ANTHROPOMORPHIC PHANTOM ORGAN DOSE ASSESSMENT USING OPTICALLY STIMULATED LUMINESCENCE DOSIMETERS UNIFIED IN MULTI-DETECTOR COMPUTED TOMOGRAPHY

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DEDICATION

This thesis is dedicated to my beloved husband, Nabil bin Mohd Zamzuri who has been a constant source of support and encouragement during the challenges of my PhD life.

It is also dedicated to my mother, Sopiah binti Othman who has always loved me unconditionally and who good examples have taught me to work hard for the things that I aspire to achieve.

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ABSTRACT

This study focuses on a comprehensive performance assessment of different types of Multi-Detector Computed Tomography scanners, with particular focus given to quality control (QC) performance tests based on data and dose mapping using an anthropomorphic phantom. The performance test of microStar InLight® reader recorded intrinsic precision within ≤ 2% of the manufacturer's recommendation. The calibration of the thermoluminescence dosimeter (TLD-100™) and nanoDot™ optically stimulated luminescence dosimeter (OSLD) comprised of optical annealing (illumination), signal depletion, signal fading, the linearity of dose-response, sensitivity and energy dependence. The optical annealing procedure using five light sources showed that the compact fluorescent lamp (CFL) recorded the highest response, with an average signal loss of ~93% in 60 minutes illumination time compared to ultra-violet light (UV), light-emitting diode (LED), tungsten-halogen lamp (THL), and bright room office environment light (BRL). The screened nanoDot™ OSLDs recorded a low signal depletion loss, with an average decrease of 1.0% depletion per reading. The recorded signal fading showed that screened nanoDot™ OSLDs displayed a small signal fading (becoming stabilised after 12 days), compared to unscreened nanoDot™ OSLDs and TLD-100™. The linearity dose-response of TLD-100™ and nanoDot™ OSLDs for 0 to 500 mGy exposed dose recorded a linear regression of coefficient values of 0.99981 and 0.99868. The results were very close to the value of one; both dosimeters showed an excellent linear dose response for different absorbed doses. The computed tomography dose index ($CTDI_w$) fulfils the manufacturer's guidelines (< ±20%), thus revealing that the nanoDot™ OSLDs could be used as alternative to Unfors detector and indicating their similar dose detection potential for CT scan applications. By comparing the QC performance tests for overall locations and model names, all the recorded data for scan localisation, X-ray generators, radiation dosimetry, image display, hard copy output, quantitative accuracy, image quality, as well as scattered radiation and radiation leakage, from the year 2015 to the year 2019, remained within the optimum achievable standard. Both lung and thyroid doses found in this study for CT chest-abdomen and head-neck protocol respectively, are particularly high since both thyroid and lung are situated along the main beam. This is in agreement with the fact that radiation doses from diagnostic radiology for similar examinations and modality differ, depending on several magnitudes such as tube voltage, exposure time, tube current, slice collimation and pitch factor. This study proves the importance of altering CT scan parameters accordingly, to initiate the optimisation process of current imaging practice.

