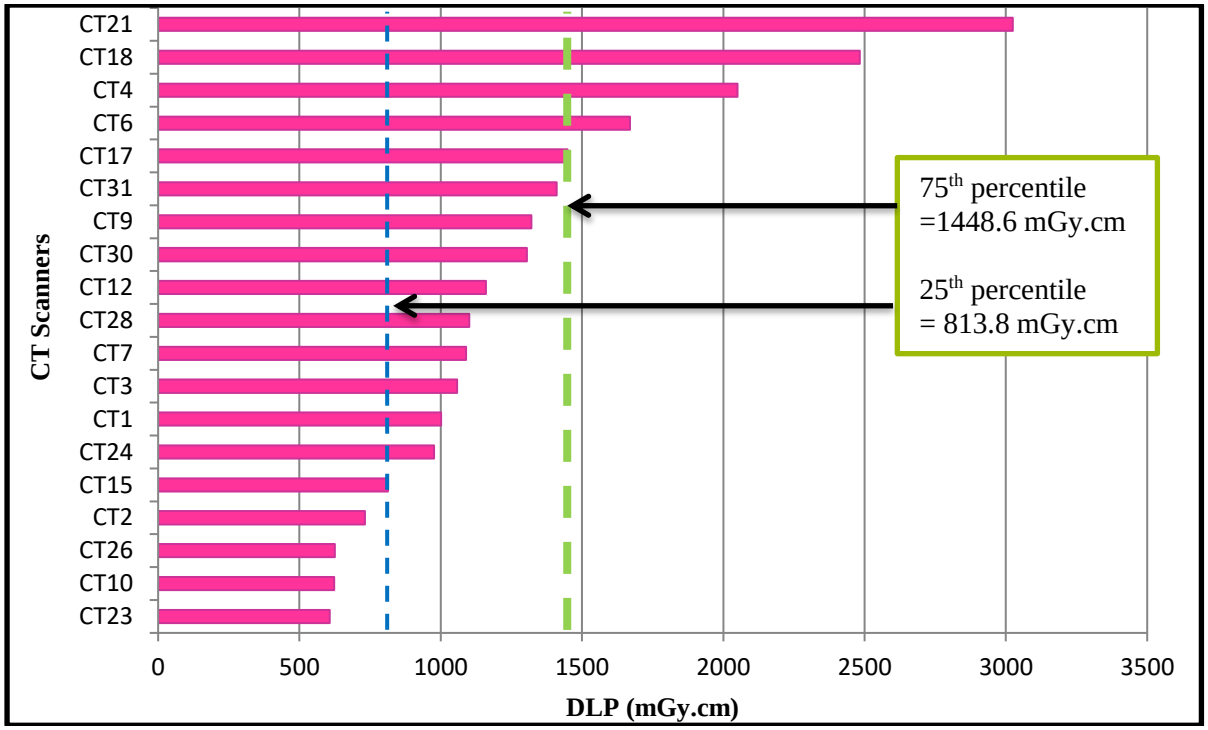


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.20: Distribution of $CTDI_{vol}$ values for CT of urothelial malignancy (CT-IVU) indication

Table 4.46: Descriptive statistics of representative DLP values for CT of urothelial malignancy indication

Total Scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
19	1101.4	607.6	3024.0	641.8



The DLP values are derived from between 2-4 sequences (Pre-contrast and 2-3 other post-contrast series). AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.21: Distribution of DLP values for CT of urothelial malignancy indication

Table 4.47: A comparison of indication-based DRL values for CT of urothelial malignancy indication/ CT-IVU with international values.

Country	75th percentile		Image quality
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Mean SNR
Current study (Ghana)	11	1449*+	10. 8 ± 2.4
Widmark, (2018), NO	13	1300?	-
Public Health England, (2016), UK	13	1150?	-
Lajunen (2015), (FI).	-	-	-
Van der Molen et al., (2013), (NL)	-	1371?	-

**+=2-4 sequences (pre-contrast and 2-3 other post-contrast series),? = undeclared number of sequences. NO represents Norway, UK represents United Kingdom, FI represents Finland and NL represents Netherlands. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

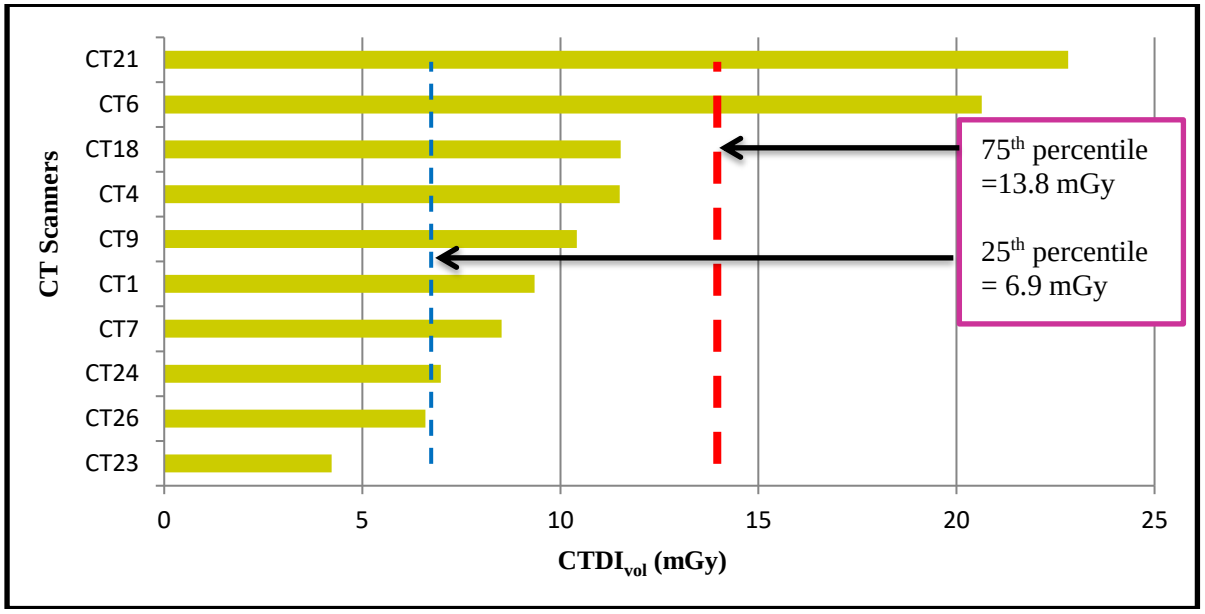
Nineteen CT facilities undertook CT-IVU scanning mainly for the urothelial malignancy indication. A mean SNR of 10.8 ± 2.4 observed across the images suggested that good images were produced for such examinations in the facilities. The median dose observed across the facilities varied by a factor of 4.7. The estimated 75^{th} and 25^{th} ($CTDI_{vol}$ and DLP) percentiles for the CT-IVU (urothelial malignancy indication) procedure have been displayed in green and blue dashed lines, respectively, in Figures 4.20 and 4.21. Accordingly, the proposed national $CTDI_{vol}$ DRL for urothelial malignancy (CT-IVU) indication was approximately 11 mGy, while the achievable $CTDI_{vol}$ dose was approximately 9 mGy. The projected national DLP DRL for the same indication was approximately 1449 mGy.cm, whereas the achievable DPL dose was approximately 1101 mGy.cm.

Comparatively, the DRL ($CTDI_{vol}$) value CT for urothelial malignancy from this study was lower than the established value of 13 mGy in Norway (Widmark, 2018) and the UK (Public Health England, 2016). Interestingly, the corresponding DRL value in terms of DLP was slightly higher than values from their counterparts (Table 4.47). It is worth noting that facilities in Ghana use 2-4 sequences (pre-contrast and 2-3 other post-contrast series) to produce diagnostic images in CT-IVU examinations for the detection of urothelial malignancy and its related conditions. However, there was a lack of information about the number of sequences used by other countries outlined in Table 4.47. Therefore, conclusions have to be drawn with caution.

Table 4.48 and Figure 4.22 present the descriptive statistics and projected DRL values with respect to $CTDI_{vol}$ for PE, respectively. The respective DRL values with respect to DLP are also presented in Table 4.49 and Figure 4.23. A comparison of developed DRL values ($CTDI_{vol}$ and DLP) for PE with international values is shown in Table 4.44.

Table 4.48: Descriptive statistics of representative $CTDI_{vol}$ values for CT of pulmonary embolism indication

Total scanners	AD $CTDI_{vol}$ (mGy)	Min. median $CTDI_{vol}$ (mGy)	Max. median $CTDI_{vol}$ (mGy)	SD
10	9.9	4.2	22.8	6.0

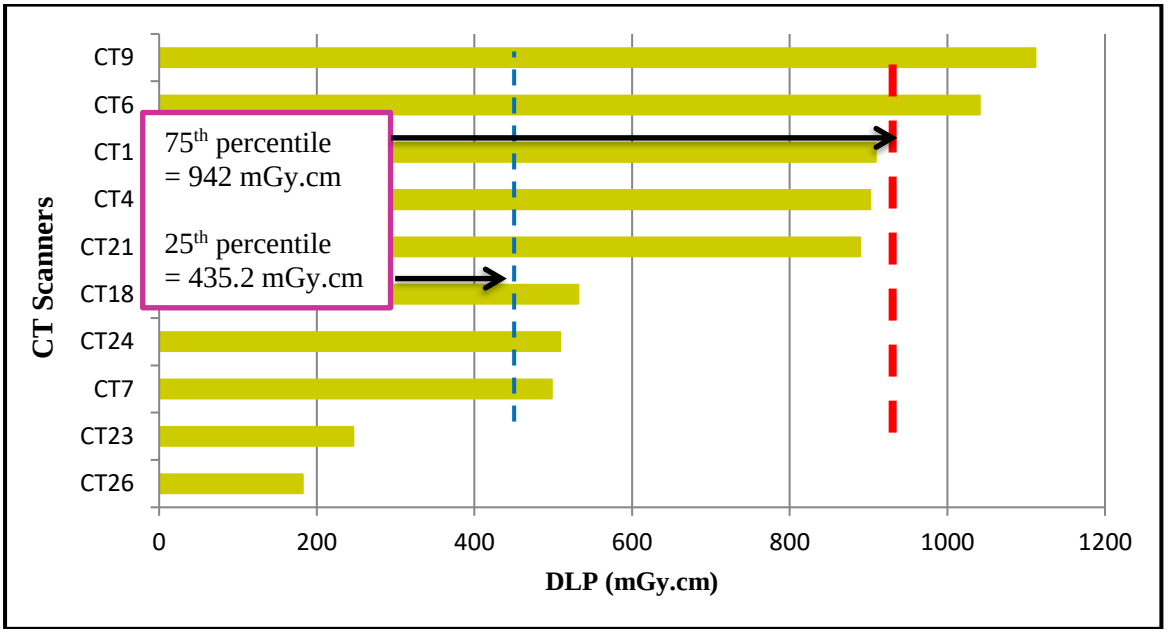


AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.22: Distribution of $CTDI_{vol}$ values for CT of pulmonary embolism indication

Table 4.49: Descriptive statistics of representative DLP values for CT of pulmonary embolism indication

Total scanners	AD DLP (mGy.cm)	Min. median DLP (mGy.cm)	Max. median DLP (mGy.cm)	SD
10	710.6	184.0	1111.7	330.4



The DLP values are derived from between 1-2 sequences (Pre-contrast phase and actual PE phase). The monitoring phases are not included as it is the situation for all established DRLs. AD: Achievable dose; $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product, SD: standard deviation, Min: minimum, Max: maximum.

Figure 4.23: Distribution of DLP values for CT of PE indication

Table 4.50: A comparison of indication-based DRL values for CT of pulmonary embolism indication with international values.

Country	75th percentile		Image quality Mean SNR
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	
Current study (Ghana)	14	942+	12.5 ± 5.1
Public Health England, (2016), UK	13	440*	-
Foley et al., (2012), IR	13	432*	-
Kanal et al., (2017), USA	19	557*	-
Schegerer et al., (2017), DE	15	300*	-
Van der Molen et al., (2013), NL	-	371*	-
Wachabauer et al., (2017), AU	-	400*	-

**=Single sequence procedure; + =1-2 sequences (pre- and post-contrast). UK represents United Kingdom, IR represents Ireland, USA represent the United States of America, DE represents Germany, NL represents the Netherlands, AU represents Australia. SNR: Signal to noise ratio, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.*

The DRL values for PE are presented in Figures 4.22 and 4.23, and the 75^{th} and 25^{th} percentile ($CTDI_{vol}$ and DLP) values have been displayed in red and blue dashed lines, respectively. The results showed that the proposed national $CTDI_{vol}$ DRL for PE was about 14 mGy. Approximately 10 mGy was found to be the achievable $CTDI_{vol}$ dose value for PE CT examination. In terms of the DLP descriptor, the proposed NDRL for CT of PE was approximately 942 mGy.cm. The achievable DLP for PE was also estimated to be approximately 711 mGy.cm. The image quality in terms of mean SNR value (12.5 ± 5.1) was considered acceptable across the images, although the dose levels varied by a factor 5.4.

The projected $CTDI_{vol}$ DRL value was lower than those reported in the USA (19 mGy) and Germany (15 mGy), but higher than those reported in UK (13 mGy) and Ireland (13 mGy). The corresponding DLP was, however, higher than those reported in the UK (440 mGy.cm), Ireland (432 mGy.cm), USA (557 mGy.cm), Germany (300 mGy.cm), Netherlands (371 mGy.cm) and Australia (400 mGy.cm) (Public Health England, 2016; Foley et al., 2012; Kanal et al., 2017; Schegerer et al., 2017; Van der Molen et al., 2013; Wachabauer et al., 2017).

The projected indication-based DRL values as outlined are recommended for adoption and implementation by the NRA in collaboration with relevant professional bodies for dose management and accountability of CT imaging in Ghana. The national values may be revised at regular intervals (every 5 years), especially when significant changes in technology and new imaging procedure standards and protocols are available.

For an effective implementation of the proposed DRLs, a Microsoft Excel-based tool (**BOT^{B}**) for inspection and monitoring of DRL compliance purposes was developed in this study. An interphase of the tool is presented in Figure 4.24.

MONITORING RADIATION DOSE LEVELS FOR CT BRAIN TUMOUR/SOL PROCEDURES

NIBDRLV

Percentile	$CTDI_{vol}$	DLP
75%	77	2696
25%	39	1291

CONDITION: Adults 18 ≥ ;Weight 50 ≤ X ≤ 90 kg

$CTDI_{vol}$ (mGy), DLP (mGy.cm), Sequnce: 2

RESULTS INTERPRETATION/ACTION	
BLACK	PASS
BLUE	PASS, IMAGE QUALITY TEST REQUIRED
RED	FAIL, INVESTIGATION & OPTIMISATION REQUIRED

RESULTS

YEAR	Median $CTDI_{vol}$	Median DLP	75th per.$CTDI_{vol}$	75th per.DLP
2019	68	683.5	77.25	975
2020	34	1001.5	36.5	1450
2021				
2022				
2023				
2024				
2025				
2026				
2027				
2028				
2029				
2030				
2031				

HOSPITAL NAME	CT MODEL/mfr	DETECTOR ROW
A	Toshiba Aquilion one	320

2019					2020				
INSPECTOR			CONTACT: TEL		INSPECTOR		CONTACT:TEL		
Benard Botwe			23324402365						
Date	Age(y)	Weight(kg)	$CTDI_{vol}$	$DLP_{(T)}$	Date	Age(y)	Weight(kg)	$CTDI_{vol}$	$DLP_{(T)}$
20-Jun-19	77	80	90	900		65	78	45	1455
20-Jun-19	77	70	60	1990		56	77	34	1450
20-Jun-19	66	50	10	1200		75	67	33	1234
20-Jun-19	75	89	58	689		55	56	24	678
20-Jun-19	65	78	56	678		47	78	24	678
20-Jun-19	56	77	67	678		65	77	23	567
20-Jun-19	75	67	76	567		45	67	12	568
20-Jun-19	55	56	66	568		65	78	45	589
20-Jun-19	47	78	45	589		43	56	41	769
20-Jun-19	65	77	77	769		65	78	35	700
20-Jun-19	45	67	66	700		56	77	34	556
20-Jun-19	65	78	77	556		75	67	43	455
20-Jun-19	43	56	66	455		55	56	34	678
20-Jun-19	43	55	78	678		47	78	21	1455
20-Jun-19	4	65	81	356		65	77	34	1450
20-Jun-19	67	65	56	555		45	67	43	1234
20-Jun-19	49	60	69	2345		65	78	23	1455
20-Jun-19	56	67	69	2345		43	56	31	1450
20-Jun-19	56	67	80	1239		75	89	34	1234
20-Jun-19	66	70	86	778		65	78	32	1234

CVA | H trauma | BTSOL | Lung T | CHEST LESION CKD | ABDOMINOPELVIC LESION | KIDNEY STONE | CT IVU | F ...

Figure 4.24: Interphase of a Microsoft Excel-based developed tool (BOT^B) for inspection and monitoring of DRLs compliance purposes.

The tool (**BOT^{B}**) shown in Figure 4.24 has been developed for each indication-based DRL. The interphase enables input of demographic data (such as age, weight, etc.), and dose output/descriptor ($CTDI_{vol}$, DLP) data. The dose output data entries are calculated automatically for 75^{th} and 25^{th} percentiles. The results are displayed in the 'results' section of the interphase. Results displayed in black and red are interpreted as pass (within National indication-based DRL value [NIBDRLV]) and fail (above NIBDRLV), respectively. A blue coloured displayed result indicates that a facility's doses are below the 25^{th} percentile and hence, image quality tests are required to ensure examinations of acceptable diagnostic image quality are produced.

Once the developed indication-based DRLs in this study are approved and duly implemented by the appropriate authority, such as the NRA, this simple tool could be used as part of the NRA's QMS to encourage DRLs compliance purposes. Crucially, individual facilities could also use this tool for internal audit purposes to monitor their compliance to NIBDRLV and where necessary, corrective actions could be taken when typical patient dose output values are higher than the indication-based DRLs.

4.5 PHASE 5: Dose Impact and Estimation of Cancer Risk Associated with the Doses

Effective doses and cancer risks were estimated for purposes of understanding the impact of the dose associated with each of the indications. The results are presented in Tables 4.51-4.56.

Table 4.51: Indication-specific effective doses and their equivalent background radiation levels

Indications	Effective dose, $E_{D,}$ (mSv)			
	Non-contrast phase Mean± SD	Contrast phase Mean± SD	Overall for examination Mean± SD	Background radiation equivalent*
CVA/stroke	2.23 ± 0.80	-	2.23 ± 0.80	11 months
Head trauma/Injury	2.73 ± 1.20	-	2.73 ± 1.20	13.7 months
Brain tumour/ SOL	2.27 ± 0.90	2.26 ± 0.90	4.53 ± 1.70	22.7 months
Lung tumour/cancer	5.50 ±1.51	5.10 ± 0.50	10.37 ± 3.10	4.3 years
Chest lesion with CKD	5.40 ± 3.00	-	5.40 ± 3.00	27 months
Abdomino-pelvic lesion	8.30 ± 5.24	8.87 ± 5.18	17.17 ±10.00	7.2 years
Kidney stones	8.51 ± 5.01	-	8.51 ± 5.01	3.5 years
Urothelial malignancy (CT-IVU)	6.71± 3.78	14.26 ± 8.74	20.09 ± 12.19	8.4 years
Pulmonary angiogram	5.04 ± 4.50	6.56 ± 3.70	11.61± 6.5	4.8 years

**Average yearly natural background radiation used ≈ 2.4 mSv (Canadian Nuclear Safety Commission, 2019). CVA: cerebrovascular accident, CKD: chronic kidney disease, SD: standard deviation, E_D: effective dose.*

The estimated mean effective doses (Table 4.51) for single phase (non-contrast) procedures were generally lower than multiple phase (both contrast and non-contrast) procedures, due to the number of examination series. The result was consistent with that previously reported (Smith-Bindman et al., 2009). The highest (20.09 ± 12.19 mSv) and least (2.23 ± 0.80 mSv) mean effective doses were recorded for the CT-IVU examination for diagnosing urothelial malignancy, and CVA/stroke procedure, respectively. The doses associated with these two examinations differ by a factor of 9. The results further showed that the high dose examinations could subject a patient to radiation levels equivalent to 8.4 years of natural background radiation. Radiation dose optimisation is therefore very important in CT imaging.

Table 4.52: Various organ doses associated with the CT imaging for the CVA, head trauma/Injury and brain tumour/SOL indications

Organ	Organ doses (mGy)								
	CVA			Head trauma/Injury			Brain tumour/ SOL		
	20 yrs	40 yrs	60 yrs	20 yrs	40 yrs	60 yrs	20 yrs	40 yrs	60 yrs
	Mean± SD	Mean±SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD
Brain	40.2 ± 17.3	39.2±14.4	39.9±14.2	40.2 ±13.4	42.6± 13.5	43.7 ±14.5	84.5± 27.9	81.9 ± 26.2	82.2 ± 31.1
Pituitary gland	32.9 ± 10.7	32.4±12.9	33.5±11.8	36.6 ±12.4	38.3± 13.1	37.1 ± 12.0	68.1± 24.5	67.7 ± 22.8	67.7 ± 23.7
Lens	46.7 ± 18.0	44.7±18.8	46.5±17.6	47.9 ±15.7	50.7± 16.2	51.2± 16.9	94.0 ±37.3	94.0 ± 33.6	95. 5 ± 34.8
Eyeballs	44.4 ± 17.4	43.0±16.7	44.5±16.0	45.6 ±15.0	48.1±15.4	48.7 ± 16.1	90.9 ±33.3	90.8± 29.4	90.9 ± 33.2
Salivary glands	21.9 ± 17.9	19.9±15.5	17.1±13.3	35.2 ±20.2	37.1± 21.4	32.3 ± 16.7	43.9 ±28.2	40.0± 24.8	42.5 ± 23.6
Oral cavity	14.5 ± 14.9	11.6 ±11.3	10.8±11.2	26.8±16.6	28.8± 18.4	24.8 ± 15.6	28.1± 21.4	25.5 ± 20.7	25.1±17.1
Spinal cord	3.7 ± 4.6	3.2 ± 1.8	2.5±2.7	7.0±6.3	6.9± 6.3	6.2 ± 5.1	8.2 ±9.1	5.4 ± 4.6	5.5 ± 3.9
Thyroid	2.3 ± 3.7	1.2±1.1	1.1±1.3	8.5±9.7	4.2± 6.3	5.8± 2.2	4.8 ±4.0	4.4 ± 2.4	2.4 ± 1.7

CVA: cerebrovascular accident, SOL: space occupying lesion, SD: standard deviation, Yrs: years

The results in Table 4.52 indicated that varying amounts of organ doses were delivered to patients of different ages during CT imaging for various head indications. The lenses of the eye in particular, were impacted the most among all the organs in the head region. For the CVA indication, the mean lens doses were 46.7 mGy, 44.7 mGy and 46.5 mGy for patients aged 20, 40 and 60 years old, respectively. The upper range value was lower than the upper limit (41.7-71.0 mGy) as reported by a study (Yamauchi-Kawara et al., 2010) for similar examination.

The higher mean lens doses of 47.9 mGy, 50.7 mGy and 51.2 mGy were recorded for 20, 40- and 60-years old patients in head injury examinations, respectively. Brain tumour/ SOL imparted the highest lens dose of 94.0 mGy, 94.0 mGy and 95.5 mGy in patients of the stated age categories, respectively. The lens doses were relatively high because the gantry angulation needed to project the lenses out of the primary beam during head CT imaging was often not utilised at various facilities. According to a study (Nikupaavo et al., 2015), head CT imaging performed with gantry angulation of 15-20^{o} to project the x-ray beam parallel to the infraorbitomeatal line effectively reduced lens doses. Apart from the lenses, other organs which were greatly impacted by head related CT radiation in a descending order were: eyeballs, brain, pituitary gland, salivary glands, oral cavity, spinal cord and thyroid.

Table 4.53: Various organ doses associated with CT imaging for lung tumour/cancer, chest lesion with CKD and PE indications

Organ	Organ doses (mGy)								
	Lung tumour/cancer			Chest lesion with CKD			PE		
	20 yrs	40 yrs	60 yrs	20 yrs	40 yrs	60 yrs	20 yrs	40 yrs	60 yrs
	Mean± SD	Mean± SD	Mean± SD	Mean±SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD	Mean± SD
Thyroid	29.4 ± 15.6	40.5 ± 24.8	38.1 ± 21.4	15.9 ± 9.8	20.0 ±11.5	20.4 ± 10.7	36.7 ± 32.9	22.9 ± 10.4	26.7 ± 13.9
Oesophagus	17.3 ± 8.7	25.6 ± 15.9	24.1 ± 13.8	9.2 ± 5.7	12.5 ± 7.1	12.9 ± 6.8	24.4 ± 21.9	14.5 ± 6.2	17.0 ± 8.8
Trachea	22.4 ± 12.0	30.81 ± 8.8	29.0 ± 16.3	12.1 ± 7.6	15.2 ± 8.8	15.5 ± 8.2	27.7 ± 24.8	17.5 ± 7.9	20.3 ± 10.4
Thymus	24.9 ± 13.9	33.7 ±20.3	31.9 ± 17.9	13.7 ± 8.7	16.7 ± 9.7	17.1 ± 9.0	29.2 ± 26.2	19.2 ± 8.9	22.1 ± 10.9
Lungs	21.3 ± 11.0	31.2± 19.0	29.6 ± 16.7	11.5 ± 7.2	15.2 ± 8.7	15.8 ± 8.3	28.8 ± 25.8	17.7 ± 7.7	20.5 ± 10.2
Breast	17.8 ± 11.4	29.2 ± 18.0	27.5 ± 15.5	9.7 ± 7.3	14.0 ± 8.5	14.7 ± 7.7	27.0 ± 24.2	16.5 ± 7.3	19.3 ± 10.0
Heart wall	21.7 ± 12.3	32.8 ± 20.0	31.1 ± 17.6	11.8 ± 7.7	15.9 ± 9.3	16.7 ± 8.8	30.3 ± 27.1	18.7 ± 8.1	21.4 ± 10.4

CKD: chronic kidney disease, PE: pulmonary embolism, SD: standard deviation, Yrs: years.

