UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION ON RADIATION DOSE AND IMAGE QUALITY IN PAEDIATRIC COMPUTED TOMOGRAPHY EXAMINATION

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FS 2022 34

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By

NOR AZURA BINTI MUHAMMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

September 2021

DEDICATIONS

To my beloved husband, mothers and daughters.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

OPTIMIZATION ON RADIATION DOSE AND IMAGE QUALITY IN PAEDIATRIC COMPUTED TOMOGRAPHY EXAMINATION

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September 2021

Chair : Muhammad Khalis bin Abdul Karim, PhD
Faculty : Science

Computed tomography (CT) scan examinations have been acknowledged for its high dose exposure contribution. This is troublesome for paediatric as they are susceptibility to radiation and receives higher probability of radiation - induced cancer risk. Lowering the radiation dose while maintaining patient diagnostic value is a vital feature of all dose management practices. Henceforth, the first phase of this study is to establish the local Diagnostic Reference Levels (DRLs) for paediatric CT examination with consideration of the noise index. This retrospective study was approved by Medical Research Ethics Committee (MREC) of University of Malaya Medical Center (approval no: MREC id no 2018920-6690). One thousand one hundred and ninety-two (1192) paediatric patients underwent CT brain, CT thorax and CT chest-abdomen-pelvis (CAP) examinations were recorded. For each group, data such as scanning acquisition parameters and dose information, volume weighted CT dose index ($CTDI_{vol}$), dose-length product (DLP) and the effective dose (E) were evaluated. The CT dose values between all age groups have differed significantly with p-value = 0.0001. There was a significant variation in doses and noise intensity among children of different ages.

The second phase of this study involves adoption of ICRP Publication 103 report and Biological Effects of Ionizing Radiation (BEIR) VII report to determine the radiation-induced cancer risk among subjects. Notably, the highest incidence lifetime attributable risk (LAR) of liver cancer is found in the age group (10-15) with 5.9 out of 100,000 and 2.5 out of 100,000 respectively. The highest cancer risk was in the liver based on the ICRP 103 recommendations for both genders in age group of (1 - < 5) were 3.6 and 1.5 per 100,000 procedures in male and female respectively. The final phase of this study observed the impact of dose in radiosensitive organ and its influence towards image quality in CT Chest-Abdomen-Pelvis (CAP) examination after applying CT optimization process. The organ doses were evaluated by using a 1-year-old anthropomorphic phantom with a thermoluminescence dosimeter (TLD) as a passive dosimeter. In a whole, nine CT protocols were applied for optimization process and the image quality was evaluated by determine the signal to noise ratio (SNR) and contrast to noise ratio (CNR) of phantom images. Notably, the optimization process indicates a potential reduction in a dose up to 20 % to 50 % along with reducing tube voltage, tube current and with increasing slice collimation without compromising the diagnostic value. By turning off the Automatic Tube Current Modulation (ATCM) feature increases the radiation absorbed dose by 80%. Hence, regular CT dose monitoring and optimization procedures will reduce the probability of radiation-induced cancer risk and provide safer imaging practices.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGOPTIMUMAN PADA DOS SINARAN DAN KUALITI IMEJ DALAM PEPERIKSAAN TOMOGRAFI PEDIATRIK

Oleh

NOR AZURA BINTI MUHAMMAD

September 2021

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Pemeriksaan tomografi berkomputer (CT) telah dikenalpasti dapat menyumbang kepada dos sinaran yang tinggi. Hal ini membahayakan kanak-kanak kerana kerentanan mereka terhadap sinaran dan boleh menyumbang kepada kemungkinan risiko kanser disebabkan oleh dos sinaran yang tinggi. Pengurangan dos sinaran dengan mengambil kira keadaan pesakit adalah kriteria penting dalam keseluruhan amalan pengurusan dos radiasi. Seterusnya, fasa pertama dalam kajian ini adalah untuk mewujudkan Aras Rujukan Diagnostik (DRLs) tempatan untuk pemeriksaan CT pediatrik dengan mempertimbangkan indeks hingar. Kajian retrospektif ini telah diluluskan oleh Jawatankuasa Etika Penyelidikan Perubatan (MREC) Pusat Perubatan Universiti Malaya (no kelulusan: MREC 2018920-6690). Seribu satu ratus sembilan puluh dua (1192) pesakit pediatrik yang menjalani pemeriksaan CT kepala, CT dada dan CT dada-abdomen-pelvis (CAP) direkodkan. Bagi setiap kumpulan, data seperti indeks dos CT berwajaran volum ($CTDI_{vol}$), hasil darab panjang dos (DLP) dan dos efektif (E) dinilai. Nilai dos sinaran CT di antara semua kumpulan umur menunjukkan perbezaan yang signifikan dengan nilai p = 0.0001. Terdapat variasi yang ketara di antara dos sinaran dan keamatan hingar imej di kalangan kanak-kanak yang berbeza usia.