ABSTRAK

Kajian ini memfokus kepada penaksiran prestasi komprehensif pelbagai jenis pengimbas Tomografi Berkomputer Pengesan Berbilang, dengan fokus khusus diberikan kepada ujian prestasi kawalan kualiti (QC) berdasarkan data dan pemetaan dos menggunakan fantom antropomorfik. Ujian prestasi pembaca microStar InLight® mencatatkan kepersisan intrinsik dalam ≤ 2% daripada cadangan pengeluar. Penentukuran dosimeter perdarkilau terma (TLD-100™) dan dosimeter perdarkilau teransang secara optik nanoDot™ (OSLD) terdiri daripada penyepuhlindapan optik (pencahayaan), penyusutan isyarat, kepudaran isyarat, kelinearan sambutan-dos, kepekaan dan kebergantungan tenaga. Prosedur penyepuhlindapan optik menggunakan lima sumber cahaya menunjukkan bahawa lampu pendarfluor padat (CFL) mencatatkan sambutan tertinggi, dengan kehilangan isyarat purata ~ 93% dalam masa pencahayaan 60 minit berbanding dengan cahaya ultra-ungu (UV), diod pemancar cahaya (LED), lampu tungsten-halogen (THL), dan lampu persekitaran pejabat bilik terang (BRL). OSLD nanoDot™ yang disaring mencatatkan kehilangan penyusutan isyarat rendah, dengan penurunan purata 1.0% penyusutan setiap bacaan. Kepudaran isyarat yang dirakam menunjukkan bahawa OSLD nanoDot™ yang disaring memaparkan kepudaran isyarat kecil (menjadi stabil selepas 12 hari), berbanding dengan OSLD nanoDot™ yang tidak disaring dan TLD-100™. Kelinearan sambutan-dos TLD-100™ dan nanoDot™ OSLD untuk dedahan dos 0 hingga 500 mGy mencatatkan nilai-nilai pekali regresi linear pada 0.99981 dan 0.99868. Dapatan kajian hampir dengan nilai satu; kedua-dua dosimeter menunjukkan kelinearan sambutan-dos yang sangat baik untuk pelbagai dos yang diserap. Indeks dos tomografi berkomputer yang dikira ($CTDI_w$) memenuhi garis panduan pengeluar (< ±20%), membuktikan bahawa OSLD nanoDot™ boleh digunakan sebagai alternatif kepada dosimeter Unfors dan menunjukkan potensi pengesanan dos yang serupa untuk penggunaan imbasan CT. Dengan membandingkan ujian prestasi QC untuk keseluruhan lokasi dan nama model, semua data yang direkodkan untuk penyetempatan imbasan, penjana sinar-X, dosimetri sinaran, paparan imej, output salinan keras, ketepatan kuantitatif, kualiti imej, serta sinaran terserak dan kebocoran sinaran, dari tahun 2015 hingga tahun 2019, kekal dalam piawaian yang boleh dicapai secara optimum. Kedua-dua dos paru-paru dan tiroid yang didapati dalam kajian ini untuk protokol CT abdomen-dada dan kepala-leher masing-masing, adalah sangat tinggi kerana kedua-dua tiroid dan paru-paru terletak di sepanjang alur utama. Ini adalah sesuai dengan fakta bahawa dos sinaran dari radiologi diagnostik bagi pemeriksaan yang sama dan modaliti yang berbeza, bergantung pada beberapa magnitud seperti voltan tiub, masa dedahan, arus tiub, pengkolimatan hirisan dan faktor pic. Kajian ini membuktikan pentingnya mengubah parameter imbasan CT dengan sewajarnya, untuk memulakan proses pengoptimuman amalan pengimejan semasa.

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LIST OF ABBREVIATIONS

2D	–	2-Dimensional
3D	–	3-Dimensional
ADC	–	Automatic Dose Control
AEC	–	Automatic Exposure Control
AF	–	Adaptive Filtration
ART	–	Alderson Radiation Therapy
BRL	–	Bright Room Light
CAT	–	Computed Axial Tomography
CFL	–	Compact Fluorescent Lamp
CT	–	Computed Tomography
CTDI	–	Computed Tomography Dose Index
CW-OSL	–	Continuous-Wave Optically Stimulated Luminescence
DAP	–	Dose Area Product
DAS	–	Digital Acquisition System
DLP	–	Dose-Length Product
E	–	Effective Dose
EBCT	–	Electron Beam CT Scanner
EM	–	Electromagnetic
FK	–	Filter Kernel
FOV	–	Field of View
LED	–	Light Emitting Diode
LM-OSL	–	Linear Modulation Optically Stimulated Luminescence
MC	–	Monte Carlo
MDCT	–	Multi-Detector Computed Tomography
MOH	–	Ministry of Health
MOSFET	–	Metal Oxide Semiconductor Subject Effect Transistor
MDCT	–	Multi-Slice Computed Tomography
OSL	–	Optically Stimulated Luminescence

OSLD	–	Optically Stimulated Luminescence Dosimeter
PC	–	Personal Computer
PMMA	–	Polymethyl-Methacrylate
PMT	–	Photomultiplier Tube
PO-OSL	–	Pulsed Optically Stimulated Luminescence
QAP	–	Quality Assurance Protocol
QC	–	Quality Control
QMP	–	Qualified Medical Physicist
RL	–	Radioluminescence
RPL	–	Radiophotoluminescence
RQT	–	Standard Radiation Qualities
SSCT	–	Single-Slice Computed Tomography
THL	–	Tungsten-Halogen Lamp
TLD	–	Thermoluminescence Dosimeter
UTM	–	Universiti Teknologi Malaysia
UV	–	Ultra-Violet
WinREMS	–	Windows Radiation Evaluation and Management System