Table 4.53 indicated that the highest organ dose during CT imaging for lung tumour/cancer, chest lesion with CKD and PE was received by the thyroid gland, which is sensitive to the carcinogenic effect of ionising radiation. The mean ranges of thyroid dose for the various indications were 20.4-40.5 mGy (lung tumour/cancer), 15.9-40.4 mGy (chest lesion with CKD), and 22.9-36.7 mGy (PE). Relatively lower mean organ doses in the ranges of 17.8-29.2 mGy and 21.3-31.2 mGy were received by the breast and lungs in lung tumour/cancer examinations, respectively. A previous study (Saltybaeva et al., 2016) however, reported a lower lung dose of 8.6 mGy for 60-year-old patients undergoing lung tumour/cancer CT imaging.

The organ doses for the breast and lungs ranged from 16.5-27.0 mGy and 17.7-28.8 mGy, and from 9.7-14.7 mGy and 11.5-15.8 mGy, for PE, and chest lesion with CKD indicated examinations, respectively. A recent study (Haspi et al., 2019) in Malaysia reported lower breast organ dose range of 10.9-23.8 mGy and lung organ dose range of 10.6- 23.4 mGy during PE examination. Other ograns such as oesophagus, trachea, thymus and heart wall also received mean organ doses in a range of 11.8-32.8 mGy across the indications in the chest region.

Table 4.54: Various organ doses associated with CT imaging for AP lesion, kidney stones and urothelial malignancy indications

Organ	Organ doses (mGy)								
	AP lesion			Kidney stones			Urothelial malignancy		
	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD
Stomach wall	39.3 ± 25.8	39.0 ± 22.8	38.3 ± 22.8	17.2 ±11.1	17.2 ± 10.4	16.3 ± 9.9	38.0 ± 24.1	49.5 ± 30.2	51.7 ± 30.2
Liver	37.9 ± 25.1	37.7 ± 22.2	37.2 ± 22.2	16.7 ±10.8	16.7 ± 10.2	15.6 ± 9.5	36.6 ± 23.3	49.1 ± 29.5	49.6 ± 28.9
Gall bladder	35.6 ± 22.8	35.5 ± 20.2	35.5 ± 21.1	15.6 ± 9.9	15.7 ± 9.0	15.1 ± 9.4	34.9 ± 21.9	46.4 ± 27.6	47.7 ± 28.3
Adrenals	32.7 ± 20.9	32.7 ± 18.5	32.7 ± 19.4	14.3 ± 9.0	14.4 ± 8.2	13.9 ± 8.7	32.1 ± 20.1	42.8 ± 25.6	44.0 ± 26.1
Spleen	36.6 ± 24.0	36.4 ± 21.3	36.1 ± 21.5	16.1 ±10.4	16.1 ± 9.7	15.2 ± 9.3	35.5 ± 22.5	47.3 ± 28.3	48.2 ± 28.2
Pancreas	38.0 ± 25.4	37.8 ±22.5	37.2 ± 22.3	16.7±10.9	16.7 ± 10.3	15.6 ± 9.5	36.7 ± 23.4	49.0 ± 29.4	49.5 ± 28.8
Kidney	39.9 ± 25.7	39.8 ±22.8	39.7 ± 23.6	17.5±11.1	17.6 ± 10.2	16.8 ± 10.4	39.0 ± 24.5	51.7 ± 30.7	53.3 ± 31.5
Small intestine	39.9 ± 25.1	40.2 ±22.3	40.4 ± 24.1	17.6±11.0	17.8 ± 9.9	17.3 ± 10.9	39.7 ± 24.8	52.0 ± 30.4	54.9 ± 33.0
Colon	41.7 ± 26.4	41.8 ±23.4	41.9 ± 24.9	18.3±11.5	18.5 ± 10.4	17.9 ± 11.2	41.1 ± 25.7	54.4 ± 32.1	56.7 ± 33.8
Rectosigmoid	29.8 ± 19.0	32.5 ±17.7	32.3 ± 20.0	13.9 ± 9.1	14.3 ± 7.8	13.6 ± 8.7	32.2 ± 20.2	39.7 ± 24.7	45.5 ± 28.4
U. Bladder	34.0 ± 21.9	37.4 ±21.2	36.2 ± 22.1	16.2±10.6	16.3 ± 9.5	15.0 ± 9.2	36.2 ± 23.0	43.4 ± 26.3	50.9 ± 30.9
Prostate	8.1 ± 10.9	11.0 ±14.2	12.1 ± 16.2	4.2 ± 6.1	4.6 ± 5.6	5.5 ± 7.0	11.3 ± 15.8	14.1 ± 21.3	22.6 ± 27.6
Uterus	13.9 ± 19.2	15.3 ±19.4	12.0 ± 17.1	7.0 ± 9.1	6.6 ± 9.2	3.8 ± 5.7	12.7 ± 18.6	16.2 ± 18.7	13.5 ± 19.4
Testes	1.6 ± 3.1	2.1 ± 3.8	3.8 ± 8.0	0.6 ± 0.9	1.0 ± 2.3	2.0 ± 5.7	1.6 ± 2.4	1.9 ± 3.4	5.0 ± 7.0
Ovary	14.9 ± 20.5	16.3 ±20.6	12.8 ± 18.2	7.5 ± 9.6	7.0 ± 9.8	4.1 ± 6.1	13.5 ± 19.8	16.1 ± 19.6	14.4 ± 20.7
Skin	11.2 ± 7.2	11.8 ± 6.5	12.0 ± 7.2	5.1 ± 3.4	5.3 ± 3.0	5.0 ± 3.0	11.6 ± 7.1	14.1 ± 8.5	16.5 ± 9.7
Muscle	12.7 ± 8.3	13.6 ± 7.5	13.8 ± 8.5	5.9 ± 4.0	6.1 ± 3.5	5.6 ± 3.5	13.4 ± 8.2	16.6 ± 9.3	19.1 ± 11.3
*Act. marrow	16.9 ± 11.0	17.5 ±10.1	17.2 ± 10.3	7.5 ± 5.0	7.6 ± 4.6	7.1 ± 4.4	17.0 ± 10.8	21.6 ± 12.5	23.4 ± 13.9
$^{+}$S. marrow	14.5 ± 9.6	13.8 ± 8.1	14.2 ± 8.6	5.9 ± 3.1	6.4 ± 4.1	5.8 ± 3.5	14.1 ± 9.2	18.3 ± 10.7	19.3 ±11.3

**Act. = Active marrow; $^{+}$S = Shallow; AP= abdominopelvic, SD = standard deviation, Yrs = years.*

Table 4.54 explains that many organ doses were estimated for CT examinations involving AP lesion, kidney stones and urothelial malignancy. These organs included very radiosensitive ones such as colon, uterus, testes, ovary, active marrow and shallow marrow, among others.

The highest organ dose for CT imaging was received in the colon associated with AP lesion (41.7-41.9 mGy), kidney stones (17.9 - 18.5 mGy) and urothelial malignancy (41.1 - 56.7 mGy) across all ages (20, 40 and 60 years old). A study (Pai et al., 2018) also reported colon organ doses of 9.33-24.2 mGy in kidney stones indicated CT imaging, with an upper limit 30.8% higher than the observed value in this study.

Table 4.55: Cancer and mortality risks associated with CT doses for lung tumour/cancer, lung lesion with CKD and PE indications.

Cancer site	Lung tumour/cancer				Chest lesion with CKD			PE		
	Ages (yrs)	Organ dose (mGy)	LARi/ 100,000	LARm/ 100,000	Organ dose (mGy)	LARi/ 100,000	LARm/ 100,000	Organ dose (mGy)	LARi/ 100,000	LARm/ 100,000
Lung	20	21.3 ± 11.0	52.7	48.6	11.5 ± 7.2	28.5	26.2	28.8 ± 25.8	71.3	65.7
	40	31.2 ± 19.0	53.7	49.8	15.2 ± 8.7	26.1	24.2	17.7 ± 7.7	30.4	28.2
	60	29.6 ± 16.7	42.9	40.8	15.8 ± 8.3	22.9	21.8	20.5 ± 10.2	29.7	28.3
Thyroid	20	29.4 ± 15.6	19.7	-	15.9 ± 9.8	10.7	-	36.7 ± 32.9	24.6	-
	40	40.5 ± 24.8	10.1	-	20.0 ± 11.5	5.0	-	22.9 ± 10.4	5.7	-
	60	38.1 ± 21.4	20.6	-	20.4 ± 10.7	0.1	-	26.7 ± 13.9	0.2	-
Breast	20	17.8 ± 11.4	76.4	18.0	9.7 ± 7.3	41.6	10.0	27.0 ± 24.2	115.8	27.3
	40	29.2 ± 18.0	41.2	10.2	14.0 ± 8.5	19.7	4.9	16.5 ± 7.3	23.3	5.8
	60	27.5 ± 15.5	8.5	2.5	14.7 ± 7.7	5.3	1.3	19.3 ± 10.0	6.0	1.8

LARi: lifetime attributable risk of cancer incidence, LARm: Lifetime attributable risk of cancer mortality, CKD: chronic kidney disease, PE: pulmonary embolism, Yrs: years.

The risks of radiation-induced lung, thyroid and breast cancer incidence and mortality from CT imaging of the investigated indications were relatively low as upper LAR values were within 1 in 10,000 to 1 in 1,000 of the population (Table 4.55). However, the risk of PE radiation-induced breast cancer was moderate (1 in 1,000 to 1 in 500) (Varghese et al, 2019). In particular, the LAR of lung cancer incidence for patients aged 20, 40 and 60 years old due to CT scans for lung tumour/cancer detection were 52.7, 53.7 and 42.9 in 100,000 patients, respectively. Their corresponding risk of death was 48.6, 49.8 and 40.8 in 100,000 patients, respectively. For patients who received radiation for chest lesion with CKD indication, the populations in 100,000 patients likely to develop lung cancer were 28.5 (among 20 years old), 26.1 (among 40 years old) and 22.9 (among 60 years old); and possibly deaths were 26.2, 24.2 and 21.8, respectively. The risk of developing PE examination-induced lung cancers and resulting in death were more likely in the 20 years group compared with their counterparts who received radiation from other indications in the chest region. Numerically, 71.3 (among 20-years old), 30.4 (among 40 years old) and 29.7 (among 60 years old) were likely to develop lung cancer, from which 65.7, 28.2 and 28.3 were likely to die, respectively.

The number of patients at risk of developing thyroid cancer from CT of lung tumour/cancer, chest lesion with CKD and PE ranged from 10.1-20.6, 0.1-10.7 and 0.2-24.6 in 100,000 patients, respectively. Radiation induced-breast cancer from CT of lung tumour/cancer was also likely in 76.4 (among 20 year old), 41.2 (among 40 years old) and 8.5 (among 60 years old) patients among a population of 100,000, while, 18.0, 10.2 and 2.5 were likely to die, respectively. Radiation subjected to patients for chest lesion with CKD and PE examinations were likely to induce breast cancer in 5.3-41.6 (1 in 18,868 to 1 in 2,404) and 6.0-115.8 (1 in 16,667 to 1 in 857) patients per 100,000 procedures, respectively. The corresponding likely radiation-induced cancer deaths were estimated at 1 in 76,923 to 1 in 10,000 patients for chest lesion with CKD and 1 in 55,556 to 1 in 3,663 patients for PE examinations.

Table 4.56: Cancer and mortality risks associated with CT doses for AP lesion, kidney stones and urothelial malignancy

Cancer site		AP lesion			Kidney stone			Urothelial malignancy/CT-IVU		
	Age (yrs)	Organ dose (mGy)	LARi/ 100,000	LARm /100,000	Organ dose (mGy)	LARi/ 100,000	LARm /100,000	Organ dose (mGy)	LARi/ 100,000	LARm /100,000
Stomach	20	39.3 ± 25.8	18.1	9.8	17.2 ± 11.1	7.9	4.3	38.0 ±24.1	17.5	9.5
	40	39.0 ± 22.8	10.5	6.6	17.2 ± 10.4	4.6	3.0	49.5 ±30.2	13.4	8.7
	60	38.3 ± 22.8	7.7	3.0	16.3 ± 9.9	3.3	2.2	51.7 ±30.2	10.3	7.0
Liver	20	37.9 ± 25.1	8.3	6.6	16.7 ±10.8	3.7	2.9	36.6 ±23.3	8.1	6.4
	40	37.7 ± 22.2	7.9	4.5	16.7 ± 10.2	3.5	2.0	49.1 ±29.5	10.3	5.9
	60	37.2 ± 22.2	5.2	3.5	15.6 ± 9.5	2.2	1.5	49.6 ±28.9	6.9	4.7
Colon	20	41.7 ± 26.4	59.8	28.6	18.3 ±11.5	26.3	12.5	41.1 ±25.7	59.0	28.2
	40	41.8 ± 23.4	51.0	20.3	18.5 ± 10.4	22.6	9.0	54.4 ±32.1	66.4	26.4
	60	41.9 ± 24.9	39.4	16.8	17.9 ± 11.2	16.8	7.2	56.7 ±33.8	53.3	22.7
Prostate	20	8.1 ± 10.9	3.8	0.7	4.2 ± 6.1	2.0	0.4	11.3 ±15.8	5.4	1.0
	40	11.0 ± 14.2	3.9	0.7	4.6 ± 5.6	1.6	0.3	14.1 ±21.3	5.0	0.8
	60	12.1 ± 16.2	3.2	0.9	5.5 ± 7.0	1.4	0.4	22.6 ±27.6	6.0	1.6
Leukaemia	20	16.9 ± 11.0	14.1	10.0	7.5 ± 5.0	14.6	10.3	17.0 ±10.8	14.4	10.1
	40	17.5 ± 10.1	12.8	10.4	7.6 ± 4.6	12.8	10.5	21.6 ±12.5	12.5	10.2
	60	17.2 ± 10.3	12.0	11.0	7.1 ± 4.4	15.0	13.8	23.4 ±13.9	16.3	15.0
Urinary Bladder	20	34.0 ± 21.9	37.1	18.4	16.2 ± 10.6	17.7	4.4	36.2 ± 23.0	39.5	9.8
	40	37.4 ± 21.2	29.5	7.5	16.3 ± 9.5	12.9	3.3	43.4 ± 26.3	34.3	8.7
	60	36.2 ± 22.1	23.5	7.1	15.0 ± 9.2	9.8	2.9	50.9 ± 30.9	33.1	9.9
Uterus	20	13.9 ± 19.2	3.6	0.8	7.0 ± 9.1	1.8	0.42	12.7 ± 18.6	3.3	0.76
	40	15.3 ± 19.4	2.4	0.6	6.6 ± 9.2	1.1	0.31	16.2 ± 18.7	2.6	0.65
	60	12.0 ± 17.1	1.9	0.4	3.8 ± 5.7	0.3	0.11	13.5 ± 19.4	1.2	0.41
Ovary	20	14.9 ± 20.5	7.5	4.2	7.5 ± 9.6	3.8	2.1	13.5 ± 19.8	6.8	3.8
	40	16.3 ± 20.6	5.1	3.3	7.0 ± 9.8	2.2	1.4	16.1 ± 19.6	5.0	3.2
	60	12.8 ± 18.2	2.3	1.9	4.1 ± 6.1	0.7	0.6	14.4 ± 20.7	2.6	2.2

LARi: lifetime attributable risk of cancer incidence, LARm: Lifetime attributable risk of cancer mortality, AP: abdomino-pelvic, CT-IVU: computed tomography intravenous urography, Yrs: years.

Among the organs subjected to CT exposures for various indications in the abdominal and pelvic regions, radiation-induced colon cancer risks were highest and likely among 39.4 - 59.8 patients in 100,000 AP lesion procedures. The risk was even higher in CT-IVU examinations, in a range of 53.3- 66.4 patients in 100,000 procedures but were less (16.8-26.3 patients) in kidney stone procedures. Accordingly, the risk of radiation-induced colon mortality was common in CT-IVU than AP lesion and kidney stone procedures.

Although the organ dose likely to cause radiation-induced leukaemia was lower than that received by the urinary bladder across all indications, the LAR of leukaemia mortality was higher than those observed in the urinary bladder. This suggests a high likelihood of leukaemia mortality. The ovaries were likely to develop AP lesion radiation-induced cancer in 7.5/100,000 (1 in 13,000), 5.1/100000 (1 in 19,608), and 2.3/100,000 (1 in 43,478) people at age 20, 40 and 60 years, respectively. Kidney stone examinations were also likely to induce ovarian cancer in 3.8, 2.2 and 0.7 patients in a pool of 100,000 procedures at ages of 20, 40 and 60 years, respectively. More so, about 1 in 38, 462 to 1 in 14,706 patients were also likely to develop ovarian cancer due to CT-IVU examinations in Ghana. Since the ovaries contain reproductive information, it is indicative that hereditary effects were also possible in patients who received high ovarian doses. Although all the upper LAR values for all the indications were within 1 in 10,000 to 1 in 1,000 of the population and suggested a low radiation risk, there was a need for further optimisation to reduce the dose levels and risks, as noted by Varghese et al., (2019). This is because small individual risks applied to a large population could lead to a public health issue some years in the future (IAEA, 2018; Do, 2016).

4.6 PHASE 6: Optimisation Methods

As observed in the descriptive comparison, the developed NDRLs were relatively higher than some European values. Optimisation interventions were investigated to manage the observed dose levels to further reduce the radiation risks.

4.6.1 Optimisation method 1: Dose reduction through optimisation of scan length

The tolerable additional scan length (along the z-axis) provided above upper target (DAUT) and below lower target (DBLT) were first investigated and the results are presented in Table 4.57.

Table 4.57: Descriptive statistics of average extra scan length allowed above and below the target anatomic regions/areas.

Indication	Average extra scan length (mm)		
	DAUT	DBLT	Total DAUT+ DBLT
Routine CVA	8.1 ± 9.4	20.1 ± 13.7	28.2± 21.3
Head trauma/Injury	9.0 ± 12.9	40.1 ± 33.5	49.1 ± 25.4
Brain tumour/ SOL	7.1 ± 8.0	20.7 ± 14.8	27.8 ± 10.7
Lung tumour/cancer	24.1 ± 16.1	34.0 ± 17.0	58.1 ± 16.6
Chest lesion with CKD	22.0 ± 14.1	30.9 ± 15.2	52.9 ± 14.9
Abdominopelvic lesion	25.1 ± 16.4	23.6 ± 17.3	46.7 ± 17.1
Kidney stones	24.5 ± 17.8	20.1 ± 16.4	44.6 ± 17.3
Urothelial malignancy	27.7 ± 18.6	21.9 ± 16.6	49.6 ± 16.9
Pulmonary angiogram	30.0 ± 12.3	33.3 ± 19.0	63.3 ± 14.5

DAUT= Distance above upper target; DBLT= Distance below lower target; CVA= cerebrovascular accident; CKD =chronic kidney disease.

Table 4.57 shows that varying DAUT and DBLT values were used across the facilities for each indication. These have the potential to cause detrimental effects to patients. For CVA, the average DAUT and DBLT were 8.1± 9 mm and 20.1±13.7 mm, respectively, making a total of 28.2 ± 21.3 mm extra scan coverage along the z-axis and considered as unnecessary radiation

coverage. The estimated total average extra scan length ranged from 27.8 to 63.3 mm across all the indications. The largest extra total scan coverage of 63.3 ± 14.5 mm was recorded for PE examinations, while brain tumour/SOL (27.8 ± 10.7 mm) followed by routine CVA (28.2 ± 21.3 mm) were scanned with smaller extra total scan coverage. Moreover, the DBLT values recorded the highest extra scan coverage along the z-axis which suggested that more extra scan coverage was allowed at the distal part of the organ compared to the proximal part. The difference between the smallest and the largest extra total scan coverage was 2.3 folds. The results indicated the need to explore optimal scan coverage for indication-based CT procedures.

The results of a CT phantom-based study that explored optimal scan coverage for routine CVA imaging are presented in Table 4.58. Evaluated extra scan length (z-axis), mean scores for subjective image quality analysis, and level of agreement between raters are also presented.

4.6.1.1 Phantom-Based Optimisation study

Table 4.58: Extra scan length (z-axis) evaluated, mean scores for subjective image quality analysis, and level of agreement between raters in head region examination; routine CVA

Protocol/ image ID	Average extra scan length		$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SNR	% DLP reduction over current practice	Subjective image quality scores			
	DAUT (mm)	DBLT (mm)					Mean	SD	*ICC value*	*p-value*
A	8.1 ± 9.4	20.1 ±13.7	21.28	385.58	5.3	-	3.92	0.74		
B	0	0	21.28	323.87	5.3	16.0	3.92	0.67		
C	10*	0	21.28	307.17	5.4	22.0	3.92	0.74		
D	10	10	21.28	366.43	5.3	5.0	3.89	0.67	0.78	< 0.001
E	0	5	21.28	335.58	5.1	13.0	3.92	0.67		
F	5	5	21.28	345.15	5.2	10.5	3.90	0.67		

Key: * *= below the vertex, A= Average extra scan used across the CT facilities (approximately 8 mm above the vertex and 20 mm below the base of skull; B= No extra scan length above the vertex and below base of skull; C= 10 mm below the skull vertex and 0 mm below the base of skull at foramen magnum; D=10 mm above vertex and 10 mm below the base of skull; E= No extra scan lengths above the vertex and 5 mm extra scan lengths below the base of skull; F=5 mm extra scan length above the vertex and below the base of skull; DAUT= Distance above upper target; DBLT= Distance below lower target; ICC = Intraclass Correlation Coefficients;* $CTDI_{vol}$ *= volume weighted computed tomography dose index; DLP= dose length product, SD =Standard deviation.*

Among the scan coverage protocols (A-D) investigated, Table 4.58 indicates that image sets A, B, C and E had the highest subjective image quality with mean score of 3.92 each out of a maximum of 5. This indicated that they presented the best image quality among all evaluated protocol-based images. Image D also had a mean lower score of 3.89. Intraclass correlation coefficient tests were run using SPSS version 23.0 (SPSS Inc., Chicago, IL USA) to determine statistical agreement between the two raters about the image quality scores. Studies (Koo and Li, 2016; McHugh, 2012), have indicated that an ICC value of 0.78, $p < 0.001$ suggests a good agreement between the two raters. Hence, protocol C (a brain scan covering 10 mm below the vertex and 0 mm below the base of skull at foramen magnum) was considered a very suitable intervention for dose reduction in CVA CT imaging, since it produced a very good objective (SNR = 5.3) and subjective image qualities similar to the original protocol, and also generated the best dose output (DLP) reduction of 22.0% (Table 4.58).

4.6.1.2 Patient-Based Optimisation Study

A patient-based optimisation study was undertaken to evaluate the application of phantom results in clinical practice. The demographic characteristics of the patients used in this particular evaluation are presented in Table 4.59.

Table 4.59: Demographics and clinical history of the patients

Variables	Categories	*n*	%	Mean ± SD (yrs)	Range (yrs)
Age		-	-	57.92 ±15.9	28 – 92
Gender	Male	54	54	-	-
	Female	46	46	-	-
Weight	-	-	-	70.8 ± 10.3	50-90
Clinical CVA-based History	Suspicion of ischemic infarctions	41	41		
	Suspicion of recurrent bleed	15	15		
	Transient ischemic attack	7	7		
	Hemiparesis	5	5		
	Recurrent CVA	14	14		
	Haemorrhagic stroke	10	10		
	Hypertensive, mild stroke	8	8		

n= frequency, % = percentage, SD=standard deviation

The ages of the sample size of 100 patients used in the patient-based interventional study ranged from 28 to 92 years with a mean age of 57.92 ± 15.9 years. The weight range was 50 - 90 kg with a mean of 70.8 ± 10.3 kg. There were more males (54.0%) than females (46.0%). Ischemic infarction was presented as the clinical history of majority (41%) of them while 5% presented with signs of hemiparesis, which are both conditions relating to poor blood supply to the brain. Ischemic infarction is common because it accounts for about 68% of all strokes globally, while haemorrhagic types are 32% prevalent (Chugh, 2019).

Table 4.60 shows the results of the measured SNR and subjective image quality scores for full and reduced CVA CT procedures.

Table 4.60: Measured SNR and subjective image quality scores for full range and reduced range CVA CT procedures

Protocol/ image ID	SNR	Subjective image quality scores		
	Mean ± SD, Range	Mean ± SD	*ICC value*	*p-value*
Full range CT	8.4 ± 1.8 (5.1-15.3)	4.6 ± 0.56		
			0.9	0.001
Reduced range CT	8.4 ± 1.8 (5.1-15.3)	4.6 ± 0.54		

SNR: Signal to noise ratio, SD: standard deviation, ICC: interclass correlation coefficient; CT: computed tomography.

A subjective analysis of the resultant images using radiologists indicated a similar (4.6 out of 5) subjective image quality scores for both full and reduced range CT scanners. The agreement between the two raters were statistically similar (ICC value: 0.9; p = 0.001). Similarly, a mean SNR value of 8.4 was observed across the image set which was 68% above the needed value to distinguish image features at 100% certainty (Bushberg et al., 2011). These results suggested that the reduced protocol was capable of achieving similar diagnostic quality as the full range CT for purposes of identifying CVA pathologies which constitute the second leading cause of death and a major cause of disability worldwide (Katan and Luft, 2018).

The dose output characteristics in terms of DRL, effective dose (E_D) and organ dose for both full range and reduced range CVA CT procedures are presented in Table 4.61. Comparative descriptive statistics of dose impact of full range CVA CT and reduced range CVA CT procedures are presented in Table 4.61. Figure 4.27 provides the pictorial presentation of the organ doses for the reduced and full range CVA CT scans.

Table 4.61: Comparison of dose impact of full range and reduced range CVA CT procedures

Parameter		Full range CT	Reduced range CT	DR (%)	*p-value*	*t-value*	*Mean difference*	*95% Confidence interval of difference*
DLP (mGy.cm)		926.7 ± 280	715.1 ± 213	22.8	<0.001	21.21	211.65	(191.850, 231.450)
Effective dose (E_D)(mSv)		2.1 ± 0.6	1.6 ± 0.5	23.8	<0.001	21.21	0.487	(0.441, 0.532)
Organ dose (mGy)	Brain	39.3 ±13.8	35.0 ±11.5	10.9	<0.001	13.34	4.285	(3.648, 4.923)
	Pituitary gland	33.3 ±10.3	23.2 ± 7.9	30.2	<0.001	10.76	10.04	(8.193, 11.896)
	Lens	46.1 ±15.4	31.3 ± 15.6	32.0	<0.001	6.98	14.76	(10.56, 18.950)
	Eyeballs	43.9 ±14.7	30.2 ± 13.4	31.1	<0.001	7.44	13.64	(10.000, 17.280)
	Salivary glands	21.3 ± 9.3	5.3 ± 4.8	75.0	<0.001	17.68	15.982	(14.189, 17.776)
	Oral cavity	14.4 ± 7.7	3.5 ± 2.9	75.6	<0.001	16.09	10.907	(9.562, 12.253)
	Spinal cord	2.9 ± 1.6	0.8 ± 0.6	70.7	<0.001	15.64	2.016	(1.760, 2.272)
	Thyroid	1.1 ± 0.7	0.5 ± 0.3	57.2	<0.001	14.58	0.637	(0.550, 0.723)

DR: dose reduction, DLP: dose length product; CT: computed tomography.

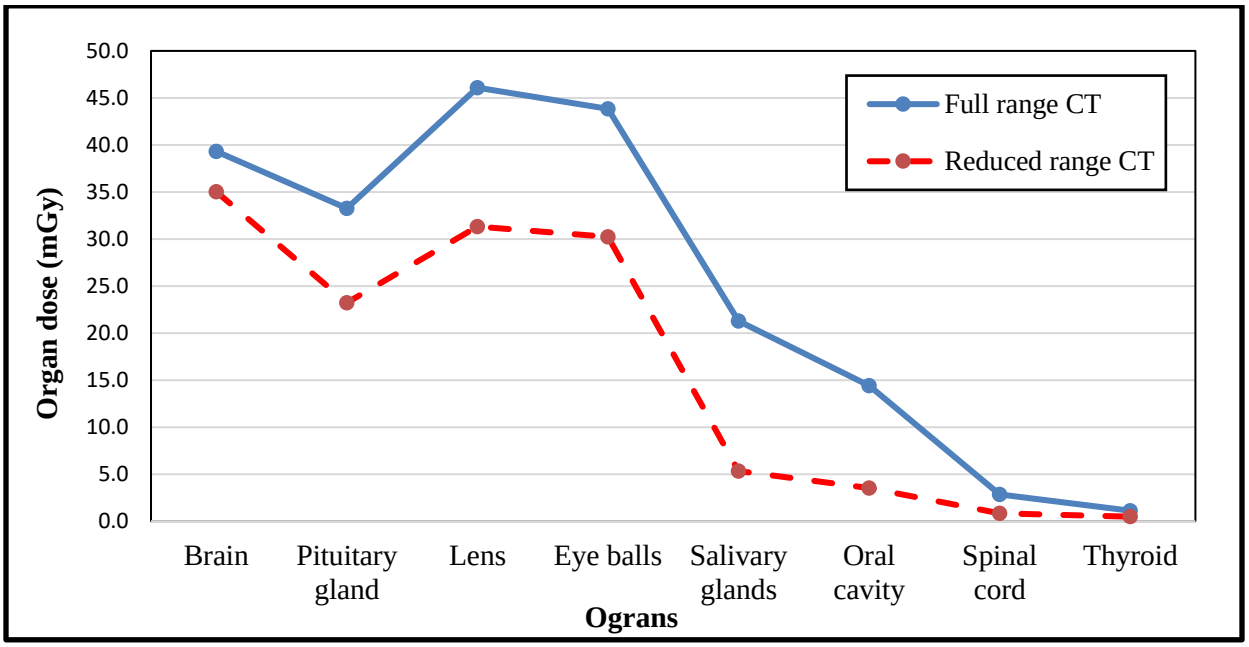


Figure 4.25: Pictorial presentation of the organ doses for reduced and full range CVA CT scans.

Table 4.61 and Figure 4.25 indicated that when the reduced range intervention was used in patient-based stroke/CVA examinations across the CT facilities in Ghana, the DLP and E_D values reduced by 22.8% and 23.8%, respectively. In terms of organ doses, the brain, pituitary gland, eye lens and the eyeballs doses reduced by 10.9%, 30.2%, 32.0% and 31.1%, respectively. Moreover, the doses to the salivary glands, oral cavity, spinal cord and thyroid reduced by 75.0%, 75.6%, 70.7% and 57.2%, respectively. All the dose reductions were found to be statistically significant. A recent study (Zinsser et al., 2019) which also explored reduced scan length in patients with suspected acute appendicitis demonstrated that a judicious use of scan range could reduce testicular, breasts and red marrow doses by 81%, 97.4% and 29.6%, respectively. Therefore, an implementation of the developed reduced scan range protocol in CT facilities could reduce radiation exposure levels in routine CVA examinations. This could potentially reduce the population organ dose, since CVA is the most common indication in CT imaging in Ghana.

The effect of the proposed reduced scan protocol on diagnosing CVA-related and other conditions through radiologists' reports are presented in Table 4.62.

Table 4.62: Diagnoses based on radiologists' reports

Diagnosis	**Full range detection**	**Reduced range detection**	**Sensitivity of reduced range**
	n	*N*	*(%)*
Normal CT brain	34	34	100
CVA-related diagnosis			
Thalamus infarcts	3	3	100
Small vessel ischemic disease	23	23	100
Posterior limb of the internal capsule infarcts	11	11	100
Bilateral cerebral infarcts	14	14	100
Bilateral subacute cerebral and pontine infarcts	5	5	100
Lacunar infarct	13	13	100
Chronic occipital lobe deep white matter infarct	4	4	100
Midbrain infarcts	3	4	100
Frontal lobe infarct	12	12	100
Parieto-temporal infract	6	6	100
Subarachnoid haemorrhage	2	2	100
Intracerebral haemorrhage	9	9	100
Subdural haemorrhage	9	9	100
Incidental findings			
Maxillary sinus disease	12	6	50
Ethmoid sinus disease	4	1	25
Sphenoid sinus disease	3	0	0
Frontal sinus disease	2	2	100
Pneumatized mastoid air cells	1	1	100
Brain atrophy	51	51	100

Note: There were multiple disease conditions in some patients, CVA: cerebrovascular accident

During the subjective image analysis, radiologists reported on the diagnosable conditions on both the reduced and full range images. Table 4.62 shows that the reduced range images had the same sensitivity (100%) as the full range regarding the identification of normal brain and CVA-related pathologies. This is expected as the CVA-related pathologies are found mainly within the brain region (Mayo Clinic, 2020). However, for incidental findings, the sensitivity was 100%, 100%, 50%, 25% and 0% for detection of brain atrophy, frontal sinus disease, maxillary sinus disease, ethmoid sinus disease and sphenoid sinus diseases, respectively. The results further clarify that the proposed reduced range could provide 100% results on normal brain and CVA-related diagnoses. However, it could not be utilised to provide accurate diagnostic information on some conditions (such as sphenoid, maxillary, and ethmoid sinus diseases) outside the brain tissue. Therefore, this reduced range protocol is a recommended procedure targeted for only CVA-related diagnosis.

4.6.2 Regression Modelled Equations

From the patient-based study data, equations (4.1-4.8) were produced for easy estimation of organ doses from CVA examinations using $CTDI_{vol}$, slice thickness (*ST*) and scan length (*SL*) parameters. These are supportive tools for optimisation of radiation dose levels. All variables used in modelling the equations passed normality tests [The significant levels, *p*-values, of Shapiro-Wilk and Grubbs' tests for outlies were all > 0.05). The optimum multicollinearity tests (VIF ranged from 1.767 – 2.065] (Appendices X-XII).

Mathematical algorithms developed for estimating brain dose (Brain*D*), salivary gland dose (S-gland*D*), eye lens dose (E-lens*D*) and eyeballs dose (E-balls*D*) have been expressed in equations 4.1, 4.2, 4.3 and 4.4, respectively. Other equations for oral cavity dose (O-cavity*D*),

spinal cord dose (S-cord*D*), thyroid dose (Thyroid*D*) and pituitary gland dose (P-gland*D*) have been also been expressed in equations 4.5 to 4.8, respectively.

$$\text{Brain}D\ (\text{mGy}) = -5.19 + 0.7218\ \text{CTDI}_{\text{vol}} + 0.285\ \text{ST} + 0.0241\ \text{SL} \quad (4.1)$$

(SD=2.12, R-Sq=97.7%, *p*-value = <0.001).

$$\text{S-gland}D\ (\text{mGy}) = -104.5 + 0.3874\ \text{CTDI}_{\text{vol}} - 0.358\ \text{ST} + 0.6158\ \text{SL} \quad (4.2)$$

(SD=6.22, R-Sq= 56.09%, *p*-value =<0.001)

$$\text{E-lens}D\ (\text{mGy}) = -12.35 + 0.8392\ \text{CTDI}_{\text{vol}} - 0.148\ \text{ST} + 0.0764\ \text{SL} \quad (4.3)$$

(SD=2.50, R-Sq=97.44%, *p*-value =<0.001).

$$\text{E-balls}D\ (\text{mGy}) = -10.79 + 0.7970\ \text{CTDI}_{\text{vol}} - 0.102\ \text{ST} + 0.0668\ \text{SL} \quad (4.4)$$

(SD=2.24, R-Sq=97.74%, *p*-value =<0.001).

$$\text{O-cavity}D\ (\text{mGy}) = -98.91 + 0.2738\ \text{CTDI}_{\text{vol}} - 0.117\ \text{ST} + 0.5747\ \text{SL} \quad (4.5)$$

(SD=4.49, R-Sq=66.66%, *p*-value =<0.001).

$$\text{S-cord}D\ (\text{mGy}) = -18.15 + 0.05423\ \text{CTDI}_{\text{vol}} + 0.0935\ \text{ST} + 0.1031\ \text{SL} \quad (4.6)$$

(SD=1.13, R-Sq=50.81%, *p*-value =<0.001).

$$\text{Thyroid}D\ (\text{mGy}) = -5.04 + 0.02214\ \text{CTDI}_{\text{vol}} + 0.0836\ \text{ST} + 0.02715\ \text{SL} \quad (4.7)$$

(SD=0.54, R-Sq=32.8%, *p*-value =<0.001).

$$\text{P-gland}D\ (\text{mGy}) = -19.69 + 0.5890\ \text{CTDI}_{\text{vol}} - 0.778\ \text{ST} + 0.1363\ \text{SL} \quad (4.8)$$

(SD=3.05, R-Sq=91.51%, *p*-value =<0.001).

From equations 4.1 to 4.8, the respective R-squares (R-Sq) indicated the influence of the independent variables ($CTDI_{vol}$, ST and SL) in the model on the respective organ doses. Per equations 4.1, 4.3 and 4.4, the models suggested that over 97% of the respective organ doses were predicted by $CTDI_{vol}$, ST and SL. In the case of equations 4.2, 4.5, 4.6, 4.7 and 4.8, the variation in respective doses were accounted for by 56.1%, 66.7%, 50.8%, 32.8% and 91.5% of the respective independent variables. Models with low R-square values, particularly, equation 4.7 must be used with caution because the model could not entirely predict the respective organ doses.

4.6.3 Optimisation Method 2: The role of AEC Utilisation

In the Phase 5 study, it was observed that some of the CT scanners were operated without activating their AEC systems. The impact of AEC systems was investigated in those facilities. A pictorial diagram with four plates (A-D) showing tube loading variations across different z-positions for different scanners operating with and without the activation of AEC systems is presented in Figure 4.26.

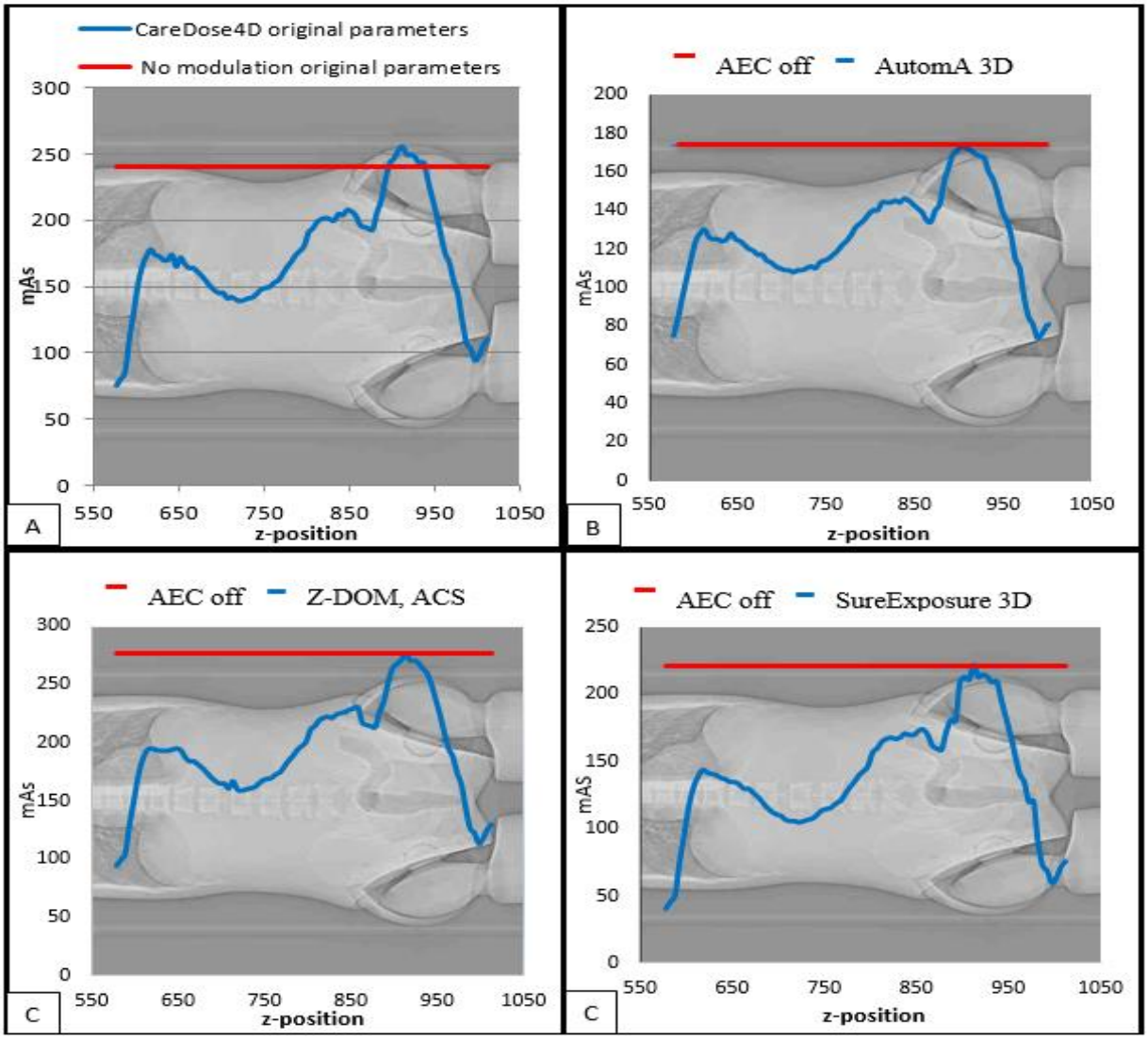


Figure 4.26: AEC modulated tube current and fixed tube current profiles across different z-positions

As illustrated in plate A-D, the blue and red lines show the variation of the tube loading with and without activation of AEC systems, respectively, as the phantom was scanned from the dome of the liver to the pubic symphysis. The above shows that with the use of AEC (of various models), the tube loading varied with the density of the anatomical region along the z-axis. However, constant tube loading was used along the entire z-axis positions for fixed-mAs procedures. This phenomenon was same for all the types of AECs used in the study, hence, for

examinations without AEC activation, both smaller and bigger abdominal regions along the z-axis would receive the same dose without any optimisation.

The dose output results of the study undertaken to compare AEC and fixed tube current systems (in facilities operating without AEC systems) for optimisation actions have been presented in the Table 4.63.

Table 4.63: Comparison of dose output for abdomino-pelvic procedures undertaken with and without AEC systems.

Scanner models	AEC setting	Mean mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	DLP DR (%)	Mean noise (SD)	Mean SNR
Siemens	AEC: off	240	16.1	731.0	-	7.2	7.3
Somatom Emotion	CareDose4D	166	6.9	312.0	57.3	11.1	12.1
GE	AEC: off	200	12.5	572.1	-	5.6	6.4
Lightspeed Pro 16	AutomA 3D	105	6.6	306.8	46.4	8.6	9.7
Toshiba	AEC: off	187	22.3	1027.6	-	6.1	5.3
Aquilion 16 TSX	SureExposure 3D	54.45	9.3	428.2	58.3	9.1	7.9
Philips	AEC: off	355	14.1	637.0	-	5.3	5.6
Brilliance 64	DoseRight Z-DOM, ACS	278.9	5.9	284.0	55.4	7.8	12.2
Cumulative comparative results							
	AEC		7.2 ± 0.9	332.8 ± 64.8	55.2,		6.5 ± 0.9
	Without AEC		16.3 ± 1.4	741.9 ± 29.6	p=0.01		10.5 ± 2.1

DR: dose reduction: AEC: automatic exposure control: $CTDI_{vol}$: computed tomography volume weighted dose index, DLP: dose length product, SD: standard deviation. ACS: automatic current selection.

Table 4.63 shows the cumulative mean dosimetric results of AP CT imaging with AEC and fixed mAs. The cumulative mean $CTDI_{vol}$ values were 7.2 ± 0.9 mGy and 16.3 ± 1.4 mGy, respectively. The corresponding mean DLP values were 332.8 ± 64.8 mGy.cm and 741.9 ± 296.0 mGy.cm, respectively. The results indicated that the non-AEC scanning CT facilities could reduce CT radiation dose output (DLP) by a factor of 2.2 (55.2%) while ensuring acceptable image quality if the AEC systems were activated and utilised. The DLP dose reduction found across the four facilities varied from 46.4-58.3% which was closely similar to values (36.8 -73.8%) reported by Sulemana et al. (2020) in a single centre. Moreover, the dose reduction benefits observed with respective AEC systems were even higher compared with values (about 20–40%) reported by Higaki et al. (2019) and Merzan et al. (2017). It suggested lack of training, policy on CT infrastructure and proper organisational programmes driving CT purchasing, installation, acceptance testing, commissioning and operations are some of the drawbacks in the utilisation of AEC systems. Due to some of these challenges, CT machines are sometimes purchased and commissioned for work without any training offered by application specialists, thereby, creating a knowledge gap on the best ways to utilise equipment configurations such as the AEC. Therefore, training of radiographers on technical application of AEC systems, particularly, before equipment commissioning is absolutely crucial for dose management in Ghana. Moreover, strict adherence to policies regarding AEC usage is necessary in order to ensure that dose optimisation benefits are derived from the available CT scanners with AEC activated systems.

As part of the study, all the facilities operating fixed-mAs settings have been assisted to activate their AEC systems.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.0 Overview

The summary, conclusion, challenges/limitations and recommendations from this study are presented in this chapter.

5.1 Summary and Conclusion

The main objective of this study was to develop national indication-based DRL values for common and prioritised indications of the adult human body for clinical application in Ghana, and assess the risk of undertaking each indication-based CT examination, and also propose steps for dose optimisation. Studies on CT infrastructure and common indications as well as assessment of QMS were undertaken. The study found that there were 28 functional CT scanners out of the 31 that participated in the study. Most of the scanners (58.1%) were installed in the Greater Accra Region, and all those included in the DRL study (n=25) passed the QC tests. However, the needed infrastructure for QMS was unavailable in some of the CT facilities. Particularly, more than half (51.6%) of the facilities lacked a documented protocol for CT scanning for some indications. Radiologists were, therefore, used mainly to define the basic diagnostic requirements of each indication, prior to collecting the needed dose descriptors for the DRL study.

The observed common indications and their projected DRL values in terms of $CTDI_{vol}$ (mGy) and DLP (mGy.cm) were CVA/stroke (77 mGy; 1313 mGy.cm), head trauma/injury (76 mGy; 1596 mGy.cm), brain tumour/SOL (77 mGy; 2696 mGy.cm), lung tumour/cancer (12 mGy; 828 mGy.cm) and chest lesion with chronic kidney disease (13 mGy; 467 mGy.cm). Others were AP lesion (17 mGy; 1299 mGy.cm), kidney stones (15 mGy; 731

mGy.cm), urothelial malignancy/CT-IVU (11 mGy; 1449 mGy.cm) and PE (14 mGy; 942 mGy.cm). These values could be used as a QA/QC tool and a trigger to detect CT imaging centres utilising remarkably high doses (outliers) in a particular indication-based radiological task, for which optimisation measures are required.

It is also anticipated that these benchmarks would guide stakeholders to further unearth better ways of optimising radiation doses in CT imaging.

For an effective implementation of the proposed DRL values, a Microsoft Excel-based tool (**BOT^{B}**) for inspection and monitoring of DRLs' compliance was developed in this study. The tool had a capability for internal audit purposes to monitor individual facility's compliance to the national indication-based DRL values and where necessary, corrective actions could be taken to promote dose management.

The estimated risk of PE radiation-induced breast cancer ranged from 6-115.8 people in 100,000 procedures. Moreover, the risk of CT-IVU radiation-induced colon cancer ranged from 53.3-66.4 people in 100,000 patients. About 1 in 38, 462 to 1 in 14,706 patients were also likely to develop ovarian cancer due to CT-IVU examinations in Ghana. The risk of leukaemia mortality as a result of radiation accruing from CT-IVU for urothelial malignancy, also ranged from 1 in 1,901 to 1 in 6,667 patients. Although the LARi and LARm were considered minimal to moderate levels across the various indications, there was a need for further optimisation measure in CT imaging to reduce the dose levels and radiation risks.

The study found a novel protocol that could be used to scan stroke/CVA related conditions with optimal image quality, while reducing facilities' radiation dose levels. In particular, it found that using a scan range covering 10 mm below the vertex and 0 mm below the base of skull at foramen magnum could reduce the mean effective dose of the facilities by 23.8%, and organ doses

by 32% (eye lens), 70.7% (spinal cord), 57.2% (thyroid), 75.6% (oral cavity), 10.9% (brain), 31.1% (eyeballs) and 30.2% (pituitary gland) with negligible effect on the image quality. However, this protocol was not 100% sensitive in diagnosing incidental findings that were not within the brain region. Therefore, it was strictly recommended for stroke/CVA-related CT imaging. Eight organ dose equations were also developed to aid in dose management. It is believed that CT imaging facilities could utilise these equations to estimate organ doses with ease, and guide in appropriate decisions. Finally, the study concluded that if AEC systems were used in facilities operating with fixed tube loading systems, radiation doses could also be reduced by a range of 46.4-58.3% without any significant compromise on image quality. Therefore, there was a need to ensure proper utilisation of AEC systems in all the CT facilities in Ghana.

5.2 Challenges/Limitations

Many challenges were encountered during the study. Some of them include:

i. Though the study attempted to include all the CT facilities in the study, four of them did not to participate. These few numbers did not affect the generalisation of the findings. However, their inclusion would have provided full information on CT scanners and dose levels for their inclusion in the DRL values and implementation of optimisation measures where necessary.

ii. Long equipment downtimes prevented the inclusion of broken-down CT scanners in the study, although several follow-ups were made to inquire about their status and possible inclusion in the study.

iii. In Ghana, patient dose information recording, and automatic dose tracking systems are not mandatory, and are not readily available in most facilities. In the absence of these, several days were spent in the facilities collecting data.

iv. The study was solely focused on adults. Paediatrics were therefore not considered.

5.3 Recommendations

5.3.1 Nuclear Regulatory Authority

i. The developed indication-based DRL values are recommended for adoption and implementation by the NRA, in collaboration with the relevant professional bodies for dose management and accountability of CT imaging in Ghana. The national values may be revised at regular intervals (every 5 years), especially when significant changes in technology, and new imaging procedure standards and protocols are available.

ii. The developed monitoring tool (**BOT^{B}**) in this study could be used by the NRA for inspection and monitoring of DRLs compliance purposes, if the proposed DRL values are implemented.

iii. In view of the observed lack of QMS in the various CT facilities, the NRA should liaise with the Ministry of Health and all appropriate stakeholders to ensure that all policies needed for CT QMS in Ghana are implemented, and adhere to accordingly.