LIST OF SYMBOLS

δ	-	Minimal error
D, d	-	Diameter
F	-	Force
v	-	Velocity
p	-	Pressure
I	-	Moment of Inertia
r	-	Radius
Re	-	Reynold Number

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Since the introduction of X-ray computed tomography (CT) in the early 1970s, its innovation in medical imaging has been constantly studied and tremendously improved in terms of technology, performance and clinical applications (Mutic *et al.*, 2003; Nagel, 2007). Based on the historical evolution of CT and basic CT physics, this study describes the status quo of the technology and tries to anticipate the performance of CT scanners. Besides the description of key components of Quality Assurance Protocol (QAP) in CT systems, Quality Control (QC) is one of the elements of QAP that has to be carried out at an interval period as specified by the Ministry of Health (MOH). A special focus will be placed on application-related factors in terms of assessing the dose from selected conventional CT scanners and organ dose mapping using an anthropomorphic phantom.

A CT scanner is an analytical system that utilises unique X-ray equipment to create cross-sectional images of the human body in high radiographic contrast. This characteristic is particularly important for diagnosis involving soft tissue (that is, organs not including lung or bone), as the contrast available from CT images is vastly superior to that gained from projection radiography. Therefore, this type of analytical and imaging system is medically beneficial and is increasingly the method of choice for a growing number of examinations. The complexity of two important factors in CT scanners (equipment-related factors and application-related factors) requires careful monitoring by the medical physicist in conjunction with the radiologist or radiographer to ensure that appropriate examination conditions exist and that procedures are optimised for diagnostic quality and patient dose. From a CT point of view, the dose to the patient may be significantly higher than with alternative imaging modalities. This particular fact is crucial if the examination involves a pregnant patient or a child.

An excessively high dose to a patient may be due to poor optimisation of scanner radiographic protocols or can also be due to poor equipment conditions. CT scanners are under continued technical development, resulting in a rising clinical application (Nagel, 2002; IAEA, 2012), which in turn emphasizes the need for continuous professional technical education to radiographers, as well as to radiologists, engineers, researchers, and students. Also, the use of well-designed equipment that is in proper operating condition, suitable examination protocols, and adequate viewing conditions for image interpretation should be promoted in a QA program. The involvement of a medical physicist is a key element in the QA and QC process.

It should be noted that CT scanners are being increasingly utilised by radiotherapy departments for image acquisition for treatment planning purposes (Mutic *et al*., 2003), in addition to the traditional roles of patient diagnosis and cancer staging, placing further important demands on scanner performance requirements and benefit-to-risk of CT. The vast use of CT, even in developing countries, has increased queries regarding the possible risk to public health, especially in children (Ogbole, 2010). There was increased concern in patients and parents, especially among paediatric patients undergoing CT procedure, as reported in AAPM Report No. 96. The importance of CT radiation dosage has been underlined recently by the attention given in previous studies to issues of doses and the associated risk (Brenner *et al*., 2001; Donnelly *et al.*, 2001; Pierce and Preston, 2000; Haaga, 2001; Nickoloff and Alderson, 2001; Feigal, 2002). Since CT increasingly contributes a significant portion of the total collective dose delivered to the public from clinical procedures, a compelling need for a rapid observation of CT radiation dose levels has been created. Fundamental explanations of CT dose parameters require perhaps reinterpretation and review. Hence, this study consists of the implementation of a standardised CT quality assurance program and the assessment of dose profiles in CT procedures using appropriate methods.

Although the risk-benefit balance is still strongly tilted toward benefit, caution is still crucial (Ogbole, 2010). There currently exist established QA CT scanner testing protocols, including several on acceptance and QC testing for CT (IAEA, 2012). The implementation of available resources in this area to update the CT scanner's

performance, focusing on five different models in Malaysia, are addressed in this study. It has been developed with the philosophy that CT imaging needs to be of the best quality so that it will fulfil the diagnostic obligations required of it. Good imaging performance requires that image quality should be sufficient to meet the clinical demand for the examination. At the same time, the dose should be maintained to the lowest level reasonably practicable (Mansour *et al.,* 2016). This study addresses topics with the concept of practical application in mind, such as the special requirements for scanners used for clinical treatment planning and how to ensure adequate performance in CT scanner utilisation.