5.3.2 Managers and Health Professionals in CT Imaging

i. Managers and professionals in CT imaging such as radiologists, radiographers and medical physicists may use the proposed indication-based values as a country-based guide to regulate and optimise their CT practices in Ghana.

ii. A scan range covering from 10 mm (1 cm) below the vertex and 0 mm below the base of skull at foramen magnum is recommended in CT imaging of stroke/CVA specific conditions or indications in order to significantly optimise radiation dose, while ensuring good image quality.

5.3.3 Future Research

i. Future research focusing on the development of paediatric indication-based diagnostic reference levels and optimisation methods for computed tomography examinations in Ghana is recommended.

ii. Future research focusing on the development of adult indication-based diagnostic reference levels for indications not considered in the study (non-common indications), and optimisation methods for computed tomography examinations in Ghana is also recommended.

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APPENDICES

APPENDIX I: NUMBER OF SCANNERS ON NRA'S RECORDS

In case of reply the number and date of this letter should be quoted.
Our Ref. No: NRA/SN.17/29
Your Ref. No.....
Tel. +233-(0) 303-965928
Email: official.mail@gnra.org.gh

REPUBLIC OF GHANA

NUCLEAR REGULATORY AUTHORITY
House Nos 1 & 2, Neutron Avenue
P.O. Box AE 50
Atomic Energy
Kwabenya

Date: 19th December 2017

The Head of Department
Department of Nuclear Safety & Security
School of Nuclear & Allied Sciences
University of Ghana
Atomic Campus

Dear Sir,

RE: REQUEST FOR OFFICIAL INFORMATION ON THE NUMBER OF COMPUTED TOMOGRAPHY (CT) SCANNERS IN THE COUNTRY

Your letter No. DNSAS/SNAS/ADM/3/17 dated 14th December 2017 on the above refers.

Please find attached the number of computed tomography (CT) scanners in the country as requested for your necessary action.

Thank you.

Yours faithfully,

PROF. G. EMI-REYNOLDS
AG. DIRECTOR GENERAL

Encl.:

NUMBER OF COMPUTED TOMOGRAPHY SCANNERS IN THE COUNTRY

No.	REGION	NUMBER
1	Greater Accra	20
2	Ashanti	8
3	Northern	3
4	Western	1
5	Central	1
6	Eastern	1
7	Brong Ahafo	1
	TOTAL	35

APPENDIX II: INTRODUCTORY LETTER FROM NRA

In case of reply the number
and date of this letter should
be quoted.
Our Ref. No: NRA/BM.17/35
Your Ref. No: .....
Tel. +233-(0) 303-965928
Email: official.mail@gnra.org.gh

REPUBLIC OF GHANA

NUCLEAR REGULATORY AUTHORITY
House Nos 1 & 2, Neutron Avenue
P.O. Box AE 50
Atomic Energy
Kwabenya

Date: 6th April 2018

TO WHOM IT MAY CONCERN

Dear Sir/Madam,

INTRODUCTION: BENARD BOTWE

Mr. Benard Botwe is a second year PhD Radiation Protection student at the Department of Nuclear Safety and Security of the School of Nuclear and Allied sciences (SNAS), Ghana Atomic Energy Commission.

His research area is "Development of Indication-Based Diagnostic Reference Levels for Computed Tomography (CT) Examinations in Ghana". The main aim of the study is to develop national radiation dose diagnostic reference levels and benchmarks for dose monitoring and optimization procedures to reduce radiation doses associated with CT examinations. For reasons that dose limits are not applicable in medical exposures, it is required that every country establishes diagnostic reference levels to guide users in the medical field and this research seeks to contribute to that course. The data will help in the formulation of guidelines for the safe operation of these facilities and ultimately contribute to improve the radiation protection infrastructure in Ghana.

The data from the study will be very useful to Nuclear Regulatory Authority (NRA) since it will facilitate the work of the Authority in the development of regulations and guides in the field.

It is for these reasons that the NRA wishes to associate itself with the research to be undertaken by Mr. Botwe and would be very grateful if access could be granted him by your facility to enable him carry out the needed measurements.

Counting on your usual cooperation.

Yours faithfully,

Dr. Augustine Faanu
Ag. Director, Radiological & Non-Ionising Inst.
Nuclear Regulatory Authority

APPENDIX III: PARTICIPANT INFORMATION SHEET

Participant Information Sheet

Researcher: My name is Benard Botwe and I am a PhD candidate in Department of Nuclear Safety and Security at the University of Ghana.

Project Title: Development of Indication-Based Diagnostic Reference Levels and Optimization Methods for Computed Tomography Examinations in Ghana.

General Outline of the Project:

Description and Methodology: Diagnostic Reference level (DRL) is a numerically established radiation dose value for which, when standards and best practices as well as standard technical performances are adhered to, they are expected not to be exceeded. The concept of DRL has been introduced into medicine to offer standard dose parameters against which patients' dose estimates can be related to in order to assess practices with the overall aim of reducing radiation doses, including that of computed tomography (CT). However, there are no established national DRLs in Ghana, against which doses could be compared to ensure effective dose management. This project is aimed at developing indication-based DRLs for common indications in CT imaging and also propose some steps for dose optimization for clinical application in Ghana.

Participants: The study intends to administer questionnaires to technical heads and radiologists responsible for the CT scanners to gather information on technical data on the CT infrastructure, common indications and basic diagnostic imaging requirements. CT dose data and image quality information would be collected from the scanners directly.

Use of Data and Feedback: The data will be used for my thesis write-up. In addition, the data will be published in a peer-review journal. Feedback in the form of a summary of the research will be made available to participants through emails.

Project Funding: The BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana and the ISRRT-Chesney research fund provided financial support.

The Ghana-Norway NORPART project also provided a scholarship package for an exchange studies at NTNU, Norway.

Participant Involvement:

Voluntary Participation and Withdrawal:

Your participation in this research is voluntary, and you may decline to take part or to withdraw from the research without providing an explanation at any time until the work is completed. Within the research, you may also decline to answer any question. If you withdraw, the data you have provided prior to withdrawal will be destroyed and not used.

What does participation in the research entail?

You are invited to take part to provided answers to questionnaires and where appropriate help to gather CT quantity data and image quality information. With your consent, I would provide you with a questionnaire to fill and subsequently follow up with the dose quantity and image quality information collection.

Location and Duration:

The completion of the questionnaire is expected to last about I hour, and will be conducted at a place of your choosing. The other CT data and image quality information would be collected on the CT units and it may take a total duration of about 6 months.

Risks: The research carries very negligible risk although you may feel distressed if you have had negative experiences with CT DRLs.

Benefits: It is unlikely that you will personally benefit from participation in this research. However, the work would be used as a trigger to identify radiologic facilities using unusually high doses in a specified procedure, for which optimisation actions are required. This will help to put in place measures to mitigate the challenges and subsequently help to promote CT imaging practices in Ghana. This could also provide some information on which some policy decisions and directions can be built.

Exclusion criteria:

Participant Limitation: Excluded will be those who will not consent to participate or those who will voluntarily withdraw from the study.

Confidentiality:

Confidentiality: Confidentiality will be protected as far as the law allows. No participant details will be linked with his or her responses. Moreover, no CT facilities and their identifiers would be linked in the final data analysis.

Data Storage:

Where: The data will be stored on the computer hardrive of the researcher's computer. This will be secured with a password.

How long: The data will be available for five years from the date of the analysis and it will be archived for future research projects if necessary.

Queries and Concerns:

Contact Details for More Information: Should have any concerns, you may contact me on: 0244029365, email: sirbenard13@gmail.com/ bebotwe@ug.edu.gh

Ethics Committee Clearance:

Ethical clearance for this study was first sought and granted by The Ethics Committee For Basic and Applied Sciences (ECBAS), University of Ghana (REF. No: ECBAS 041/17-18), The Ghana Health Service Ethics Review Committee (REF NO: GHS-ERC002/04/18) and The Korle Bu Teaching Hospital's Scientific and Technical Committee (KBTH-STC) and the Institutional Review Board (KBTH-IRB) (REF NO: KBTH-IRB/00092/2017).

APPENDIX IV: CONSENT FORM

I confirm that I have been briefed on the nature of the research and my role as a participant. I understand that the researcher is a student in the Department of Nuclear Security and Safety, University of Ghana and this research is a PhD student's dissertation.

I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it and any question I have asked have been answered to my satisfaction. I consent voluntarily to participate as a subject in this study and understand that I have the right to withdraw from the study at any time without in any way it affecting my further medical care

.....	.....
Participant's Signature	Date
.....	.....
Researcher' Signature	Date

APPENDIX V: QUESTIONNAIRE A
PART 1
(To be completed by a radiographer, radiologist or a medical physicist in charge as the technical head)

1. Your professional grade/rank……Gender:……..
2. Name of Centre/Hospital: …….……
3. Ownership: Private ☐ Public ☐
4. Region of location Location…….…….....
5. CT Type/Model: …..……..
6. Manufacturer and Year of manufacture:……..…….
7. Year of installation:…….……..
8. Number of CT Slice and detector row: …….
9. Scanning Mode:……
10. Is the CT equipment working?……...
11. How many CT scanners do you have in your facility? …….
12. Is your equipment having an automatic exposure control/tube current modulation system?
    Yes ☐ No ☐
13. Number of CT operating radiographers. ……...…….
14. Number of CT attending/reporting radiologists:…… …….….
15. Number of CT attending medical physicists…….....……
16. Are data on the following dose descriptors displayed on the control console?
    (i) $CTDI_{vol}$ Yes ☐ No ☐
    (ii) DLP Yes ☐ No ☐
17. Is there any AEC system incorporated in the CT in your facility? Yes ☐ No ☐
18. How long does it normally take to repair your equipment when it is broken down? .....
19. Overall average number of CT cases per a year: …….
20. Average number of CT cases per a year for the following:
    Head: …….……
    Chest: ……
    Abdomen: …….
    Pelvis……..

Abdominopelvic ……

Lumbar spine……

Others……..

21. Indicate the commonest indications and their average frequencies (***example, 2 a day or 100 a year***) for which adult patients come for **Head** CT examinations [***Please select more than one(1) but not more than four (4)***] For the selected ones, use alphabets (A-Z) to represents those that are scanned with uses similar scanning protocol.

I. CVA/Stroke ☐ Frequency ……

II. Head injury/trauma ☐ Frequency ……

III. Tumour(Metastasis/cancers/lesion) ☐ Frequency ……

IV. Sinusitis ☐ Frequency ……

V. Facial bone injuries/trauma ☐ Frequency ……

VI. Blurred vision ☐ Frequency ……

VII. Dizziness ☐ Frequency ……

VIII. Psychiatric disorders ☐ Frequency ……

IX. Others and their frequencies, please specify

……

……

……....

22. Indicate the commonest indications and their average frequencies (***example, 2 a day or 100 a year***) for which adult patients come for **Chest** CT examinations [***Please select more than one (1) but not more than three (3)*****]** For the selected ones, use alphabets (A-Z) to represents those that are scanned with uses similar scanning protocol.

I. Chest tumour (nodules/cancer/abscess) ☐ Frequency ……

II. Chest injury/trauma ☐ Frequency ……

III. Plueral effusion/Airway assessment ☐ Frequency ……

IV. Interstitial lung diseases ☐ Frequency ……

V. Pulmonary embolism ☐ Frequency ……

VI. Others and their frequencies, please specify

……

……

……...

23. Indicate the commonest indications and their average frequencies (***example, 2 a day or 100 a year***) for which adult patients come for CT examinations involving the abdomino-pelvic region of the body **[*Please select more than one (1) but not more than five (5)*]** For the selected ones, use alphabets (A-Z) to represents those that are scanned with uses similar scanning protocol.

I. Liver metastases ☐ Frequency ……..…

II. Kidney stone/colic ☐ Frequency ……..……

III. Abdomino-pelvic abscess/tumour/cancer ☐ Frequency …….

IV. Pelvic tumour ☐ Frequency ……..

V. Pancreatic tumour ☐ Frequency……

VI. Chrohn's disease ☐ Frequency …. …….

VII. Bowel obstruction ☐ Frequency …. ……

VIII. Ischemia ☐ Frequency …. ……

IX. Urothelial malignancy (CT-IVU) ☐ Frequency …. …….

X. CT Colonoscopy (for Polys/tumour) ☐ Frequency.…….

XI. Others and their frequencies, please specify

……

……

……

24. Which indication-based diagnostic reference levels (DRLs) do you compare your CT dose parameters with? Please specify.....

25. Do you think there is the need to develop Indication-Based Diagnostic Reference Levels (IBDRLs) for CT examinations in Ghana? Yes ☐ No ☐

PART 2

i. Quality Assurance structures available at the CT facilities in Ghana

Quality Assurance structures	Availability	
	Yes	**No**
26. Availability of QA or QC Committee		
27. Availability of a written down protocol for CT scanning		
28. Post-major repair QC assessment records		
29. Do you have records of regular QC checks		
30. Certification/authorisation by Nuclear Regulatory Authority		
31. Availability of established acceptance testing procedure		
32. Availability of effective planned maintenance schedules		
33. Equipment performance record keeping		
34. Availability of radiation protection devices		
35. Availability of systems for justifying CT exposures		
36. Availability of accepted or established DRLs		
37. Availability of scheduled dose optimisation programmes		
38. Keeping of patient dose records		
39. Availability of an established patient dose and image quality audit programmes		
40. Planned schedules for frequent cleaning of equipment		
41. Documented training program and records		

42. If yes to question 41, please indicate the frequency of the QC test……

ii. Basic Quality improvement structures in the CT facilities

Quality improvement structures	Availability	
	Yes	**No**
43. **Do you have institutional leadership and support toward quality improvement?**		
44. Do you have regular meetings involving all the stakeholders to communicate QC results?		
45. Has your facility establish a culture of quality in your practice?		
46. Has your facility established an improvement team?		
47. Do you have a quality implementation protocol or manual 48. Do you have a system that engages all the professional groups in the department on quality improvements?		
49. Do you have a system that regularly receives and analyses feedback from customers and stakeholders?		
50. Do you have surveillances system for monitoring quality improvements indicators?		
51. Does your facility have a system to reward hard work associated with quality improvement?		
52. Do you have an educational programme on quality improvement?		

iii. Policy infrastructure and their availability in Ghana

Please indicate whether or not the following are available in your facility or you are aware of it in the country by indicating yes or no against each statement

Policy infrastructure	Availability	
	Yes	No
53. Policy on CT authorisation for use in Ghana		
54. Policy driving CT infrastructure and distribution		
55. Policy on operation and maintenance		
56. Policy and availability of quality management systems		
57. Policy on purchasing, construction and installations		
58. Policy on decommission of a CT facility		
59. Policy on education and training		
60. Policy and availability of diagnostic reference levels		
61. Policy on CT referrer guidelines		
62. Policy on recommended frequency for QC tests		
63. Standardised policy on AEC application		
64. Policy on patient dose optimisation, image quality and audit programmes		
65. Policy on acceptance testing and record keeping		
66. Policy on human resources in CT facilities		
67. Policy on CT maintenance systems		

APPENDIX VI: QUESTIONNAIRE B

(To be completed by a radiologist)

Please tick (✔) the basic requirement that pertains to your facility regarding each of the routine indications

i. Basic diagnostic imaging requirements for CVA/stroke, head injury and brain tumour/SOL procedures in Ghana.

Diagnostic imaging requirements		CVA/stroke		Head injury		Brain tumour/SOL	
		Yes	No	Yes	No	Yes	No
Scan coverage:	Scan should cover from just below the base of skull to the vertex						
	Scan should cover from C3 to the vertex if the base of skull injury is suspected						
Scan series:	None contrast						
	Once (only IV contrast phase)						
	Twice (both non-contrast and contrast phases)						
Image quality should be acceptable to the reporting radiologists and should meet national/international standards							
Slice thickness-	5 mm-10 mm						
	<5 mm						
Scan mode:	Helical only						
	Axial only						
	Both						
Scan Technique:	Low dose						
	Optimised dose						
	High dose						
AEC usage:	Yes						
	No						

C3= Third Cervical vertebrae; CVA: cerebrovascular accident, IV: intravenous; SOL: space occupying lesion.

Please tick (✔) the basic requirement that pertains to your facility regarding each of the routine indications

ii. : Basic diagnostic imaging requirements for CT lung tumour, *Chest lesion with CKD* and PE procedures in Ghana

Diagnostic imaging requirements		**Lung tumour**		**CL CKD**		**PE**	
		Yes	No	Yes	No	Yes	No
Scan coverage:	Scan should cover from just above lung apices to below lung bases						
Scan series:	Once (only non- contrast phase)						
	Once (only IV routine contrast phase)						
	Once (only IV contrast "*angiogram*" phase)						
	Twice (both non-contrast and contrast "*angiogram*" phases						
	Twice (both non-contrast and contrast phases)						
	Twice (IV contrast scan of the lung filed and scan of the liver)						
Image quality should be acceptable to the reporting radiologists and should meet national/international standards							
Slice thickness-	< 5 mm						
	5 mm-10 mm						
Scan mode:	Helical only						
	Axial only						
	Both						
Scan technique:	Low dose						
	Optimised dose						
	High dose						
AEC usage:	Yes						
	No						

Key: Chest lesion with CKD= CL CKD, PE: pulmonary embolism, IV: intravenous.

Please tick (✔) the basic requirement that pertains to your facility regarding each of the routine indications

iii. Basic diagnostic imaging requirements for abdomino-pelvic lesion, kidney stone and urothelial malignancy indication (CT-IVU) examinations

Diagnostic imaging requirements		**AP lesion**		**Kidney stone**		**UM (IVU)**	
		Yes	No	Yes	Yes	No	Yes
Scan coverage:	Scan should cover from just top of higher hemidiaphragm to below the ischium or symphysis pubis						
Scan series:	Once (Non-contrast phase)						
	Once (*only contrast phase; "oral with IV"*)						
	Twice (both non-contrast and contrast phases)						
	*3-4 phases (*pre-contrast* and *2-3 other post IV contrast phases* including *nephrographic*, *corticomedullary** and *excretory* phases*)*						
	2 phases (slip bolus technique involving *nephrographic* and *excretory* phases)						
Image quality should be acceptable to the reporting radiologists and should meet national/international standards							
Slice thickness:	≤ 5 mm						
	7-10 mm						
Scan mode:	Helical only						
	Axial only						
	Both						
Scan technique:	Low dose						
	Optimised dose						
	High dose						
AEC usage:	Yes						
	No						

Key: IV *represents intravenous; UM=Urothelial malignancy. IVU: intravenous urography*

APPENDIX VII: CT DOSE PARAMETERS DATA SHEET

CT DOSE PARAMETERS DATA SHEET (1)

Name of Institution.....CT MANUFACTURER/ MODEL.....
Indication: **CVA / STROKE**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SE	P	RT	No. of slices	ST (mm)	A	SM	C	**SCAN COVERAGE** Scan length/range (mm)
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
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13																	
14																	
15																	
16																	
17																	
18																	
19																	
20																	

Key: Wt. =weight, kVp= tube potential, mAs=milliampere second, SE= number of sequences, P=pitch, RT=rotation time, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage

CT DOSE PARAMETERS DATA SHEET (2)

Name of Institution.....CT MANUFACTURER/MODEL.....
Indication: **HEAD INJURY / TRAUMA**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SE	P	RT	No. of slices	ST (mm)	A	S M	C	**SCAN COVERAGE** Scan length/range (mm)
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
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14																	
15																	
16																	
17																	
18																	
19																	
20																	

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, SE= number of sequences, P=pitch, RT=rotation time, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage

CT DOSE PARAMETERS DATA SHEET (3)

Name of Institution.....CT MANUFACTURER/MODEL.....
Indication: **HEADACHES? SOL/TUMOUR**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)		DLP (mGy.cm)			SE	P	RT	No. of Slices per SE	ST (mm)	A	SM	C	**SCAN COVERAGE** SL (mm)
							Pre CE	Post CE	Pre CE	Post CE	Total DLP									
1																				
2																				
3																				
4																				
5																				
6																				
7																				
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Key: Wt =weight, kVp= tube potential, mAs=milliampere second, CE= contrast, SE= number of sequences, P=pitch, RT=rotation time,? = suspicion of, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

CT DOSE PARAMETERS DATA SHEET (4)

Name of Institution.....CT MANUFACTURER/ MODEL.....
Indication: **COUTH and CHEST PAIN? LUNG CANCER/TUMOUR**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)		DLP (mGy.cm)			SE	P	RT	No. of Slices Per SE	ST (mm)	A	SM	C	**SCAN COVERAGE** SL (mm)
							Pre CE	Post CE	Pre CE	Post CE	Total DLP									
1																				
2																				
3																				
4																				
5																				
6																				
7																				
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19																				
20																				

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, CE= contrast, SE= number of sequences, P=pitch, RT=rotation time,? = suspicion of, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

CT DOSE PARAMETERS DATA SHEET (5)

Name of Institution.....CT MANUFACTURER /MODEL.....
Indication: **SUSPICION OF LUNG LESION WITH CKD**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SE	P	RT	No. of slices	Slice thickness (cm)	ST (mm)	A	SM	C	**SCAN COVERAGE** Scan length/range (mm)
1																		
2																		
3																		
4																		
5																		
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16																		
17																		
18																		
19																		
20																		

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, SE= number of sequences, P=pitch, RT=rotation time, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage

CT DOSE PARAMETERS DATA SHEET (6)

Name of Institution.....CT MANUFACTURER/ MODEL.....
Indication: **? ABDOMINO-PELVIC TUMOUR/ LESION**

	Patient ID	Age	Sex	Wt.	kVp	mAs	$CTDI_{vol}$ (mGy)		DLP (mGy.cm)			SE	P	RT	No. of Slices per SE	ST (mm)	A	S M	C	**SCAN COVERAGE** SL (mm)
							Pre CE	Post CE	Pre CE	Post CE	Total DLP									
1																				
2																				
3																				
4																				
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20																				

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, CE= contrast, SE= number of sequences, P=pitch, RT=rotation time, ? = suspicion of, ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

CT DOSE PARAMETERS DATA SHEET (7)

Name of Institution.....CT MANUFACTURER/MODEL.....

Indication: **? KIDNEY STONES**

	Patient ID	Age	Sex	Wt	kVp	mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	SE	P	RT	No. of Slices per SE	ST (mm)	A	SM	C	**SCAN COVERAGE** SL (mm)
1																	
2																	
3																	
4																	
5																	
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7																	
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18																	
19																	
20																	

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, SE= number of sequences, P=pitch, RT=rotation time, ? = suspicion of ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

CT DOSE PARAMETERS DATA SHEET (8)

Name of Institution.....CT MANUFACTURER/MODEL.....

Indication: **? UROTHELIAL MALIGNANCY (CT-IVU)**

	ID	Age	Sex	Wt.	kVp	mAs	$CTDI_{vol}$ (mGy)						DLP (mGy.cm)							SE	P	RT	No. of Slices per SE	ST (mm)	A	SM	C	**SCAN COVERAGE** SL (mm)
							Pre CE	Post CE series					Pre CE	Post CE series					Total DLP									
								1	2	3	4	5		1	2	3	4	5										
1																												
2																												
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18																												
19																												
20																												

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, CE= contrast, SE= number of sequences, P=pitch, RT=rotation time, ? = suspicion of. ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

CT DOSE PARAMETERS DATA SHEET (9)

Name of Institution..... CT MANUFACTURER/ MODEL.....

Indication: **? PULMONARY EMBOLISM (Pulmonary Angiogram)**

	Patient ID	Age	Sex	Wt	SE	mAs	kVp	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)		P	RT	No. of slices	ST	A	SM	C	**SCAN COVERAGE**
									SE DLP	Total DLP								SL
1					PRE CE													
					1st SE													
					2nd SE													
					3rd SE													
					4th SE													
					5th SE													
2					PRE CE													
					1st SE													
					2nd SE													
					3rd SE													
					4th SE													
					5th SE													
3					PRE CE													
					1st SE													
					2nd SE													
					3rd SE													
					4th SE													
					5th													
4					PRE CE													
					1st SE													
					2nd SE													
					3rd SE													
					4th SE													
					5th SE													
5					PRE CE													
					1st SE													
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					4th SE													
					5th SE													
					3rd SE													
					4th SE													
					5th SE													

This data sheet continues to page 20.

Key: Wt =weight, kVp= tube potential, mAs=milliampere second, CE= contrast, SE= number of sequences, P=pitch, RT=rotation time,? = suspicion of. ST= slice thickness, A= AEC, SM=scan mode, C=contrast usage, SL= scan length.