1.2 Problem Statement

A CT scanner is a powerful tool that allows high-resolution three-dimensional images for better surgery, better diagnosis, accurate and useful medical treatment. As the number of CTs continues to increase globally, there are concerns about patient protection to track patient doses and the lifetime cumulative dose from medical sources. At low doses of below 100 mGy, it is a difficult task to evaluate cancer risk in humans. However, a comprehensive assessment of available biological data by the National Academies in BEIR VII report has demonstrated that risk would continue linearly at lower doses without any threshold, and the smallest dose has the potential to cause a slight increase of risk to individuals. The need for CT examinations has recently increased due to the tremendous demand for diagnostic procedures. Patient exposure in a CT procedure may be up to 10 -60 mGy (Smith-Bindman *et al*., 2009), which means requiring optimisation is worthwhile to achieve the lowest doses possible. Such doses might be of stochastic effect, since there is no threshold for the stochastic effect to occur. Hence, these effects might reduce by adopting quality assurance (QA), and quality control (QC) measures according to international standards and practices, as highlighted in the IAEA Human Health Series No. 19.

Despite the potential risk associated with an individual patient during CT examinations being relatively small, the gradual increase in the number of people exposed and the increase in exposure per examination may translate into numerous

cancer cases that are attributed to radiation exposure from CT. As such, this creates the need for a quality assurance technique to obtain the clinical information associated with the acceptable dose levels in CT (IAEA, 2012). The acceptable dose levels can be achieved by either standardising the existing QC protocol as established by a relevant organization such as IAEA, or developing a new method. Thus, to identify the level of potential risk in CT examinations, one must recognise the estimated radiation exposure to the patient, which requires the use of dosimeters in patients or phantoms.

QC in CT scanner systems has to be carried out at an interval period as specified by the Ministry of Health (MOH). Since the development of the CT scanner in the early 1970s, CT scanner technology has continuously developed through technical advancement, faster computer processing, superior detectors, and helical and multi-detector scanning modes. Radiologists have given the significant concern of radiation risk from CT examinations and CT radiation dose optimisation a great deal of attention. The significant interest in this study lies between assessing the risk of cancer from CT examinations by measuring the organ dose specifically for an individual, and finding a way to optimise the radiation dose. The implementation from the key components of QC in CT scanner systems may promote the effective use of radiation for diagnostic outcomes through monitoring and reducing the dose to the patient, as well as maintaining appropriate image quality. There is no work had been done in Malaysia regarding the equipment-related factors based on the QC performance test comprised of the QC data. Therefore, regular updates of this issue are necessary, particularly for radiologists who play a decisive role in this activity. In some areas, resources, both technological and human, are limited, and therefore this has incited us to establish and introduce the concept of practical application knowledge. A particular focus is placed on the detailed and precise information based on data on equipment-related factors and the application-related factors (in terms of CT Dose Index; CTDI and organ dose mapping). This study is an attempt to focus on the performance assessment of different Multi-Detector Computed Tomography (MDCT) scanners. It will provide an update on how we can optimise the CT dose to maximize the benefit-to-risk of this clinically useful diagnostic imaging technique. Figure 1.1 illustrates the schematic diagram of the problem statement of this study. Hence, at the end of this study hope to answer the fundamental questions below:

(a) What are the CT parameters that influence the CT dose and CT quality image?

(b) How do CT scanner protocols affect the radiation dose and CT image quality?

(c) What are the testing protocols that must be included in QC of CT scanners to balance the benefit to risk of CT?

(d) How does the organ dose relate to CT scanners' protocols?

(e) What are the best CT scanner parameter settings that will give an acceptable, safe and optimum absorbed dose to the patient's organs?