APPENDIX VIII: CONTROL CHART FOR ALL INDICATION DATA SETS (CTDI$_{VOL}$ AND DLP)

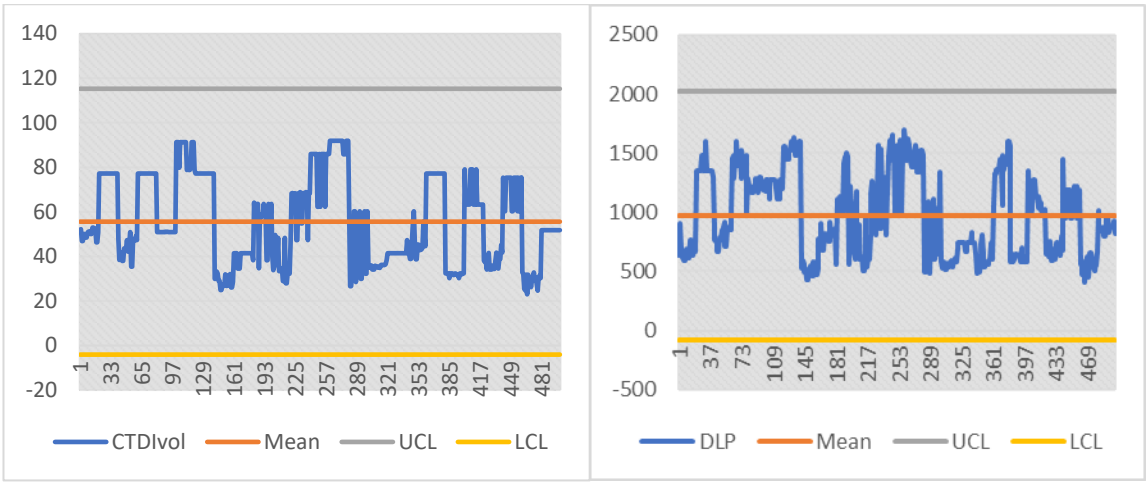

Figure 1: Control chart for *CVA* data sets (CTDI$_{vol}$ and DLP)

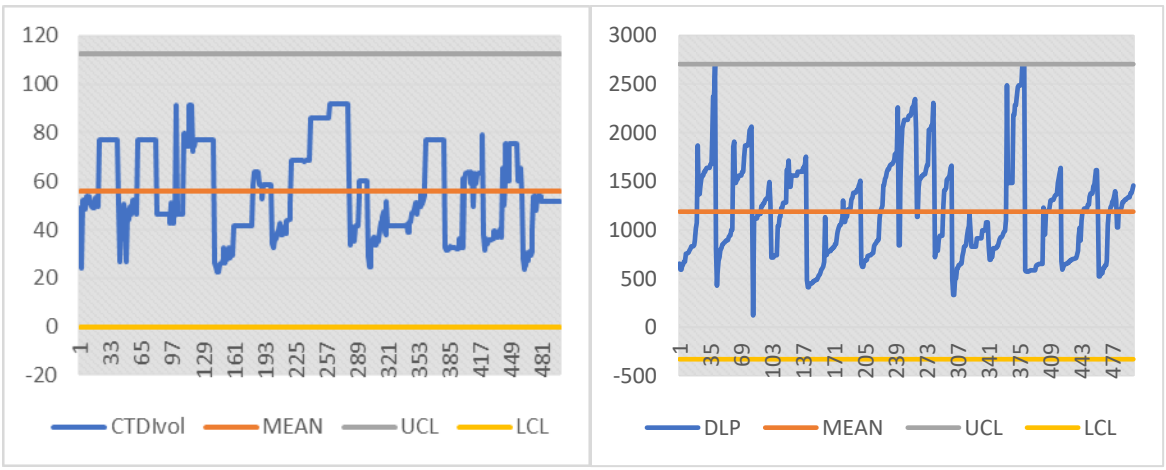

Figure 2: Control chart for *head injury/trauma* data sets (CTDI$_{vol}$ and DLP)

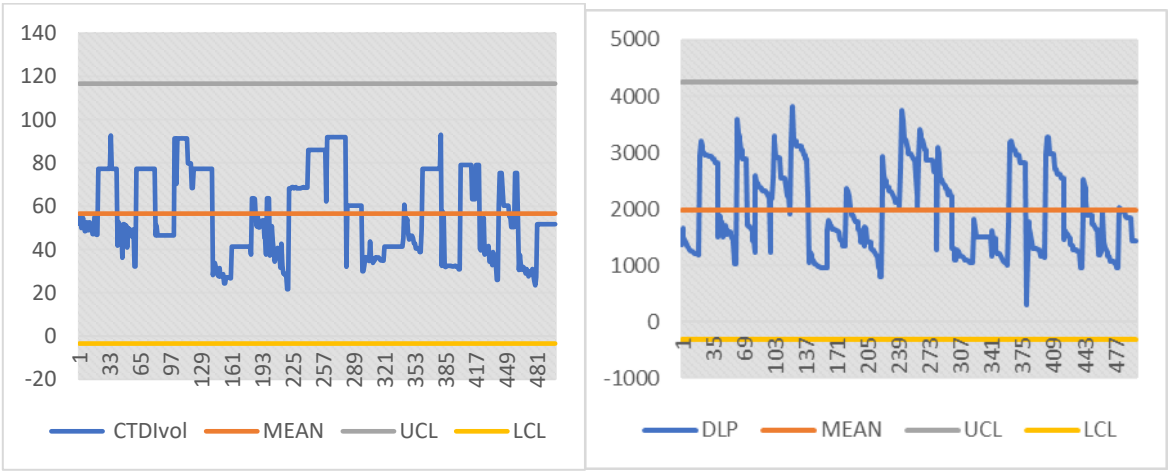

Figure 3: Control chart for *brain tumour/SOL* data sets (CTDI$_{vol}$ and DLP)

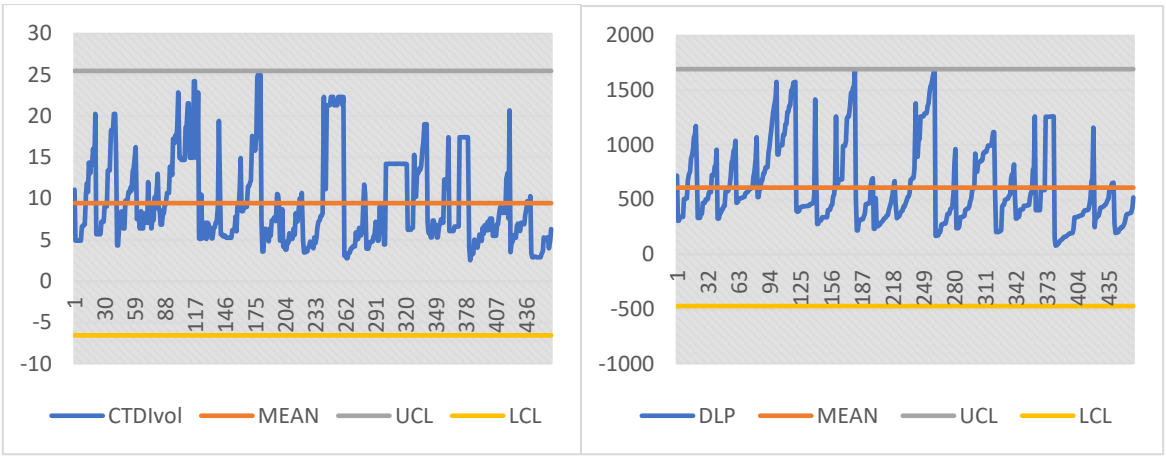

Figure 4: Control chart for *lung tumour/cancer* data sets ($CTDI_{vol}$ and DLP)

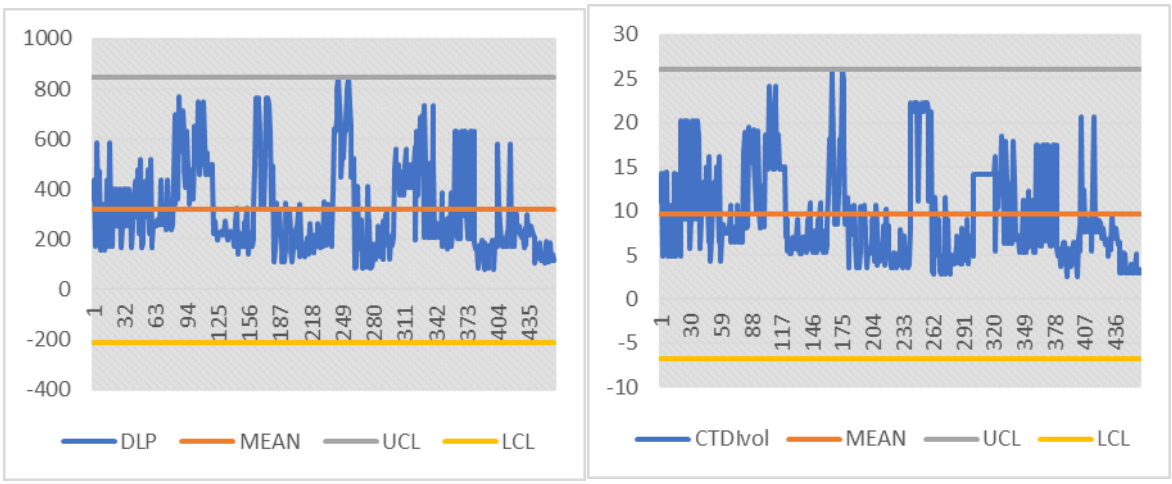

Figure 5: Control chart for *chest lesion with CKD* data sets ($CTDI_{vol}$ and DLP)

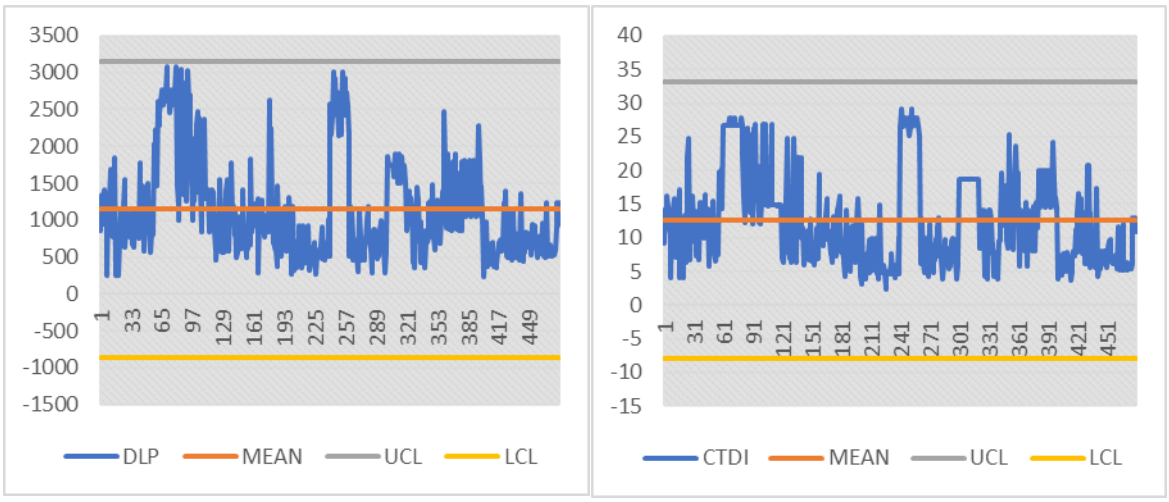

Figure 6: Control chart for *abdominopelvic lesion* data sets ($CTDI_{vol}$ and DLP)

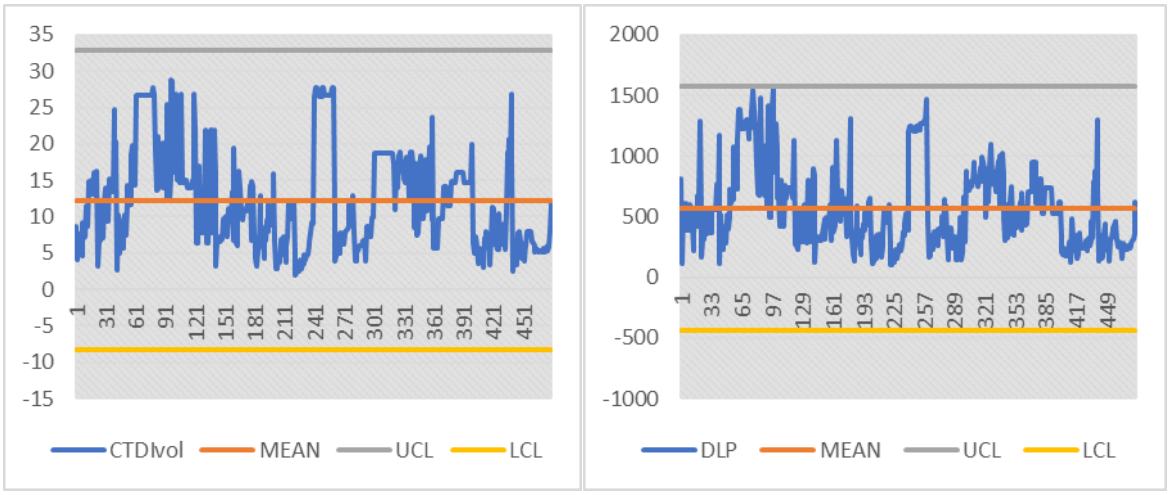

Figure 7: Control chart for *kidney stone* data sets ($CTDI_{vol}$ and DLP)

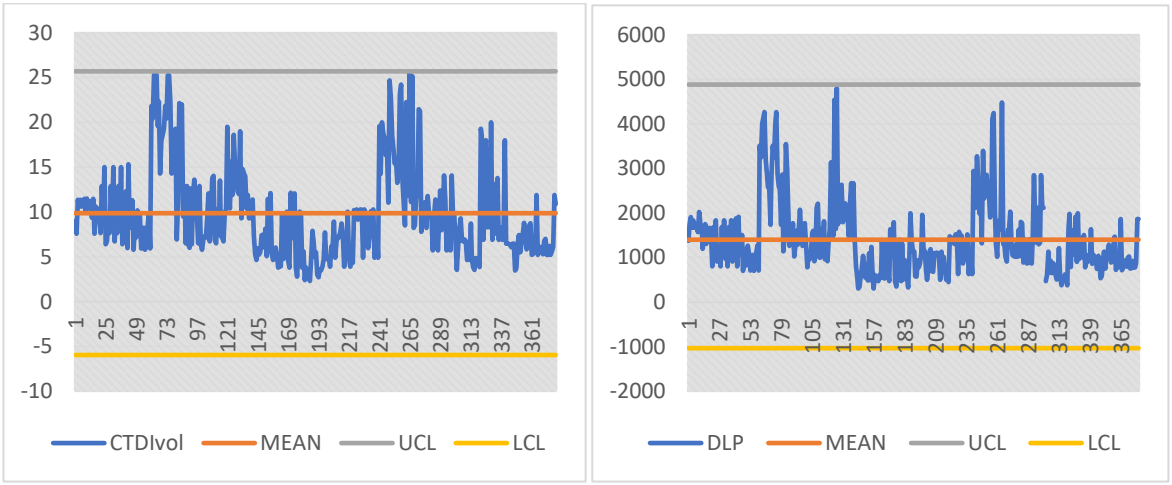

Figure 8: Control chart for *Urothelial malignancy* data sets ($CTDI_{vol}$ and DLP)

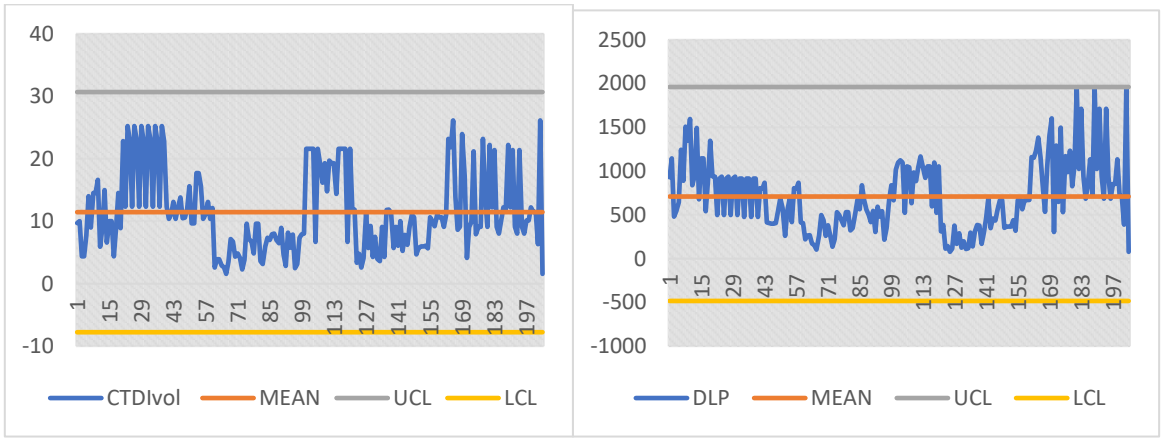

Figure 9: Control chart for *PE* data sets ($CTDI_{vol}$ and DLP)

APPENDIX IX: DISTANCES COVERED ABOVE AND BELOW UPPER TARGETS

Name of Institution.....CT MANUFACTURER/ MODEL.....

	Patient ID	CVA		Head injury / trauma		Headaches? SOL/tumour		Couth and chest pain? Lung cancer/tumour		Suspicion of lung lesion with CKD		? Abdomino-pelvic tumour/ lesion		? Kidney stones		? Urothelial malignancy (CT-IVU)		PE	
		DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)	DAUT (cm)	DBLT (cm)
1																			
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14																			
15																			
16																			
17																			
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19																			
20 etc																			

Key: DAUT=distance above upper target, DBLT=distance below lower target.

APPENDIX X: TESTING OF NORMALITY

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
BrainO	.220	39	.060	.832	39	.060
BrainR	.185	39	.052	.890	39	.061
EDoriginal	.210	39	.060	.900	39	.052
EDreduced	.116	39	.200*	.925	39	.073
Reduced	.116	39	.200*	.925	39	.073
ORIGINAL	.210	39	.060	.900	39	.052
P.glandO	.215	39	.075	.865	39	.070
Eye lensO	.217	39	.057	.849	39	.060
EyeballsO	.218	39	.076	.845	39	.076
S.glandO	.222	39	.089	.924	39	.067
O.cavityO	.215	39	.068	.871	39	.067
S.cordO	.235	39	.076	.863	39	.068
ThyriodO	.255	39	.056	.803	39	.091
p.glandR	.179	39	.083	.874	39	.067
Eye lensR	.245	39	.087	.875	39	.085
EyeballsR	.203	39	.052	.905	39	.067
S.glandR	.212	39	.056	.791	39	.067
O.cavityR	.323	39	.080	.534	39	.089
S.cordR	.308	39	.060	.553	39	.123
ThyroidR	.236	39	.000	.762	39	.057
DLP	.240	39	.100	.872	39	.089
N.Slices	.241	39	.006	.837	39	.097
CTD_{Ivol}	.224	39	.060	.801	39	.060
kVp	.475	39	.070	.522	39	.062
mAs	.187	39	.071	.856	39	.067
P	.347	39	.080	.768	39	.087
Thickness	.369	39	.052	.728	39	.056
SL	.145	39	.057	.928	39	.016
DAUT	.151	39	.025	.916	39	0.17
DBLT	.184	39	.002	.897	39	0.07
BOTHDAUTDBLT	.103	39	.200*	.940	39	0.08

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

APPENDIX XI: TESTING FOR OUTLIES

Grubbs' Test

Variable	N	Mean	StDev	Min	Max	G	P
SNR	100	9.274	3.401	5.437	15.760	1.91	1.000
Wt.	100	72.780	9.138	51.000	90.000	2.38	1.000
Age	100	57.92	15.87	28.00	92.00	2.15	1.000
kVp	100	121.90	3.94	120.00	130.00	2.05	1.000
mAs	100	223.3	102.5	100.0	400.0	1.72	1.000
$CTDI_{vol}$	100	54.59	18.99	30.27	86.00	1.65	1.000
DLP	100	1028.1	336.7	486.6	1699.6	1.99	1.000
P	100	0.6883	0.1692	0.4000	1.0000	1.84	1.000
N. slices	100	48.44	15.76	29.00	80.00	2.00	1.000
N. slices	100	48.44	15.76	29.00	80.00	2.00	1.000
SL	100	171.87	14.21	135.00	202.32	2.59	0.845
DAUT	100	8.065	7.078	0.000	32.000	3.38	0.052
DBLT	100	20.21	11.33	6.00	50.30	2.66	0.697
DAUT+ABLT	100	28.28	13.55	6.00	60.60	2.39	1.000
Original SL	100	926.7	279.7	486.6	1582.4	2.34	1.000
ED full range	100	2.1315	0.6434	1.1192	3.6395	2.34	1.000
10*	100	715.1	213.3	395.8	1238.4	2.45	1.000
ED reduced	100	1.6447	0.4905	0.9103	2.8483	2.45	1.000
BrainO	100	39.31	13.75	21.27	65.44	1.90	1.000
P. glandO	100	33.27	10.30	17.67	57.03	2.31	1.000
Eye lensO	100	46.09	15.41	25.90	75.93	1.94	1.000
Eye ballsO	100	43.85	14.67	24.58	71.97	1.92	1.000
S. glandO	100	21.297	9.251	5.600	52.810	3.41	0.086
O.cavityO	100	14.420	7.663	3.600	41.930	3.59	0.721
S. cordO	100	2.852	1.581	0.950	9.340	4.10	0.562
ThyroidO	100	1.1141	0.6527	0.4500	3.5500	3.73	0.081
BrainR	100	35.02	11.53	20.09	61.28	2.28	1.000
P. glandR	100	23.224	7.949	1.790	47.970	3.11	0.144
Eye lensR	100	31.33	15.65	3.53	69.08	2.41	1.000
Eye ballsR	100	30.22	13.36	5.03	64.59	2.57	0.901
S. glandR	100	5.314	4.846	1.160	29.060	4.90	0.090
O.cavityR	100	3.513	2.888	1.300	23.080	6.78	0.060
S. cordR	100	0.8362	0.6362	0.3200	5.1400	6.77	0.064
ThyroidR	100	0.4773	0.2837	0.1700	1.9600	5.23	0.067
Oeff.dose brain	100	0.3931	0.1375	0.2127	0.6544	1.90	1.000
Reffe.dose brain	100	0.3502	0.1153	0.2009	0.6128	2.28	1.000
Oeffec.dose Thyroid	100	0.04456	0.02611	0.01800	0.14200	3.73	0.071
Reffec.dose Thyroid	100	0.01909	0.01135	0.00680	0.07840	5.23	0.670
OEffective dosesalivary gland	100	0.21297	0.09251	0.05600	0.52810	3.41	0.076
REffective dosesalivary gland	100	0.05314	0.04846	0.01160	0.29060	4.90	0.700

APPENDIX XII: TEST FOR MULTICOLLINEARITY

Ist test for multicollinearity

Coefficients[a]

Model		Collinearity Statistics	
		Tolerance	VIF
1	$CTDI_{vol}$	.474	2.110
	P	.716	1.396
	Slice thickness	.211	4.730
	SNR	.179	5.587
	SL	.558	1.791
	kVp	.273	3.658

a. Dependent Variable: LensO

Final test for multicollinearity after removal of some highly corelated variables

Coefficients[a]

Model		Collinearity Statistics	
		Tolerance	VIF
1	$CTDI_{vol}$	.566	1.767
	Slice thickness	.484	2.065
	SL	.559	1.789

a. Dependent Variable: LensO

APPENDIX XIII: ETHICAL APPROVAL-UNIVERSITY OF GHANA ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES (ECDAS)

UNIVERSITY OF GHANA
ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES (ECBAS)
P. O. Box LG 1195, Legon, Accra, Ghana

Ref. No: ECBAS 041/17-18

4th May, 2018.

Mr. Benard Botwe
Dept. of Nuclear Security and Safety
School of Nuclear and Applied Sciences
University of Ghana
Legon, Accra

Dear Mr. Botwe,

ECBAS 041/17-18: DEVELOPMENT OF INDICATION-BASED DIAGNOSTIC REFERENCE LEVELS FOR COMPUTED TOMOGRAPHY EXAMINATON IN GHANA

This is to inform you that the above reference study has been presented to the Ethics Committee for Basic and Applied Sciences for a full board review and the following actions taken subject to the conditions and explanation provided below:

Expiry Date:	3/05/19
On Agenda for:	Initial Submission
Date of Submission:	27/02/2018
ECBAS Action:	Approved
Reporting:	Annual

Please accept my congratulations.

Yours sincerely,

ETHICS COMMITTEE FOR BASIC AND APPLIED SCIENCES
APPROVED
07 MAY 2018
UNIVERSITY OF GHANA

Professor Daniel Bruce Sarpong
ECBAS Chairperson

Tel: +233-207684121
Email: eoghartey@ug.edu.gh / ethicscbas@ug.edu.gh

APPENDIX XIV: ETHICAL APPROVAL-GHANA HEALTH SERVICE ETHICS REVIEW COMMITTEE

GHANA HEALTH SERVICE ETHICS REVIEW COMMITTEE

In case of reply the number and date of this Letter should be quoted.

Research & Development Division
Ghana Health Service
P. O. Box MB 190
Accra
Tel: +233-302-681109
Fax + 233-302-685424
Email: ghserc@gmail.com

MyRef. GHS/RDD/ERC/Admin/App/18/245
Your Ref. No.

23rd May, 2018

Benard Botwe
University of Ghana
School of Nuclear and Allied Sciences
Accra

The Ghana Health Service Ethics Review Committee has reviewed and given approval for the implementation of your Study Protocol.

GHS-ERC Number	**GHS-ERC002/04/18**
Project Title	Development of Indication-Based Diagnostic Reference Levels for Computed Tomography Examinations in Ghana
Approval Date	23rd May,2018
Expiry Date	22nd May, 2019
GHS-ERC Decision	**Approved**

This approval requires the following from the Principal Investigator

- Submission of yearly progress report of the study to the Ethics Review Committee (ERC)
- Renewal of ethical approval if the study lasts for more than 12 months,
- Reporting of all serious adverse events related to this study to the ERC within three days verbally and seven days in writing.
- Submission of a final report **after completion** of the study
- Informing ERC if study cannot be implemented or is discontinued and reasons why
- Informing the ERC and your sponsor (where applicable) before any publication of the research findings.

Please note that any modification of the study without ERC approval of the amendment is invalid.

The ERC may observe or cause to be observed procedures and records of the study during and after implementation.

Kindly quote the protocol identification number in all future correspondence in relation to this approved protocol

SIGNED.....
DR. CYNTHIA BANNERMAN
(GHS-ERC CHAIRPERSON)

Cc: The Director, Research & Development Division, Ghana Health Service, Accra

APPENDIX XV: ETHICAL APPROVAL -THE KORLE BU TEACHING HOSPITAL INSTITUTIONAL REVIEW BOARD (KBTH)

In case of reply the number
And the date of this
Letter should be quoted
My Ref. No. KBTH/MD/G3/18
Your Ref. No......

KORLE BU TEACHING HOSPITAL
P. O. BOX KB 77,
KORLE BU, ACCRA.

Tel: +233 302 667759/673034-6
Fax: +233 302 667759
Email: Info@kbth.gov.gh
pr@kbth.gov.gh
Website: www.kbth.gov.gh

26th April, 2018

BERNARD BOTWE
SCHOOL OF NUCLEAR AND ALLIED SCIENCES
UNIVERSITY OF GHANA, LEGON

DEVELOPMENT OF INDICATION-BASED DIAGNOSTIC REFERENCE LEVELS FOR COMPUTED TOMOGRAPHY EXAMINATIONS AT THE KORLE BU TEACHING HOSPITAL

KBTH-IRB /00092/2017

Investigator: Bernard Botwe

The Korle Bu Teaching Hospital Institutional Review Board (KBTH IRB) reviewed and granted approval to the study entitled "Development of indication-based diagnostic reference levels for computed tomography examinations at the Korle Bu Teaching Hospital"

Please note that the Board requires you to submit a final review report on completion of this study to the KBTH-IRB.

Kindly, note that, any modification/amendment to the approved study protocol without approval from KBTH-IRB renders this certificate invalid.

Please report all serious adverse events related to this study to KBTH-IRB within seven days verbally and fourteen days in writing.

This IRB approval is valid till 30th March, 2020. You are to submit annual report for continuing review.

Sincere regards,

OKYERE BOATENG (MR)
CHAIR (KBTH-IRB)

Cc: The Chief Executive Officer
Korle Bu Teaching Hospital

The Director of Medical Affairs
Korle Bu Teaching Hospital

MEDICAL DIRECTORATE
KORLE BU TEACHING HOSPITAL

4th May, 2018

BERNARD BOTWE
SCHOOL OF NUCLEAR AND ALLIED SCIENCES
UNIVERSITY OF GHANA, LEGON

INSTITUTIONAL APPROVAL: KORLE BU TEACHING HOSPITAL-SCIENTIFIC AND TECHNICAL COMMITTEE/INSTITUTIONAL REVIEW BOARD (KBTH-STC/IRB/00092/2017

Following approval of your study entitled "Development of indication-based diagnostic reference levels for computed tomography examinations at KBTH. A study at the Korle Bu Teaching Hospital" by the Korle Bu Teaching Hospital-Scientific and Technical Committee/Institutional Review Board. I am pleased to inform you that institutional approval has been granted for the conduct of your study in Korle Bu Teaching Hospital.

Please contact the Head of Department to discuss the commencement date of the study.

Please note that, this institutional approval is rendered invalid if the terms of the Institutional Reviewed Board/Scientific and Technical Committee approval are violated.

Sincere regards,

Dr. Samuel Asiamah
Director of Medical Affairs
For: Chief Executive Officer

APPENDIX XVI: OTHER PERMISSION LETTERS

Quest Medical Imaging
RADIOLOGISTS

Dr A. Karrinta
MBChB (UGMS), DMACS, FGCPS
Dr J.W. Bergman
M.BChB(UCT), FCP(SA)MMED,DIP.RAD(SA)
Dr J. Ross
M.BChB(UCT), DIP.RAD(SA)

Dr. S. Anim-Sampong
Head of Department
Department of Radiography
School of Biomedical and Allied Health Sciences
College of Health Sciences
University of Ghana
Accra. Ghana.

Dear Sir,

I am happy to inform you that management has agreed to your request for permission for Mr Bernad Ohene Botwe to carry out research studies at Quest Medical Imaging Limited, Accra. Ghana.

The following are our research project requirement. Please can you provide us with copies of the following:

(i) Documentation of approval by the appropriate ethical committee
(ii) The detailed study protocol to review

In addition, we will sign an Non-Disclosure Agreement (NDA) with you and then set up an in-house protocol to guide the studies.

We are looking forward to this co-operation.

Yours sincerely,

EXECUTIVE DIRECTOR
QUEST MEDICAL IMAGING LTD.
27 MASERU ST.
EAST LEGON
ACCRA, GHANA

Dr Paul S-Nyantakyi
Executive Director

Quest Medical Imaging in association with MDS Lancet & Bergman Ross & Partners Radiology, Cape Town
27 Maseru Street, East Legon, Accra, Ghana. Tel: 0302 554 4023 | 0244 411 2318 | 0302 410 2310
(On the same premises as MDS Lancet Laboratories, East Legon)

www.questmedicalimaging.com

NYAHO
MEDICAL CENTRE

April 24, 2018

Head, Department of Nuclear Safety and Security

Nuclear Regulatory Authority

Dear Dr. Kpeglo,

RE: INTRODUCTION OF MR. BENARD BOTWE

We acknowledge receipt of your letter dated April 6, 2018 regarding your intent to access our facility and to collect CT dose parametric data from our CT scanner.

Your letter has been forwarded to the Diagnostics Manager who will provide assistance during your visit.

Please note that all data obtained from the Centre must be de-identified. Under no circumstances will the identifiers be made available.

Yours Sincerely,

Abdool G.H.S Amod
Operations Director

Cc: Dr. Elikem Tamaklo
Managing Director

Magzy Frimpong Dumfeh
Diagnostics Manager

GHANA COCOA BOARD

COCOA HOUSE CLINIC
P. O. BOX 933
ACCRA
GHANA

TEL: 233-302-661752/661872/
661757/678916/678972
FAX: 233-302-667104/660808
E-mail: coonbod@cocobod.gh
WEBSITE: www.cocobod.gh
CABLE: COCOBOD, ACCRA.

IN YOUR REPLY
PLEASE QUOTE: CC/ATT.35/V13/29

DATE: 19th April, 2018

The Ag. Director, Radiological
& Non-Ionising Inst.
Nuclear Regulatory Authority
P. O. Box AE 50
Atomic Energy
Kwabenya

Dear Sir/Madam,

RE: INTRODUCTION – MR. BENARD BOTWE

We refer to your letter No. NRA/SN 17/35 dated 6th April, 2018 on the above-mentioned subject and wish to convey Management's approval for Mr. Benard Botwe to carry out his research by obtaining data from the Clinic.

We however, wish to request that a copy of the findings should be made available to Management for our perusal and guidance. We should also be served with a copy of the questionnaire for our guidance before administering to our client.

You can count on our co-operation.

Yours faithfully,

AUGUSTA NYAKO (MRS.)
HOSPITAL ADMINISTRATOR
FOR: DIRECTOR (HEALTH)

cc: Director (Health)
Head, Radiology
Mr. Bernard Botwe

SCHOOL OF NUCLEAR AND ALLIED SCIENCES
UNIVERSITY OF GHANA
ATOMIC CAMPUS

DEPARTMENT OF NUCLEAR SAFETY AND SECURITY

Telephone Accra 400722,400310
Fax 233-21-400807

P. O. Box AE 1
Atomic Energy
Accra-Ghana

Our Ref. DNSAS /SNAS/ADM /EXT/4/18

Your

5th March 2018

The Head
Medical Physics Department
Sweden Ghana Medical Centre
Accra

Dear Sir,

REQUEST TO USE CT QC KIT

I am writing on behalf of Mr. Benard Botwe a PhD radiation protection student of the Department of Nuclear Safety and Security, School of Nuclear and Allied sciences, University of Ghana with the student ID number 10600444. His dissertation is on the topic "*Development of Indication-Based Diagnostic Reference Levels for Computed Tomography Examinations in Ghana*"
As part of the preparations for this study, He will need your assistance for data collection in the certified CT scanners in the country for his research.

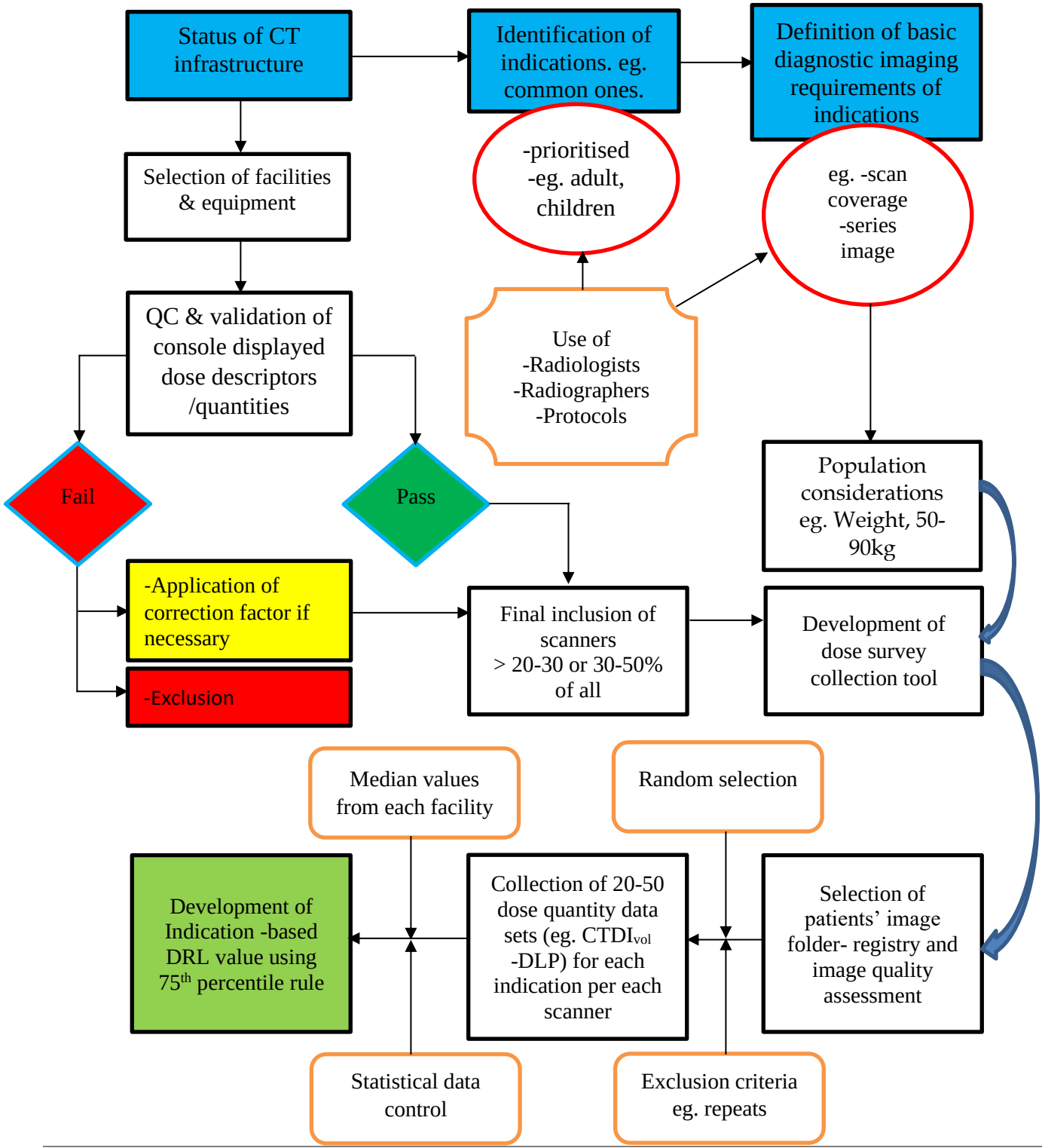
We would therefore appreciate if you could grant Mr. Benard Botwe access to use your CT QC KIT to enable him collect data from facilities with certified CT scanners in the country to carry out his research work.

Counting on your cooperation. Thank you

Yours faithfully,

Dr. David O. Kpeglo
Head, Department of Nuclear Safety and Security

APPENDIX XVII: SUPPORTING DOCUMENT SHOWING AN EXPANDED VERSION OF THE METHODOLOGICAL/CONCEPTUAL FRAMEWORK (FIGURE 3.1) USED FOR CONDUCTING PHASES 1 TO 4 STUDIES.



QC: quality control, DRL: diagnostic reference level, CT: computed tomography, $CTDI_{vol}$: volume weighted computed tomography dose index, DLP: dose length product.

APPENDIX XVIII: PUBLICATION LISTS

1. Authors: Botwe, B., Schandorf, C., Inkoom S., Faanu, A. (2020). An investigation into the infrastructure and management of Computerized Tomography units in Ghana. *Journal of Medical Imaging and Radiation Sciences,* 51(2020), 165-172.

2. Authors: Botwe, B., Schandorf, C., Inkoom S., Faanu, A. (2020). Status of Quality Management Systems in Computed Tomography Facilities in Ghana. *Radiologic Technology,* 91(4), 324-332.

APPENDIX XIX: CONFERENCE AND POSTER PRESENTATION

1. Botwe, B., Schandorf, C., Inkoom S., Faanu, A, Rolstadaas L, Goa, P.E (2019). CT indication-based diagnostic reference levels and dose optimisation steps in Ghana. 10th Pan African Congress of Radiology and Imaging Conference. 14th -16th February 2019.
2. Botwe, B., Schandorf, C., Inkoom S., Faanu, A (2019).

   An investigation into the infrastructure and management of Computerized Tomography units in Ghana. KBTH Research day. Research Unit Korle Bu Teaching Hospital. 4th December 2019.
3. Botwe, B., Schandorf, C., Inkoom S., Faanu, A, Rolstadaas L, Goa, P.E (2019). Indication-Based Diagnostic Reference Levels: Maiden Values from Ghana. Ghana-Norway Summer School under the theme Quality 3D Imaging and Applications in Radiotherapy Treatment Delivery; 24 - 28 June 2019; KNUST, Kumasi.
4. Botwe, B., Schandorf, C., Inkoom S., Faanu, A, Rolstadaas L, Goa, P.E (2018). Comparison of Indication-Based Diagnostic Reference Level Values: A case of Norway and Ghana. Norwegian University of Science and Technology (NTNU), Physics and Radiography departments. (Student Research Conference, 6th December 2018).
5. Botwe, B., Schandorf, C., Inkoom S., Faanu, A, (2018). Preliminary findings on CT Indication-Based Diagnostic Reference Levels in Ghana. Ghana Norway Summer School under the theme; MRI, Ultrasound and X-Ray Imaging. 25 - 29 June 2018; UDS, Tamale.

APPENDIX XX: AWARDS ASSOCIATED WITH THE STUDY

The research won the International Society of Radiographers and Radiological Technologists (ISRRT) 2019 Chesney Award (Winner) for the best research likely to improve quality of services in practice in the discipline of medical imaging and/or radiation therapy.

/2019-chesney-award-winner-announcment

ISRRT
INTERNATIONAL SOCIETY OF RADIOGRAPHERS & RADIOLOGICAL TECHNOLOGISTS

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Home > Blog > 2019 Chesney Award Winner announcment

2019 Chesney Award Winner announcment

ISRRT announces that the winner of the Chesney-ISRRT Research Fund 2019 is Mr. Benard Ohene Botwe, a radiographer and a doctoral student at the University of Ghana. His research title is the "DEVELOPMENT OF INDICATION-BASED DIAGNOSTIC REFERENCE LEVELS FOR COMPUTED TOMOGRAPHY EXAMINATIONS IN GHANA".

Mr. Benard Ohene Botwe is a Radiographer from Ghana and a Clinical Tutor at Department of Radiography, School of Biomedical and Allied Health sciences, University of Ghana. He is also a Ph.D. student at the School of Nuclear and Allied Sciences, University of Ghana.

Benard obtained his undergraduate and postgraduate degrees in radiography from the University of Ghana and Cardiff University (UK) respectively. He is also an alumnus of the Norwegian University of Science and Technology (NTNU) and has published 20 articles and successfully supervised 33 undergraduate radiography students to complete their research projects. He has broad clinical experience in fluoroscopy, CT, MRI and interventional radiography.

Currently, his research interests include Diagnostic reference levels in computed tomography, radiation dose optimization in diagnostic imaging, optimization of imaging practices, interventional radiography, forensic radiography and radiography ethics and education.

His current research project is entitled "Development of indication-based diagnostic reference levels for computed tomography examinations in Ghana". In line with the Bonn call for action 2, Benard is trying to develop an indication-based radiation monitoring tool that can be used as a trigger to identify radiologic facilities using unusually high doses in a specified procedure, for which optimisation actions are required.

The candidate received an exchange studentship at the Norwegian University of Science and Technology as part of the PhD studies and thesis write-up under the NORPART PROJECT.

NTNU

Norwegian University of Science and Technology
Faculty of Natural Sciences and Technology
Department of Physics

Date 2018-06-21 Our reference

Your letter dated Your reference

Botwe, Benard

Dear Mr Botwe,

Confirmation of Scholarship

This letter is to confirm that you are awarded an Exchange Student Scholarship for the period 01.08.2018-31.12.2018 from the NORPART-PROJECT 2016-10470 "Ghana-Norway Collaboration in Medical Physics and Radiography Education".

The monthly amount of the scholarship is NOK 16.000, in total for five months: NOK 80.000. This scholarship is meant to cover all living expensed, including housing. In addition you are awarded a travel scholarship of NOK 12.000. The total scholarship amounts to NOK 92.000.

Our Exchange Student Coordinator Dr. Mercy Afadzi in collaboration with the International Section at NTNU will assist you with the preparations of your stay in Trondheim. Dr Afadzi will book your flight tickets and arrange housing. The monthly rent is NOK 5640, in total for five months NOK 28200. The cost for the flight and the housing will be deducted from your scholarship before payout. A deposit of NOK 9.000 for housing will also be deducted from the scholarship. This deposit will be payed out upon leaving your room at the end of the stay in good condition as specified by the housing contract. The scholarship (after deductions) will be payed out after your arrival in Trondheim.

Please contact Dr. Mercy Afadzi (mercy.afadzi@ntnu.no, +47 948 77 294) for more information about the practical arrangements regarding the scholarship, housing and travel.

On behalf of NORPART-PROJECT 2016-10470

Pål Erik Goa, Associate Professor
Project Coordinator

Address	Org. no. 974 767 880	Location	Phone	Contact person
NO-7491	Email:	Høgskoleringen 5	+ 47 73 59 34 78	
Trondheim	postmottak@phys.ntnu.no	Realfagbygget D5-170	Fax	
Norway	http://www.ntnu.no/fysikk	Gløshaugen	+ 47	Phone: + 47

Appendix XXI: COPIES OF PUBLISHED ARTICLES

First article link: https://pubmed.ncbi.nlm.nih.gov/32057744/

ELSEVIER

Journal of Medical Imaging and Radiation Sciences 51 (2020) 165-172

Journal of Medical Imaging and Radiation Sciences

Journal de l'imagerie médicale et des sciences de la radiation

www.elsevier.com/locate/jmir

Research

An Investigation into the Infrastructure and Management of Computerized Tomography Units in Ghana

Benard Botwe, MSc[ab*], Cyril Schandorf, PhD[a], Stephen Inkoom, PhD[cd] and Augustine Faanu, PhD[ae]

[a] *Department of Nuclear Safety and Security, School of Nuclear and Allied Sciences, University of Ghana, Atomic Campus, Accra, Ghana, Legon*
[b] *Radiography Department, School of Biomedical and Allied Health Sciences, Collegue of Health Sciences, University of Ghana, Korle-Bu Campus, Accra, Ghana*
[c] *Medical Physics Department, School of Nuclear and Allied Sciences, University of Ghana, Atomic Campus, Accra, Ghana*
[d] *Radiation Protection Institute (RPI), Ghana Atomic Energy Commission, Accra, Ghana*
[e] *Radiological and Non-ionizing Radiation Directorate, Nuclear Regulatory Authority, Accra, Ghana*

ABSTRACT

Introduction: In Ghana, there is a need to document computed tomography (CT) infrastructure and management systems for the development of interventions to promote CT practices while ensuring patient protection through the establishment of diagnostic reference levels and improved dose management systems.

Methods: A quantitative inquiry using a descriptive, cross-sectional approach was used to collect data, using a semistructured questionnaire related to CT infrastructure and management from the technical heads responsible for CT scanners. Data collected included the scanner characteristics, basic management system and organizational arrangements, number of attending practitioners, clinical indications for CT examinations, and the operation of CT facilities in Ghana.

Results: Of the 35 CT scanners installed across the country, 31 were involved in the study. The majority (29%) were Toshiba models. Equipment slices ranged from 1 to 640, of which 45.2% were 16-slice scanners. Many ($n = 28$, 90.3%) were functioning, and most were installed in the capital city, Accra. The equipment mean age was 7.3 ± 4.4 years, and 25.6% were 10 or more years old. There were 107 operating radiographers, 60 reporting radiologists, and 10 medical physicists employed across the facilities. A total of 204,760 CT examinations were performed yearly (6.8 CT procedures per 1000 people in Ghana). Head CT procedures were the most common, and suspicion of cerebrovascular accident or stroke (32.8%) was the most common indication. Some basic quality management system and policy driving CT infrastructure in Ghana were lacking.

Conclusion: The results have provided essential information on the status of CT infrastructure and management systems for policy development and planning in CT facilities in Ghana. This study provides those interested in CT services, jobs, or medical equipment investment in Ghana the information needed to make appropriate decisions.

RÉSUMÉ

Introduction : Au Ghana, il est nécessaire de documenter l'infrastructure et les systèmes de gestion de tomodensitométrie (TDM) afin de développer des interventions visant à promouvoir les pratiques de TDM tout en assurant la protection des patients par l'établissement de niveau de référence pour le diagnostic et de systèmes améliorés de gestion de la dose.

Méthodologie : Une étude quantitative utilisant une approche descriptive transversale a été utilisée pour recueillir, au moyen d'un

The first author received grant from the BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana.
Competing interests: The first author received a study grant from the BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana. However, there was no relationships or activities that could appear to have influenced the submitted work. All other authors declare no financial relationships with any organizations that might have an interest in the submitted work in the previous 3 years and no other relationships or activities that could appear to have influenced the submitted work.
Authors' contributions: All authors contributed to the conception of the work. First author (BB) mainly contibuted to the design of the work, the acquisition, analysis, or interpretation of the data. All authors were involved in drafting and commenting on the paper and have approved the final version.
Ethical approval: Before the study, ethical clearance was sought and approved by the Ethics Committee for Basic and Applied Sciences, University of Ghana (Ref. No: ECBAS 041/17-18), the Ghana Health Service Ethics Review Committee (Ref no: GHS-ERC002/04/18), and the Korle Bu Teaching Hospital's Scientific and Technical Committee and the Institutional Review Board (Ref No: KBTH-IRB/00092/2017). This was in compliance with the Helsinki Declaration. Subsequently, permissions were sought and granted by the technical heads responsible for the CT scanners in the country for the study to be undertaken in their facilities.
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1939-8654/$ - see front matter
https://doi.org/10.1016/j.jmir.2019.11.140

questionnaire semi-structuré, des données sur l'infrastructure de TDM et les systèmes de gestion auprès des chefs techniques responsables de l'équipement de TDM. Les données recueillies comprennent les caractéristiques de l'appareil, le système de gestion de base et les arrangements organisationnels, le nombre de praticiens, les indications cliniques pour les examens de TRM et le fonctionnement des installations de TDM au Ghana.

Résultats : Sur les 35 appareils de TDM installés au Ghana, 31 ont été couverts par l'étude. La majorité (29 %) sont des appareils Toshiba. Le nombre de tranches de l'équipement varie de 1 à 640, dont 45,2 % sont des appareils à 16 tranches. Plusieurs appareils ($n = 28$, 90,3 %) sont en état de fonctionner et la plupart sont installés dans la capitale, Accra. L'âge moyen des appareils est de 7,3±4,4 ans, et 25,6 % ont plus de 10 ans. Les différents établissements emploient au total 107 radiographes, 60 radiologistes et 10 physiciens médicaux. Au total, 204 760 examens de TDM sont effectués chaque année (6,8 procédures par 1000 personnes au Ghana). Les procédures de TDM de la tête sont les plus communes, et la suspicion d'accident cardiovasculaire ou vasculaire cérébral (32,8 %) était l'indication la plus commune. Certains SGQ et certaines politiques de base de l'infrastructure de TDM au Ghana étaient déficients.

Conclusion : Les résultats ont permis d'obtenir des renseignements essentiels sur l'état de l'infrastructure et des systèmes de gestion de la TDM en vue du développement des politiques et de la planification des installations de TDM au Ghana. Cette étude fournit aux personnes et organismes intéressés par les services de TDM, les emplois et l'investissement dans l'équipement médical au Ghana les renseignements nécessaires à la prose de décisions appropriées.