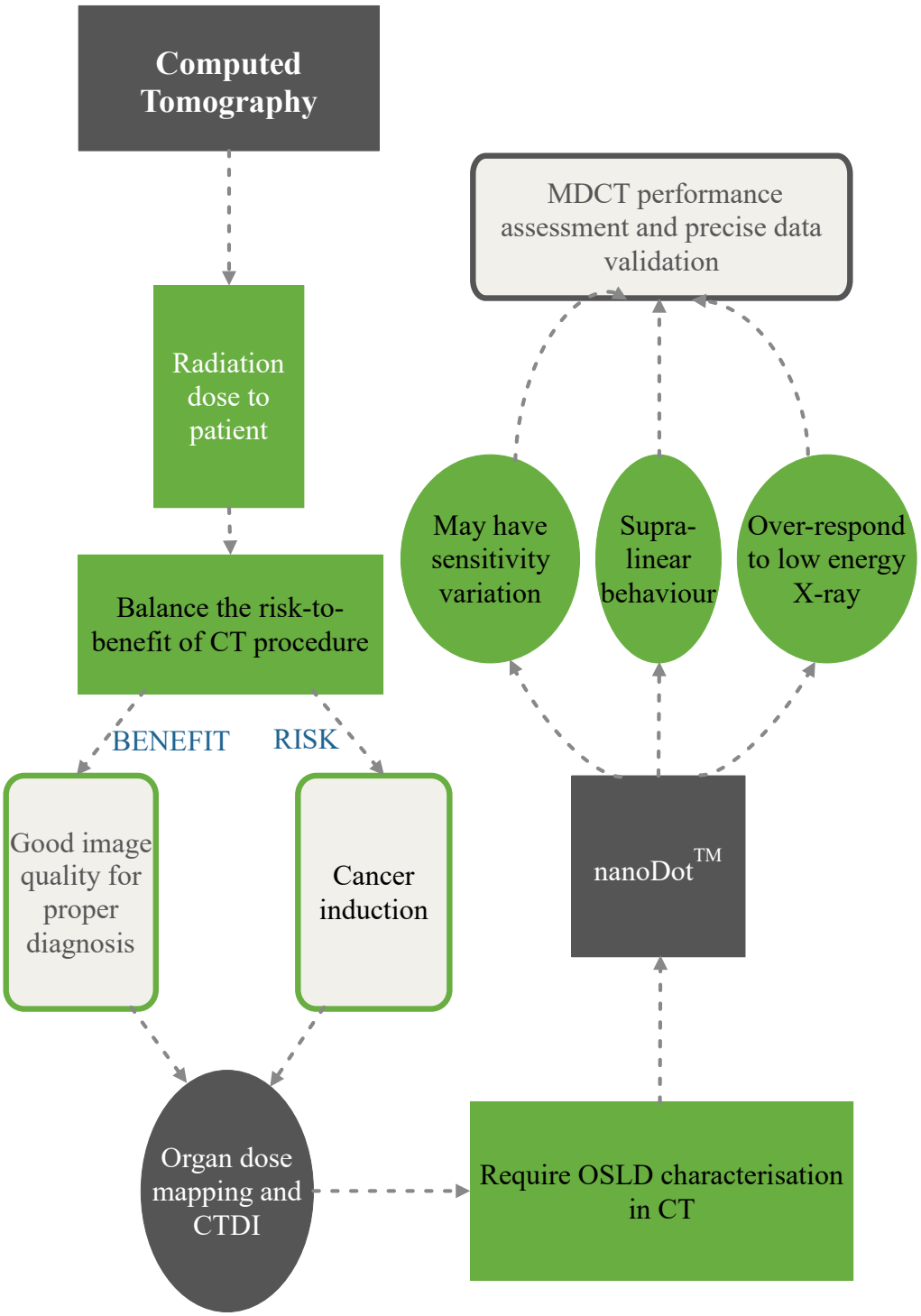

Figure 1.1 Schematic diagram of the problem statement and the current study.

1.3 Objective of the study

The objectives of the project are as following:

(a) To utilize the thermoluminescence dosimeter (TLD-100™) and nanoDot™ optically stimulated luminescence dosimeter (OSLD) for use in dose mapping measurement.

(b) To obtain the optimum CT parameters considering the benefit-to-risk of CT procedures.

(c) To determine the organ dose profile using nanoDot™ OSLDs and standard anthropomorphic phantom (Alderson Radiation Therapy phantom).