Keywords: Imaging; scanners characteristics; organizational policies

Introduction

Computed tomography (CT) is a critical tool in medicine [1,2]. Although CT is associated with higher radiation doses compared with planar radiographic imaging, it is often the most appropriate modality and first line of examination. In emergency departments alone, studies have shown that CT utilization has significantly reduced mortality, especially among patients who sustained injuries associated with road traffic accidents [3–5].

Because of the enormous clinical benefits of CT, it is used worldwide to establish medical diagnoses and perform image-guided interventions [6]. The rapid development of CT technology and the increased incidence of cancer cases globally, as well as other health conditions, have further placed more demands on CT scanners, especially in developing countries [7,8] where access to CT can be limited.

In Ghana, the first CT scanner was installed in 1994 at the Korle Bu Teaching Hospital. Since then, the number of CT installations in the public, private, and private-government (quasi) organizations has increased. In 2012, the Government of Ghana undertook a large-scale equipment replacement exercise to replace obsolete scanners. They also planned to provide at least one CT scanner in each teaching or regional hospital. This, coupled with the development of private health facilities, has resulted in the installation of a greater number of CT scanners in the country, with the intention of improving patient access. Unfortunately, there is no publication on the status of CT characteristics and infrastructure in Ghana.

The World Health Organization has encouraged countries to develop health care infrastructure [9], which includes radiological equipment, such as CT machines, because quality infrastructure can have a significantly positive impact on the provision of quality health services [9]. In response, Ghana, is making efforts toward developing CT infrastructure and management systems [10,11]. In the aspect of radiation protection, these efforts involve the development of interventions to promote CT practices while ensuring patient protection through the development of diagnostic reference levels (DRLs) and dose management systems. As a first step, this study was, therefore, directed at exploring and describing the available CT infrastructure and management systems, including the scanner characteristics, basic management system and organizational arrangements, number of attending practitioners, clinical indications for CT examinations, and the operation of CT facilities in Ghana. Apart from providing these pertinent data to local stakeholders to drive CT infrastructural expansion, the outcome was also envisaged to help international professionals—especially those with interest in CT services, jobs, or medical equipment investment in Ghana—in order to make appropriate decisions.

Method

A descriptive, cross-sectional study design was undertaken between December 2017 and March 2018. Before the study, ethical clearance was sought and approved by the Ethics Committee for Basic and Applied Sciences, University of Ghana (reference number: ECBAS 041/17-18), the Ghana Health Service Ethics Review Committee (reference number: GHS-ERC002/04/18), the Korle Bu Teaching Hospital's Scientific and Technical Committee, and the Institutional Review Board (reference number: KBTH-IRB/00092/2017). The study was also in compliance with the Helsinki Declaration. Subsequently, permissions were sought and granted by the technical heads responsible for the CT scanners in the country for the study to be undertaken in their facilities.

According to the Nuclear Regulatory Authority (NRA), Ghana, there were 35 authorized CT scanners across the country at the time of the study. Figure 1 shows the geographical location of the scanners. A census sampling method was used to contact the technical heads of the CT facilities. An online, 42-item, semistructured questionnaire was then sent to the technical heads responsible for each of the 35 CT scanners, including a description of the aims of the study and

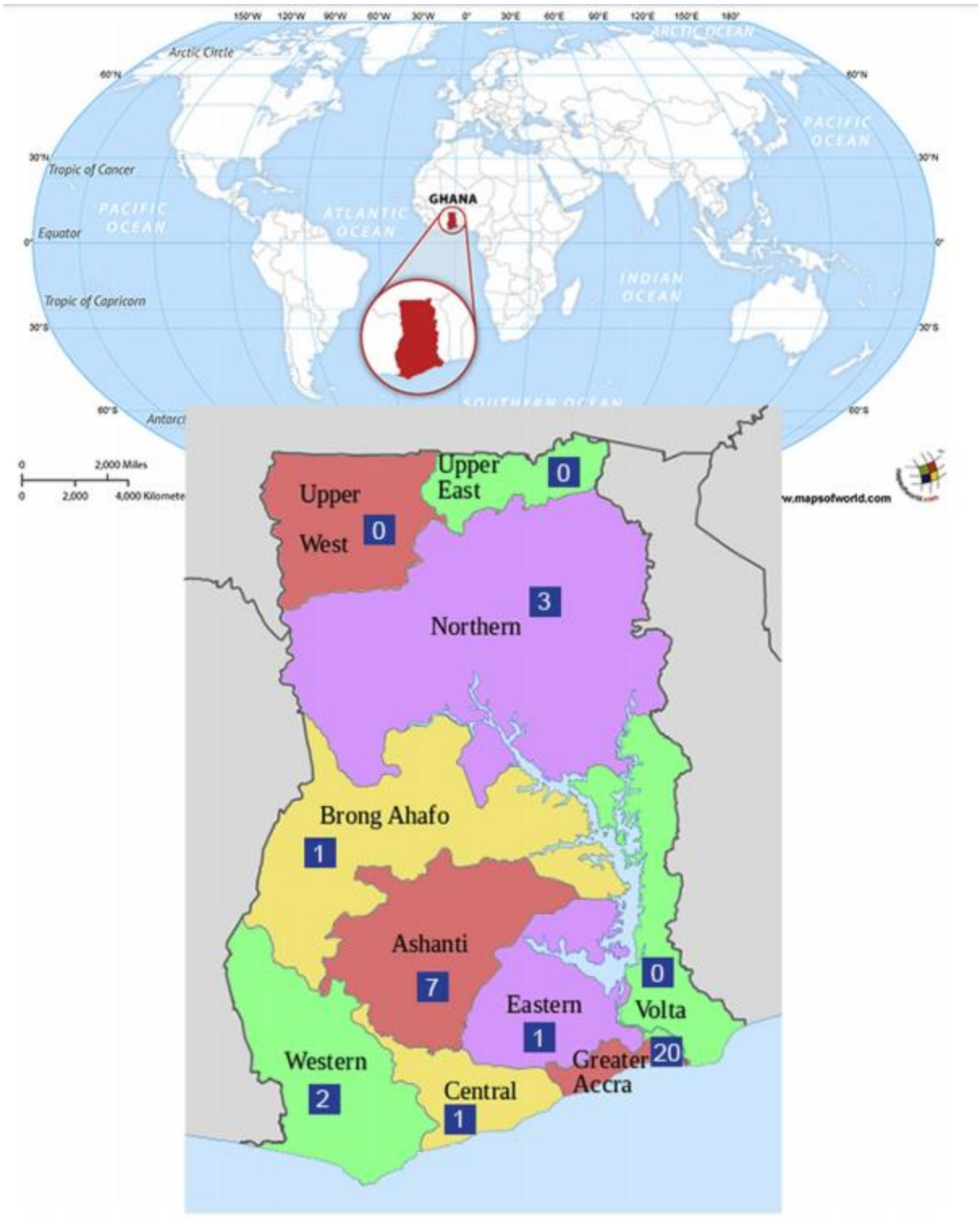

Figure 1. Geographical locations of the CT scanners in Ghana, 2017. CT, computed tomography.

Table 1
CT Models, Manufacturers, Years of Manufacture, Installation, and Number of Detector Rows/Slices ($N = 31$)

Hospital	CT ID	Manufacturer	Model	YoM	YoI	Detector Row/Slice
A	CT 1	Toshiba	Aquilion One TSX-301A	2012	2012	320/640
B	CT 2	Siemens	Somatom Emotion 6	2006	2011	6
C	CT 3	GE	Brightspeed Elite	2011	2011	16
D	CT 4	Philips	Brilliance ICT	2015	2016	128
E	CT 5	Siemens	Somatom Perspective	2016	2016	16
F	CT 6	GE	VCT Lightspeed	2008	2009	64
G	CT 7	Siemens	Somatom Perspective	2016	2017	64
H	CT 8	GE	Lightspeed Pro 16	2011	2011	16
I	CT 9	GE	Brivo CT 385 series	2015	2016	16
J	CT10	Siemens	Somatom Emotion	2007	2008	6
	CT11	Toshiba	Aquilion GX	2012	2012	128
K	CT12	Toshiba	Aquilion TSX-101A	2016	2016	16
L	CT13	Siemens	Somatom Emotion	2010	2010	16
M	CT14	Toshiba	Aquilion TSX-101A	2013	2013	16
N	CT15	Toshiba	Aquilion CXL TSX-101A	2015	2015	32
	CT16	Philips	Philips MX 16	2015	2016	16
O	CT17	Toshiba	Aquillion CXL TSX-101A	2012	2015	32
P	CT18	GE	Revolution Evo	2017	2017	64
Q	CT19	Philips	BRILLIANCE	2009	2010	4
R	CT20	Hitachi	Supria	2015	2015	16
S	CT21	Philips	Brilliance extended	2007	2010	64
T	CT22	Picker	PICKER PQ5000	1998	2017	1
U	CT23	Siemens	Somatom Emotion	2009	2010	16
V	CT24	GE	Brightspeed Edge#	1998#	2009#	8#
W	CT25	Siemens	Somatom Emotion	2010	2011	16
X	CT26	Siemens	Somatom Definition AS	2015	2016	64
Y	CT27	Philips	Brilliance 16	2010	2016	16
Z	CT28	Toshiba	Asteion	2009	2016	4
AA	CT29	Toshiba	Aquilion TSX-101A	2015	2015	16
AB	CT30	Toshiba	Aquilion TSX-101A	2012	2013	16
	CT31	GE	Optima 660	2016	2016	64

The sign "#" means that that machine was replaced with a 64-slice GE Revolution 5492001. It was manufactured and installed in 2018.
CT, computed tomography; YoI, year of installation; YoM, year of manufacture.

an information sheet that assured confidentiality and the option to decline participation at any stage.

The questionnaire was self-developed after reviewing literature [3–7] to identify conceptual information needed for this study and included both closed- and open-ended questions. Before arriving at the final questionnaire, a draft was developed that addressed the following indices: CT model; manufacturer; year of manufacture; installation and number of detector rows and slices; geographical location; ownership status; functionality; number of CT scanning radiographers, reporting radiologists, and attending medical physicists; number of examinations undertaken in a year; and the common indications for which adult CT procedures are requested and undertaken. The questionnaire also covered quality management systems (QMSs) that included quality assurance (QA) systems, quality improvement (QI) strategies, quality control (QC) records, and policies driving CT infrastructure in Ghana.

Two qualified medical physicists at the School of Nuclear and Allied Sciences took part in an exercise to validate the suitability of the questionnaire by rating the importance of each of the 45 questions for the intended objective. A scale

Table 2
Geographical Region, Ownership Status, and Functionality of the CT Scanners

Geographical Region	Ownership Status				Functional	
	Public	Private	Quasi	Total	Yes	No
Greater Accra	4 (12.90%)	11 (35.48%)	3 (9.68%)	18 (58.06%)	17 (54.84%)	1 (3.23%)
Ashanti	2 (6.45%)	4 (12.90%)	-	6 (19.35%)	5 (16.13%)	1 (3.23%)
Northern	2 (6.45%)	1 (3.23%)	-	3 (9.68%)	2 (6.45%)	1 (3.23%)
Western	1 (3.23%)	-	-	1 (3.23%)	1 (3.23%)	-
Eastern	1 (3.23%)	-	-	1 (3.23%)	1 (3.23%)	-
Brong Ahafo	1 (3.23%)	-	-	1 (3.23%)	1 (3.23%)	-
Central	1 (3.23%)	-	-	1 (3.23%)	1 (3.23%)	-
Total	12 (38.71%)	16 (51.61%)	3 (9.68%)	31 (100%)	28 (90.32%)	3 (9.68%)

CT, computed tomography; Quasi, private-government partnership.

Table 3
Number of CT Scanning Radiographers, Reporting Radiologists, and Attending Medical Physicists

Professionals	Number	Ratio to Population
Radiographers	107	1: 280,374
Radiologists	60	1: 500,000
Medical physicists	10	1: 3,000,000

of 0 (not important) to 1 (important) was used to score each question. Three questions that scored 0 were considered irrelevant and were removed. Subsequently, a pilot study and a test-retest reliability analysis were used to assess the reliability of the validated questionnaire. The Cohen's unweighted Kappa Statistic was used to test the agreement between scores obtained from the first and second questionnaires during the test-retest analysis. The Kappa value was found to be 0.80, which is considered a substantial agreement and a reliable questionnaire. The data obtained in the study were analysed with a Microsoft Excel version 2010, and the generated information were descriptive statistics.

Results

Responses were received from 31 of the 35 authorized facilities, representing an 88.6% response rate. The CT models, manufacturers, years of manufacture, installation, and number of detector rows and slices (n =31) have been presented in Table 1. Toshiba scanners (n = 9, 29%) were the most common models. The detector configuration of the scanners ranged from 1 to 640 slices (1–320 detector rows). The mean age of the equipment was 7.3 ± 4.4 years, and 25.6% of the scanners were 10 or more years old. Apart from three facilities that had two CT scanners, the remaining facilities had a single scanner each. The majority (30/31) of the scanners had the ability to display $CTDI_{vol}$ and DLP values on the console, whereas one (3.2%) could not. Automatic exposure control (AEC) systems were incorporated in 30 CT scanners (96.8%). The distribution of CT facilities in the public, private, and quasi sectors in the various geographical locations are presented in Table 2 and Figure 1. In particular, 16 of the 31 scanners were operated by the private sector, and most (n = 18, 58.1%) were located

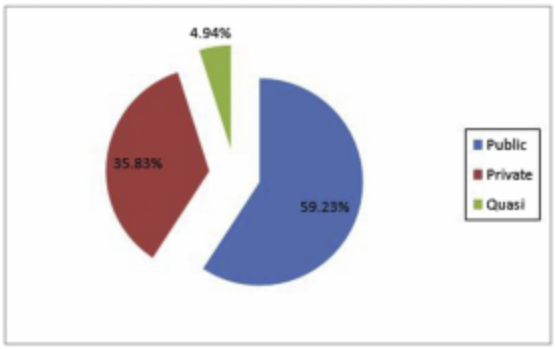

Figure 2. Percentage distribution of CT examinations in public, private and quasi hospitals. CT, computed tomography.

in the Greater Accra Region. There were 107 scanning radiographers, 60 reporting radiologists, and 10 medical physicists working in the CT facilities and responsible for CT scanners (Table 3). Table 4 shows the breakdown of the 204,760 CT examinations performed each year. The majority (59.2%) were undertaken in public hospitals (Figure 2) and in the Greater Accra region (59.8%).

Table 5 shows the common indications for adult CT head, chest, and abdominopelvic imaging performed. The suspicion of cerebrovascular accident/stroke (32.8%) was the most common indication in all locations. As shown in Table 6, apart from the availability of policy on CT authorization and education and training, many important policies relating to the use of CT facilities in Ghana were absent. Moreover, there were no established DRLs, referrer guidelines, and policy direction on the recommended frequency for QC testing. The basic quality management structures as shown in Table 7 were also lacking in some of the facilities.

Discussion

CT is a key component of modern health care in all countries. In addition to providing fast and accurate diagnosis, advances in CT technology provided new options for treatment guidance with low morbidity, resulting in the improvement of health care outcomes and quality of life for patients [12]. However, there is marked inequality in global access to such

Table 4
Annual Frequency of CT Examinations by Regional Locations

Location (Region)	Examinations									
	Head	Neck	Chest	Abdomen	Pelvic	AP	L/S	Extremities	Special	Total
Greater Accra	66,462	1873	11,204	7737	3174	21,713	1313	636	8398	122,510
Ashanti	25,387	1133	3073	1009	872	10,364	773	297	2242	45,150
Northern	6434	621	1460	201	310	1565	342	556	192	11,680
Western	3391	278	705	239	71	819	210	38	88	5840
Eastern	3559	262	652	278	147	1321	196	13	117	6545
Brong Ahafo	3899	260	169	141	141	821	157	26	78	5690
Central	4385	385	611	398	277	864	185	75	164	7345
Total	113,517	4812	17,874	10,003	4990	37,467	3177	1640	11,280	204,760

AP, abdonimopelvic; CT, computed tomography; L/S, lumbosacral spine

Table 5
Common Indications for Adult CT Head, Chest, and AP Regions Identified

Body Region	Indication Per Anatomic Region	*n* (%)
Head	CVA/stroke	37,234 (32.8)
	Head injury/trauma	25,314 (22.3)
	Headaches? SOL/tumour	17,482 (15.4)
	Sinusitis	2724 (2.4)
	Dizziness	1135 (1.0)
	Loss of consciousness	1249 (1.1)
	Psychiatric disorder	3406 (3.0)
	Others	24,974 (22.0)
Chest	Cough? lung cancer/tumour	5720 (32)
	? chest lesion with CKD	1752 (9.8)
	Tuberculosis	1662 (9.3)
	Chronic obstructive pulmonary disease	429 (2.4)
	Pulmonary embolism	2681 (15)
	Pneumonia	518 (2.9)
	Pleural effusion	500 (2.8)
	Lung abscess	894 (5)
	Interstitial lung disease	894 (5)
	Hemoptysis	375 (2.1)
	Others	2449 (13.7)
AP	? AP lesion/abscess	14,584 (27.8)
	Kidney stones (plain)	9705 (18.5)
	Liver metastasis	5403 (10.3)
	Urothelial malignancy	7974 (15.2)
	Bowel obstruction	1626 (3.1)
	AP distension	2990 (5.7)
	Ca prostate	2361 (4.5)
	Bladder mass	1312 (2.5)
	Others	6505 (12.4)

?, suspicion of; AP, abdonimopelvic; Ca, cancer; CKD, chronic kidney disease; CVA, cerebrovascular accident; SOL, space occupying lesion.

Table 6
Policy Infrastructure and Their Availability in Ghana

Policy Infrastructure	Availability	
	Yes	No
	n (%)	*n* (%)
Policy on CT authorization for use in Ghana	31 (100)	-
Policy driving CT infrastructure and distribution	-	30 (100)
Policy on operation and maintenance	-	30 (100)
Policy and availability of quality management systems	-	30 (100)
Policy on purchasing, construction, and installations	-	30 (100)
Policy on decommission of a CT facility	-	30 (100)
Policy on education and training	31 (100)	-
Policy and availability of diagnostic reference levels	-	30 (100)
Policy on CT referrer guidelines	-	30 (100)
Policy on recommended frequency for QC tests	-	30 (100)
Standardized policy on AEC application	-	30 (100)
Policy on patient dose optimization, image quality, and audit programs	-	30 (100)
Policy on acceptance testing and record keeping	-	30 (100)
Policy on human resources in CT facilities	-	30 (100)
Policy on CT maintenance systems	-	30 (100)

AEC, automatic exposure control; CT, computed tomography; QC, quality control.

imaging services [13]. Equipment and staff availability have been suggested as the main contributors to this inequality. Low- and middle-income countries, including Ghana, have the greatest need [13].

According to Statista [14], as of the year 2017, CT scanners per one million inhabitants were 64 (Australia), 44 (USA), 35 (Germany), and 15.28 (Canada), respectively. In the United Kingdom, a report [15] indicated that there were nine scanners per one million inhabitants as far back as 2014. The present study revealed that there is approximately one CT scanner per 850,000 inhabitants in Ghana (35 CT scanners for a population estimated by the Ghana Statistical Service [11] to be 30 million). Given that only 28 of 31 CT scanners were functional at the time of this study, the situation is even worse. This puts Ghana's CT infrastructure in about 94% less than the EU average (20.4 CT scanners per 1 million [16]).

In addition, only three facilities had more than a single CT scanner. This does not make for a resilient service. The CT scanners were not evenly distributed across the country. Most (18/31) were concentrated in the capital city, Accra (which has 4,943,075 inhabitants, representing 16.3% of the population [11]), and none were installed in the Upper West, Upper East, and the Volta Regions (Figure 1). This finding suggests inequality in accessibility to CT imaging services, particularly for persons living in regions with no CT scanners. The Ghana Statistical Services [11] indicates that there are about 4,730,796 people living in these regions. The lack of CT scanners in these locations means that patients requiring CT services (even in emergency cases) would have to travel to other regions to access the service, which could compromise effective patient management. In the case of Kete Krachi residents, patients requiring CT often travel 423 km to the capital, Accra, for the examination.

Schandorf and Tetteh [17] reported that the first CT scanner was introduced to Ghana in 1994. Currently, the age of the available scanners ranged from 2 to 20 years (mean 7.3 ± 4.4 years), with 8 of 31 aged more than 10 years. According to the European Society of Radiology [12], scanners older than 10 years are no longer considered state-of-the art equipment and may not have the current technology for full patient benefits. Moreover, newer CT technologies offer 10%–30% lower radiation exposure levels compared with systems installed 5 years ago [12]. There is, therefore, a need to replace older scanners in Ghana. Interestingly, one of the very

Table 7
Basic QMS Structures in the CT Facilities

QMS Structures	Findings	
	Yes	No
	n (%)	*n* (%)
Availability of QA or QC Committee	17 (54.8)	14 (45.2)
Availability of a documented protocol for CT scanning	15 (48.4)	16 (51.6)
Availability of established acceptance (QC) testing procedure	19 (61.3)	12 (38.7)
Regular QC check records	20 (64.5)	11 (35.5)
Post-major repair QC assessment records	21 (67.7)	10 (32.3)
Availability of effective planned maintenance schedule	12 (38.7)	19 (61.3)
Availability of radiation protection devices	31 (100)	0 (0)
Availability of effective quality improvement structures	10 (32.3)	21 (67.7)

CT, computed tomography; QA, quality assurance; QC, quality control; QMS, quality management system.

old scanners (GE BrightSpeed Edge manufactured; 1998 and installed; 2009) was being replaced during the study with a 64-slice GE Revolution (manufactured in 2018), which is commendable.

Many (30/31) scanners were multidetector CT (see Table 1) with AEC configurations, and Toshiba models (9/31) were the majority. Sixteen of the 31 scanners were operated by the private sector. However, one of them (a single-slice CT) lacked AEC configuration and could not display CT dose output parameters. The AEC system's advantage of yielding significant reductions in patient doses while maintaining appropriate image quality [18] could thus not be realized using this machine. In addition, advanced multidetector CT scanners offer faster imaging acquisition speed, more patient body coverage, high spatial resolution, optimal image quality, and optimized radiation dose levels [18].

With respect to staffing, there were 107 radiographers operating CT scanners, 60 reporting radiologists, and 10 medical physicists in diagnostic radiology imaging responsible for the scanners. The findings suggest that the staff to population ratio were 1: 280,374 for radiographers, 1: 500,000 for radiologists, and 1: 3,000,000 for medical physicists, respectively. These numbers are very low, necessitating the need to address the staffing gap situation. In particular, the situation with respect to medical physicists is worse because of the lack of recruitment by the public sector into the diagnostic radiology sector, although they are available for employment. Because of this limitation, many facilities mainly rely on the QC tests undertaken by the Nuclear Regulatory Authority of Ghana for purposes of inspections, verifications of compliance with regulatory requirements, and issuing authorization to practice, which are renewed every 3 years. A check every 3 years means there is a lot of scope for things to go wrong and machines to remain broken, which has the potential to compromise effective health care delivery. There is thus an urgent need to employ the relevant health professionals in CT facilities to promote patient care and patient protection and safety and to achieve sustainable development goals in health.

Evidence further indicates that 204,760 CT examinations were performed yearly. This translates into a lower national annual average of 6.8 CT procedures per 1000 people to 226.6, 94.4, and 85 CT procedures per 1000 people in the United States, Canada, and the United Kingdom, respectively [14,15]. However, Kenya has a national annual number of three CT procedures per 1000 inhabitants, which is comparable to the Ghanaian annual average [19]. The most commonly performed CT examinations were head, abdomen, and chest, which is generally consistent with the worldwide trend [20]. Cerebrovascular accident/stroke (32.8%), which is the second leading cause of death worldwide, was identified as the most common indication for head CT procedures [21].

CT infrastructure is generally driven by policies with respect to directing purchasing, installation, commissioning, and operation of CT facilities to ensure sustainable service for the population. However, as indicated in Table 6, this study revealed the lack of many structured policies, with the exception of CT authorization and education and training of staff. Qureshi [22] has cautioned that the lack of structured policies to drive practices could limit economic growth and development. From our data, it seems that better policy development is required to enable a more even distribution of services to the population of Ghana.

Regarding DRLs, the International Commission on Radiological Protection [23] and International Atomic Energy Agency [24] have recommended that each country should develop and implement its own. These international recommendations have been included in the Bonn Call for Action [24] for radiation dose monitoring and optimization. It is currently argued that indication-based DRLs decrease patient radiation dose considerably [12]. However, there was no national DRL or policy driving its development, as well as standardized CT referrer guidelines and policy on AEC application, patient dose management, and image quality audit programs in Ghana. The consequence of these structural lapses is the probable lack of uniformity of protocols, which could exponentially increase the dose [8,24–26].

QMSs enable organizations to plan effectively, do the needed work, check proper system functions as planned, and act by addressing any issues found in the checkup process that would ultimately lead to improved performance. However, some facilities lacked QA/QC committees (45.2%), established acceptance testing procedures (38.7%), and effective quality improvement structures (67.7%). Furthermore, apart from the availability of radiation protection devices in all the facilities, some facilities lacked regular QC check records (35.5%), postmajor repair QC assessment records (32.3%), and effective planned maintenance schedule (61.3%) and documented protocol for CT scanning (51.6%), which are

a concern to the standardization of practices and patient protection. Korir et al [26] had also reported the lack of written QA manual that took into consideration the radiation safety issues concerning workers, patients, and the public in Kenya, although its x-ray imaging QMSs were scored 61.0 ± 3% out of a possible 100%. Obviously, there is the need for the institutionalization of the right QMS and policies to promote patient care and protection in Ghana and beyond.