1.4 Scope of the study

In this study, the calibration of the dosimeters included the dosimetric parameters characterisation (optical annealing process, signal depletion, signal fading, dose-response, linearity, sensitivity and energy dependence), were carried out by using TLD-100™ and nanoDot™ OSLDs with exposure to a Constant Potential Industrial X-ray located in Nuclear Malaysia, Kajang, Selangor. CT QC test parameters for standardization and optimisation based on various selection types of MDCT scanners were conducted to obtain the performance of unit assembly evaluation and performance testing of: X-ray generators, CT dosimetry, scan localisation, sensitivity, leakage radiation and as well as scattered radiation. The evaluation of quantitative accuracy in QC testing also resulted in equipment-related factors: accuracy of distance measurement, CT number calibration, CT number constancy and as well as CT number dependence (scan thickness, reconstruction algorithm, phantom size, and phantom position). The test parameters from CT scanners will selectively affect image quality and CT scanner performance. The organ dose profile data set using nanoDot™ OSLDs and will be compared with Monte Carlo (MC) simulation results in the future.

1.5 Significance of the study

OSLDs offer a potential technique for accurate and fast point-based patient-specific CT dosimetry at the patient's surface by using air kerma. The precision and accuracy of dose measurement details from the dosimeters should be enough to permit the work to be interpreted and repeated for validation. Since this study included the characterisation and calibration of the (TLD-100™) and nanoDot™ OSLDs, the results may prompt validation of the dosimeters to be used for dose profile assessment throughout the study.

This study may lead to provide precise information data based on equipment-related factors, using the implementation of the QC protocol during CT procedures. This implementation is significant to ensure that the CT clinical diagnostic information is given at the lowest possible cost and with the least possible exposure of the patient to radiation. This study is designed to ensure that CT clinical diagnosis or treatment does more good than harm to the patient.

Organ dose mapping profiles using a standard anthropomorphic phantom (Alderson Radiation Therapy phantom) can be a method to obtain a point dose measurement along the z-axis that motivates the determination of densely sampled organ dose profiles for CT applications. This practical option, using nanoDot™ OSLDs, provides long-term stability that can place the dosimeters within the small cavities in the anthropomorphic phantom as well as the CTDI phantom. This method displays the reference level for the dose distribution inside different organs in a realistic CT clinical scan.

The information that is derived in this study will be beneficial to future work involving performance CT scanners and OSLDs in the medical radiation therapy area.

1.6 Research hypothesis

It is expected that a CT scanner's performance and the absorbed dose by the patient will be influenced by the present studies of the CT parameters such as voltage, current-time product and exposure time, which includes information from the QC testing parameters. Therefore, the precise data based on equipment-related factors and application-related factors in terms of CT dose mapping profiles are desired to identify a safe, minimum absorbed dose that is as low as possible. The prominent intention of this study can also lead to dose estimation and minimising of risk to Malaysia's patients that are undergoing CT examinations, since concern on the inaccuracy of standard CT dosimetry has been raised.

1.7 Thesis outline

Chapter 1 gives a brief introduction to the study. It consists of the background of the study, problem statement, objectives of the study, scope of the study, the significance of the study, research hypothesis and thesis outline. A literature review has been written in Chapter 2, which describes the background and recent studies about CT scans. It offers a brief and basic explanation of X-ray and CT, CT timeline historical studies, different types of CT generation, CT parameters included CT dose descriptors as well as CT equipment-related factors. Information about CT technical details, theoretical practice and Optically Stimulated Luminescence (OSL) dosimetry is also discussed in this chapter. Chapter 3 explains the experimental methods adopted in this study, including the method preparation and identification of the CT scanner, dosimeter, dosimeter reader, dosimeter annealer and the phantom. Also, dosimeter characterisations, such as the optical annealing process, signal depletion, signal fading, dose-response, linearity, sensitivity and energy dependence are described in this chapter. In addition, the methodology to acquire the measurement for QC testing protocols and dose mapping profiles are also discussed in this chapter. Chapter 4 presents and discusses the results of the study. Last but not least, Chapter 5 provides the conclusion of the study and gives some recommendations for possible future works.

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LIST OF PUBLICATIONS

1. Omar, R. S., Hashim, S., Ghoshal, S. K., & Shariff, N. D. (2019, September). Entrance surface dose of eyes and thyroid using nanoDot optically stimulated luminescence in 64-slices computed tomography scanner. In *AIP Conference Proceedings* (Vol. 2155, No. 1, p. 020011). AIP Publishing LLC.

2. Omar, R. S., Hashim, S., Ghoshal, S. K., Shariff, N. D., & Hashim, A. (2019, September). Light induced fading in optically stimulated luminescence dots for medical dosimetry measurement. In *AIP Conference Proceedings* (Vol. 2155, No. 1, p. 020012). AIP Publishing LLC.

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