A limitation of this work is that not all the CT facilities participated in the study.

Conclusion

This study found there are few CT scanners across the country, with none in some regions, and this inequality could affect the health care of the population. Many of the CT scanners were functioning and could display CT dose output; however, one-fourth of the scanners were 10 or more years old, and QMSs were lacking in some of the CT facilities. There is the need for a national policy to govern and drive CT infrastructure in Ghana. There is also a need to develop national DRLs (including indication-based DRLs) for the common CT examinations identified in this study to promote health care and radiation protection of patients in Ghana.

Acknowledgments

This research serves as part of the PhD study of Benard Botwe. The authors wish to thank the Technical Heads of the CT facilities who supported and participated in this study. The author acknowledges with thanks the support of Prof. Mary Boadu, Dr. William K. Antwi, Dr. Samuel Anim-Sampong, Dr. David Okoh Kpeglo, Dr. Francis Hasford, Dr. Issahaku Shirazu, Mr. Carl Edem Kokah, Ghana Sweden Medical Centre, and the Nuclear Regulatory Authority, Ghana. The authors also thank the radiographers, medical physicists, and radiologists who helped to make this work a success. The authors' special appreciation goes to the Ghana-Norway NORPART project. Finally, the first author thanks the BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana for financial support.

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Second article link: https://pubmed.ncbi.nlm.nih.gov/32102860/

Original Article

Status of Quality Management Systems in Computed Tomography Facilities in Ghana

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Purpose To assess the status of quality management systems in computed tomography (CT) facilities in Ghana.

Methods A questionnaire and quality control measurements were used to assess the status of quality management systems in CT facilities in Ghana. Thirty-one CT facilities took part in the study. The evaluation included quality assurance (QA), quality control (QC), and quality improvement (QI).

Results Seventeen (54.8%) of the 31 CT facilities had a QA-QC committee in place to ensure patient protection. Fifteen facilities (48.4%) had documented protocols for CT scanning. Ten facilities (32.3%) lacked QC assessment and recordkeeping after notable repairs. Regular QC check records were available in 20 (64.5%) facilities. All scanners passed the QC assessments; however, none of the facilities had established local diagnostic reference levels.

Discussion Quality management systems in some Ghanian CT facilities are unsatisfactory; not all facilities have the needed infrastructure in place for quality management system purposes.

Conclusion Quality management systems in Ghanaian CT facilities should be strengthened to optimize patient protection and safety with acceptable image quality.

Keywords | *computed tomography, quality management systems, image quality, patient protection*

Quality management systems are an important component of medical practice management and, in particular, medical imaging. The International Organization for Standardization (ISO) 9000—a set of standards that organizations follow to ensure their products or services meet customer and other stakeholder needs—defines quality management systems as the organizational structures, procedures, and resources needed to implement quality management in an organization and encompasses all aspects that affect the quality of products delivered to the customer.[1] Quality management systems consist of quality assurance (QA), quality control (QC), and quality improvement (QI) components.[2] The QA component, as an interdisciplinary management tool, provides a means of ensuring that all work is adequately planned, correctly performed, and thoroughly assessed. QC is a means of applying controls to the process to ensure that the product or service consistently meets specifications.[3] QI is a systematic, formal approach to analyzing and improving performance.[4] Properly understanding and implementing QI is essential to a well-functioning practice aiming to improve efficiency, patient protection, and clinical outcomes.[4] Quality management systems provide confidence that a system will perform according to established quality requirements.[2,5-8]

Advances in medical imaging, higher disease prevalence, and population explosions can increase the number of radiographic examinations needed and performed, which can increase the workload of medical personnel.[9] This development adversely can affect the quality of services a facility provides, especially in locations that have insufficient numbers of skilled medical staff. Quality management systems can help mitigate this factor, ensuring that facilities provide proper patient care and diagnostic image quality and prevent unnecessary radiation exposure that can cause health complications for patients and staff.[2] Essential components of quality management systems in imaging departments include

adhering to the basic principles of quality management, developing QA structures, and appropriate use of quality tools and QI structures.[2] The nature and extent of these programs vary with facility size and type, examinations conducted, and other technical factors.[10]

In many countries, including Ghana and the United States, computed tomography (CT) is 1 of the most widely used imaging modalities.[11-13] A disadvantage of CT is that it delivers a higher radiation dose than does other imaging modalities such as radiography; CT scans represent 12% of imaging procedures but contribute nearly half the total radiation dose to the U.S. population from medical imaging.[13] The increased contribution of CT to the population dose has raised concern because of the potential for radiation-induced malignancies. Therefore, the quality management systems and structures in imaging facilities must be functional for staff and patient protection and should cover physical and technical parameters associated with the modality and the examination being performed.[13]

Studies reporting high radiation dose levels at some CT facilities in Ghana have prompted these facilities' attempts to improve their quality management systems and, therefore, improve patient protection.[11,12] However, limited research resources for surveys and lack of literature regarding quality management systems status in Ghanaian CT facilities stymied policy development in this area. The objective of this study was to assess the baseline quality management systems status in Ghanaian CT facilities and provide updated information about quality management systems in CT imaging.

Methods

This study took place between December 2017 and August 2018 using a questionnaire and QC measurements. Ethics Committee for Basic and Applied Sciences, University of Ghana, the Ghana Health Service Ethics Review Committee, the Korle Bu Teaching Hospital's Scientific and Technical Committee, and the Korle Bu Teaching Hospital's institutional review board granted ethical clearance for this study.

Thirty-one of the 35 CT facilities authorized by the Nuclear Regulatory Authority of Ghana took part in this study. Before the data collection process started, letters were sent to the technical heads responsible for the CT facilities, inviting them to partake in this study. The data collection process was divided into 2 phases: phase 1 focused on QA and QI, whereas phase 2 focused on QC. In phase 1, a questionnaire was used to gather information on the status of QA and QI infrastructures in the CT facilities. The assessment items were based on a review of the relevant literature and included[5,6,14]:

- QA and QC committee availability
- documented protocols for CT scanning
- QC assessment records of notable repairs
- regular QC check records
- Nuclear Regulatory Authority authorization
- acceptance testing procedure
- effective maintenance schedules
- equipment performance recordkeeping
- radiation protection devices
- systems for justifying CT exposures
- diagnostic reference levels
- scheduled dose optimization programs
- patient dose and image quality audit programs
- patient dose recordkeeping
- schedules for frequent cleaning of equipment
- automatic exposure control systems on the CT scanners
- volume CT dose index and dose length product parameters displayed on the scanner console
- documented training programs and records

The QI assessment items, based on Kruskal et al recommendations, included[2]:

- institutional leadership and support for QI
- regular meetings involving all stakeholders to communicate QC results
- quality and improvement team culture
- system that engages all the professional groups in the department in QI
- system that regularly receives and analyzes feedback from customers and stakeholders
- quality implementation protocol or manual
- surveillance system for monitoring QI indicators
- QI education program
- system to reward hard work associated with quality improvement

Two clinically qualified medical physicists from the School of Nuclear and Allied Sciences assessed the suitability of the questionnaire. The assessment tool was sent to validators with a request to rate the importance of each item on a 0 to 1 scale: 0 representing not important, 1 representing important. The validators also were asked to make suggestions regarding the assessment tool. The authors decided that any item or question that scored 0 would be rejected. The Cohen's unweighted kappa statistic was used to test the agreement between scores obtained from the first and second rater, and the kappa value was found to be 0.71, which is considered a strong agreement and a reliable questionnaire. After a content validity assessment was performed, the assessment tool was revised and used for the study.

For phase 2, QC tests undertaken were:

- CT dose delivery accuracy
- geometric efficiency
- kilovolt (kV) accuracy
- half-value layer (HVL)
- CT (water) number
- homogeneity
- noise

The materials used in the QC assessment included:

- CT dose profiler probe (RTI Electronics)
- Barracuda set (Cabinet and Multipurpose Detector) with Ocean Software interface (RTI Electronics)
- standard CT head and body polymethyl methacrylate phantom (PTW)
- laptop computer (Toshiba Satellite S55-C5274, 2016 model)
- Microsoft Excel 2013
- uniform water phantom (PTW)
- ImageQC software v.1.43 (EllenWasbo, 2018)

The CT dose profiler, Barracuda (Cabinet) with Ocean Software interface connected to a laptop computer, and standard CT head and body polymethyl methacrylate phantom were used to assess the CT dose delivery accuracy and geometric efficiency. Barracuda (Multipurpose Detector) was used to assess the kV accuracy and HVL. The CT number testing, homogeneity, and noise were assessed with a uniform water phantom. The methods suggested by the International Atomic Energy Agency,[15] Institute of Physics and Engineering in Medicine,[16] and the American College of Radiology[17] were employed in the testing of kV accuracy, HVL, CT number testing, homogeneity, and noise. The methods recommended by Elimpex-Medizintechnik[18] and RTI Group AB[19] were used in measuring the CT dose delivery accuracy as well as the geometric efficiency. Twenty-five CT facilities participated in the QC assessments because of equipment breakdowns. The data collected were analyzed using Microsoft Excel. The images generated for the CT number (water) testing, homogeneity, and noise were evaluated using ImageQC software version 13.

Results

The results of the quality management systems are presented under QA structures, QC tests, and QI structures.

Quality Assurance

Seventeen (54.8%) of the CT facilities had a QA or QC committee in place to ensure patient protection, although 14 (45.2%) did not (see **Table 1**). Fifteen of 31 facilities (48.4%) had documented protocols for CT scanning, whereas 16 (51.6%) did not. Moreover, 21 (67.7%) facilities had QC assessment records of notable repairs, and 10 (32.3%) did not. Regular QC check records were available in 20 (64.5%) facilities, and CT scanners in all 31 facilities (100%) had received Nuclear Regulatory Authority of Ghana authorization. Nineteen (61.3%) had acceptance testing procedures, and 19 (61.3%) did not have maintenance schedules. Twenty-nine (93.5%) had an equipment performance recordkeeping system, and 31 (100%) had radiation protection devices and some procedures for justifying CT exposures.

In addition, 20 (64.5%) facilities had scheduled dose optimization programs, and a similar number of facilities had established a long-term system for keeping patient dose records. All facilities had automatic exposure control systems on their CT scanners, and 30 (96.8%) could display volume CT dose index and dose length product or parameters on the console. However, 21 (67.7%) facilities lacked schedules for frequent cleaning of equipment, and 26 (83.9%) lacked patient dose and image quality audit programs.

Table 1

QA Infrastructures at CT Facilities in Ghana[a]

QA Structure	Yes, n (%)	No, n (%)
QA or QC committee	17 (54.8)	14 (45.2)
Documented protocols for CT scanning	15 (48.4)	16 (51.6)
QC assessment records of notable repairs	21 (67.7)	10 (32.3)
Regular QC check records	20 (64.5)	11 (35.5)
Nuclear Regulatory Authority of Ghana Certification/Authorization	31 (100)	0 (0)
Acceptance testing procedure	19 (61.3)	12 (38.7)
Effective maintenance schedules	12 (38.7)	19 (61.3)
Equipment performance recordkeeping	29 (93.5)	2 (6.5)
Radiation protection devices	31 (100)	0 (0)
Procedures for justifying CT exposures	31 (100)	0 (0)
DRLs	0 (0.0)	31 (100)
Scheduled dose optimization programs	20 (64.5)	11 (35.5)
Maintained patient dose records	20 (64.5)	11 (35.5)
Patient dose assessment and image quality audit programs	5 (16.1)	26 (83.9)
Schedules for frequent cleaning of equipment	10 (32.3)	21 (67.7)
AEC systems on the CT scanners	31 (100)	0 (0)
Ability to display $CTDI_{vol}$ and DLP parameters on the console	30 (96.8)	1 (3.2)
Documented training program and records	5 (16.1)	26 (83.9)

[a] *(N = 31); percentages might not total 100 because of rounding.*
Abbreviations: AEC, automatic exposure control; CT, computed tomography; $CTDI_{vol}$, volume CT dose index; DLP, dose length product; DRLs, diagnostic reference levels; QA, quality assurance; QC, quality control.

In addition, 26 (83.9%) facilities lacked records and documentation on training programs, and none had diagnostic reference levels values for their facilities.

Quality Control

Among the 20 facilities that indicated routine QC was undertaken, 5 were from the public sector, 12 were from the private sector, and 3 were public-private partnerships. One of the public facilities indicated QC assessments were undertaken daily, 1 indicated that QC assessments were undertaken weekly, and 3 indicated that QC assessments were undertaken quarterly. In the private sector category, 5 out of the 12 indicated that QC assessments were undertaken daily, 5 mentioned that QC assessments were undertaken weekly, and 3 indicated that QC assessments were undertaken quarterly. Among the public-private partnership facilities, all respondents indicated that QC assessments were undertaken daily, weekly, and quarterly. The study also showed that 10 medical physicists were available in all the diagnostic CT facilities.

Moreover, all the CT scanners passed the QC tests as the determined values conformed with the standards of International Atomic Energy Agency[15] and Institute of Physics and Engineering in Medicine.[16] For CT dose accuracy, in particular, the observed discrepancies between the displayed and measured volume CT dose index were within the acceptable tolerance limit of 20% (see **Table 2**).[15] The geometric efficiency of the equipment (ie, the number of radiation quanta incident on the detector in a given interval divided by the number emitted by the radiation source in the same interval expressed in percentage) ranged from 70.8% to 100%, which is above the acceptable level of greater than 70%.[20] The homogeneity of images at all the facilities—measured with region of interest at 12 o'clock, 3 o'clock, 6 o'clock, 9 o'clock, and the center—as well as the CT number (water) also were within the achievable limit of $\pm$ 4 suggested by the International Atomic Energy Agency and Institute of Physics and Engineering in Medicine, whereas the image noise levels were all within $\pm$ 10% of baseline values (see Table 2).[15,16] In addition, the total filtration (HVL) was within the acceptable limit (observed; Min: 7.3 for 120 kV; Max: 8.8 for 140 kV).[21]

Table 2

Measured Parameters During QC Tests and the Available Limits and References[a]

Parameters	Measured	Acceptable Limit	Achievable Limit	Reference	Comment
CT dose delivery accuracy	% Deviation ($CTDI_{vol}$) Min: −8.5 Max: 9.9	± 20% of manufacturer's specifications	± 10% of baseline	IAEA[15]	Pass
kVp accuracy	% Error Min: −2.7 Max: 2.9	± 5% nominal	± 2% nominal	IAEA[15]	Pass
GE	Min: 70.8% Max: 100%	> 70%	-	Shefer et al[20]	Pass
CT (water) number	Min: 0.0 Max: 4.0	± 5 HU (water), ± 10 HU (other material) compared with baseline values	± 4 HU	IAEA[15]	Pass
Image noise	Min: 3.2 Max: 9.8	± 25% of baseline	± 10% of baseline	IAEA[15]	Pass
Image uniformity/ homogeneity	Variation Min: −0.3 Max: 2.2	± 10 HU for head and body	± 4 HU for head and body	IAEA[15]	Pass
HVL	Min: 7.3 for 120 kV Max: 8.8 for 140 kV	≥ 2.5 mm Al for kV >100	-	FDA[21]	Pass

[a] *(n = 25)*

Abbreviations: Al, aluminum; FDA, U.S. Food and Drug Administration; GE, geometric efficiency; HVL, half-value layer; IAEA, International Atomic Energy Agency; kVp, kilovoltage peak.

Quality Improvement

With respect to QI, most of the facilities lacked structures for implementing QI (see **Table 3**). In particular, other than the availability of institutional leadership and support for QI in all the facilities, 26 (83.9%) lacked a QI team. Moreover, quality implementation protocols and surveillance systems for monitoring QI indicators were missing in 28 (90.3%) facilities. In addition, 25 (80.6%) facilities had no system that engaged all the professional groups in the department to discuss QIs, and 21 (67.7%) facilities lacked systems that regularly received and analyzed feedback from customers and stakeholders. Only 3 (9.7%) facilities had a culture of quality in practice and 5 (16.1%) had an educational program on QI. However, 18 (58.1%) facilities had a system that rewarded the hard work associated with QI.

Depending on the type of equipment fault, it took between 1 day and 2 years to have broken CT equipment repaired in the public hospitals. However, it took 1 hour to 1 month in the private hospitals and 1 day to 3 months in the private-public partnership hospitals, depending on the type of fault diagnosed.

Discussion

To improve the quality of care radiology departments provide and to allow radiology staff to remain competitive in an increasingly complex environment, imaging departments should establish and maintain managed, comprehensive, and effective performance improvement programs.[2] Quality management systems provide the physical and nonphysical structures that would help radiology staff achieve the aforementioned goals and ensure patient satisfaction, protection, and safety.

In the United States, evidence suggests that CT facilities have effective quality management systems in place, as evidenced by protocols and validation

processes compliant with the American Association of Physicists in Medicine Medical Physics Practice Guidelines and a number of the ISO 9001 clauses.[22] To set up quality management systems in U.S. CT facilities, some institutions hired a part-time credentialed quality consultant to work with the CT protocol and quality management team.[22] However, this study found indications that not all CT facilities in Ghana have the needed infrastructures for quality management systems. With respect to QA, in particular, 45.2% and 51.6% of facilities, respectively, lacked a QA-QC committee and documented protocols for CT scanning. Ofori et al observed similar situations in general radiography facilities in Ghana.[6] In the radiology department, QA-QC committees maintain lines of communication among all groups with QA, QC, and QI responsibilities, including maintaining acceptable quality standards and periodic review or audit of practices for effectiveness and compliance with quality standards. Therefore, the absence of operational tools (eg, documented scanning protocols and appropriate committees to ensure functional QA, QC, and QI) could have severe consequences on the radiation protection culture.[6]

Although an established acceptance testing procedure, equipment commissioning, regular QC check records, and records of notable repairs are all important international indices to assess equipment performance after an installation, this study showed that QC assessment records of notable repairs were available in 21 (67.7%) of the facilities and that regular QC check records were available in 20 (64.5%) of them.[23] Ngoye et al reported that 6% of facilities in Tanzania had records of all QC tests.[24] Of the 20 facilities in the current study that kept records of routine QC tests, 5 were from the public sector, 12 were from the private sector, and 3 were public-private partnerships. Three of 5 public facilities perform quarterly QC, whereas 12 of 15 private facilities perform daily QC. In the public-private partnership sector, each facility performed daily, weekly, and quarterly QC. The lack of regular QC tests across the facilities could stem from inadequate numbers of medical physicists in the facilities overall (10), and the lack of effective QC systems across CT facilities potentially stymies quality service delivery.[25]

Although the facilities have Nuclear Regulatory Authority of Ghana authorization, as well as automatic exposure control systems on the CT scanners, radiation protection devices, and systems for justifying CT exposures, the absence of pertinent quality management systems could limit quality service delivery. In particular, the fact that not all facilities had a patient dose and image quality audit program, equipment performance recordkeeping, scheduled dose optimization programs, patient dose records, and documented training programs suggests weak QA structures across the CT facilities that must be addressed.

Diagnostic reference levels are a QA tool used to identify radiologic facilities using unusually high doses for a specified procedure, for which optimization actions are required.[26-28] In the United States, federal and state recommendations support the use of diagnostic reference levels.[29] On January 15, 2015, the U.S. Environmental Protection Agency's Federal Guidance Report No. 14 recommended that imaging facilities using ionizing radiation should promote development of national diagnostic reference levels for use as QA and QI tools in every examination.[29] Kanal et al recommended the use of local diagnostic reference levels and provided diagnostic reference levels for typical examinations in the United States.[27] In the United Kingdom, the application of diagnostic reference levels was reported to have resulted in a 30% decrease in radiographic doses from 1984 to 1995 and an average drop of about 50% between 1985 and 2000.[30] Therefore, the absence of established local diagnostic reference levels in CT facilities in Ghana could limit efforts to optimize dose because of the lack of supervision and monitoring of quality.

Many health institutions have implemented planning and scheduling in their maintenance operations to improve use of their CT equipment, reduce unplanned downtime, and more effectively manage their maintenance budgets. This study observed that effective maintenance schedules were missing in 61.3% of the facilities. Korir et al found that 22% of the facilities in Kenya reported semiannual preventive maintenance.[25] As a result, equipment faults are likely not to be detected on time, and when a breakdown occurs, it can take a long time to have

the equipment fixed. This current study found that the situation is worse in public hospitals. Although it takes 1 hour to 1 month to fix equipment in private hospitals and 1 day to 3 months to fix CT equipment in public-private partnership hospitals, it takes 1 day to 2 years to fix broken equipment in public facilities, depending on the fault type. The lack of parts supply, after-sales service, and training for local service personnel who perform maintenance have long been noted as part of the problem.[23] The absence of formal organizational structures for effective scheduled maintenance for CT facilities in Ghana have clinical, radiation protection, and financial implications because of long equipment downtimes.

Limited resources restricted the QC tests performed in the current study to:

- CT dose delivery accuracy
- geometric efficiency
- kV accuracy
- HVL
- CT (water) number
- homogeneity
- noise

The QC test results found no notable deficiencies with scanners; the various deviations were within tolerable limits suggested by the International Atomic Energy Agency, Institute of Physics and Engineering in Medicine, Shefer et al, and the European guidelines on quality criteria.[15,16,20,31]

A lack of effective QI infrastructures (see Table 3) is a concern for imaging services in Ghana because the goal of QI systems is to do the right thing in a timely fashion for every patient every time and to ensure that quality performance levels improve.[32] The lack of QI might have dire consequences for improved care. Only 5 (16.1%) facilities had a quality management team, 3 (9.7%) had a culture of quality, and 5 (16.1%) reported having regular meetings involving all the stakeholders for communicating QC results. However, a well-functioning, cohesive team; stakeholder relations; and a culture that recognizes quality are essential for successful implementation and functioning of a quality protection and safety program in any facility. Moreover, Kruskal et al indicated that whether one is identifying opportunities or processes for improvement, collecting and analyzing data, identifying contributing factors, or implementing and monitoring countermeasures, it is essential to correctly use the most appropriate tool because it is possible to manage only that which can be measured accurately.[32] In this study, 3 (9.7%) facilities had surveillance systems for monitoring QI indicators, and 10 (32.3%) had a system that regularly received and analyzed feedback.

Table 3

Basic Quality Improvement Structures in CT facilities[a]

	Yes, n (%)	No, n (%)
Do you have institutional leadership and support toward quality improvement?	31 (100)	-
Do you have regular meetings involving all the stakeholders to communicate QC results?	5 (16.1)	26 (83.9)
Has your facility established a culture of quality in your practice?	3 (9.7)	28 (90.3)
Has your facility established an improvement team?	5 (16.1)	26 (83.9)
Do you have a quality implementation protocol or manual?	3 (9.7)	28 (90.3)
Do you have a system that engages all the professional groups in the department on quality improvements?	6 (19.4)	25 (80.6)
Do you have a system that regularly receives and analyzes feedback from customers and stakeholders?	10 (32.3)	21 (67.7)
Do you have surveillance systems for monitoring quality improvement indicators?	3 (9.7)	28 (90.3)
Does your facility have a system to reward hard work associated with quality improvement?	18 (58.1)	13 (41.9)
Do you have an educational program on quality improvement?	5 (16.1)	26 (83.9)

[a] *(N = 31); percentages might not total 100 because of rounding.*

Although quality management systems in the facilities were not satisfactory, that all facilities had institutional leadership and support for quality improvement is a good window through which the other QI components could be improved, facilitating continuous improvement in protection and safety, performance, and outcomes.[32] Worth noting is that QI systems also thrive effectively in the presence of quality educational programs and motivation of all stakeholders. Hence, a need exists to revamp the current systems for training and for rewarding hard work associated with quality improvement. Moreover, all stakeholders involved in CT imaging in Ghana must be committed to ensuring that QA, QC, and QI culture and infrastructures are in place and functional to continuously improve quality and meet patients' needs for better health care.

Limitations

A limitation of this work includes that not all the CT facilities participated in the study because of equipment breakdown.

Conclusion

The quality management systems in CT facilities in Ghana need improvement because not all facilities have the needed infrastructure in place for quality management systems purposes. Strengthening the quality management systems and infrastructures across all CT facilities is needed to improve patient protection and quality of the care. There should be a conscious effort by CT facility managers and, in particular, CT managers in public hospitals, to fix equipment in a timely manner. To improve the use of CT equipment, effective maintenance schedules, reduced unplanned downtime, and effectively managed maintenance budgets are needed.

To meet patient needs for better health care, management, staff, and supporting organizations must be committed to working together to implement an effective quality management systems compatible with ISO standards in CT facilities in Ghana.

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This research serves as part of the PhD study of Benard Botwe. The authors wish to thank the technical heads of the computed tomography facilities who supported and participated in this study. The authors thank Dr S Anim-Sampong, Professor Mary Boadu, Dr William K Antwi, Dr David Okoh Kpeglo, Dr Francis Hasford, Mr Carl Edem Kokah, Dr Issahaku Shirazu, Ghana Sweden Medical Centre, and the Nuclear Regulatory Authority, Ghana. The authors also thank the radiographers, medical physicists, and radiologists who helped to make this work a success. Special appreciation goes to the Ghana-Norway NORPART project. Finally, the authors thank the BaNGA-Africa project funded by the Carnegie Corporation of New York with University of Ghana for financial support.

Received May 17, 2019; accepted after revision July 18, 2019.

Reprint requests may be mailed to the American Society of Radiologic Technologists, Publications Department, 15000 Central Ave SE, Albuquerque, NM 87123-3909, or emailed to publications@asrt.org.

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