Fasa kedua ialah anggaran risiko kanser berdasarkan laporan ICRP Penerbitan 103 dan Laporan Kesan Biologi Sinaran Mengion (BEIR) ke -VII. Risiko seumur hidup – diagihkan (LAR) kanser hati yang paling tinggi ialah pada kumpulan umur tertua dengan masing-masing 5.9 dan 2.5 daripada 100,000 penduduk bagi lelaki dan perempuan. Berdasarkan ICRP 103, risiko kanser tertinggi ialah pada hati bagi kedua-dua jantina untuk kumpulan umur (1 - <5) dengan masing-masing 3.6 dan 1.5 per 100,000 prosedur bagi lelaki dan perempuan. Fasa akhir kajian ini ialah mengukur dos sinaran pada organ radiosensitif dengan mengaplikasikan tetapan parameter pemerolehan CT yang berbeza dan kesanya terhadap kualiti imej dalam pemeriksaan CT Toraks-Abdomen-Pelvis (CAP) dengan menggunakan fantom antropomorfik berusia 1 tahun dan Dosimeter Pendarcahaya (TLD) sebagai dosimeter pasif. Secara keseluruhan, sembilan protokol CT diaplikasikan dalam kajian untuk proses

pengoptimuman dan kualiti imej di nilai dengan menentukan nisbah signal ke hingar (SNR) dan nisbah kontras ke hingar (CNR) pada imej fantom. Modifikasi parameter pemerolehan dalam pemeriksaan CT CAP pediatrik seperti mengurangkan voltan tiub, arus tiub dan meningkatkan kolimasi bim menunjukkan penurunan dos sinaran sebanyak 20% hingga 50% tanpa menjejaskan nilai diagnostik imej. 80% dos sinaran organ terserap meningkat disebabkan oleh fungsi Modulasi Arus Tiub Automatik (ATCM) dimatikan. Oleh itu, prosedur pemantauan dan pengoptimuman dos sinaran CT secara berkala akan mengurangkan kebarangkalian risiko kanser akibat sinaran dan menyumbang kepada amalan pengimejan yang lebih selamat.

ACKNOWLEDGEMENTS

In the name of Allah, most gracious, most merciful.
All the praises and thanks to ALLAH

First and foremost, I would like to thank Dr. Muhammad Khalis bin Abdul Karim, my project Supervisor. I feel incredibly lucky to have Dr. Khalis as a mentor, trainer and friend of mine. Dr. Khalis has been endlessly positive, patient and cooperative with me during my studies. I also express my profound gratitude to my supervisory committee members Dr. Mazliana bt Ahmad Kamarudin, Associate Professor Dr. Hasyma bt Abu Hassan, and Associate Professor Dr. Jeannie Wong Hsiu Ding for their unwavering assistance, motivation and advice. I am highly indebted to my husband (Wan Muhammad Hirzi bin Wan Din) and daughters (Iman & Imtisal), my mother, my father-in-law and my mother-in-law. I thank them for their prayer, endless support, motivation and encouragements that help me while doing this study. I am boundlessly very grateful to my sister for her support.

I would also like to thank the UMMC PACS team (Mr. Hafiz) and the UMMC CT scan team (Mr. Kamil) exclusively for preparing me with the skills to conduct this study. It was a profoundly enriching opportunity to collaborate with the CT team and the QA community (Mr. Wan Haziley). They have a wide range of experience and a common mindset, which has proven to be a valuable asset to my research efforts.

Lastly, I would also like to thanks my colleagues from the Radiography Programme College of Health Sciences UMMC for their helping in daily work. They all morally and intellectually supported me during my candidacy. Their unwavering support was crucial to the thesis's completion.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date: 09 December 2021

Declaration by graduate student

I hereby confirm that:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AAPM	American Association of Physicist in Medicine
AEC	Automatic Exposure Control
ALARA	As Low As Reasonably Achievable
ATCM	Automatic Tube Current Modulation
ASIR	Adaptive Statistical Iterative Reconstruction
ASRT	American Society of Radiology Technologists
BEIR	Biological Effects of Ionizing Radiation
BMI	Body Mass Index
CAP	Chest-Abdomen-Pelvis
CC	coefficient factor
CNR	Contrast to Noise Ratio
CT	Computed Tomography
CTDI	CT Dose Index
$CTDI_{100}$	CT Dose Index from 100 mm
$CTDI_w$	Weighted CTDI
$CTDI_{vol}$	Volume CTDI
DDREF	Dose and Dose-Rate Effectiveness Factor
DICOM	Digital Imaging and Communications in Medicine
DLP	Dose Length Product
DLR	Deep Learning Reconstruction
DRLs	Diagnostic Reference Level
EAR	Excess Absolute Risk
ERR	Excess Relative Risk
FBP	Filter-Back-Projection

FOM	Figure-of-Merit
FOV	Field of View
HU	Hounsfield Unit
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IEC	International Electrotechnical Committee
IR	Iterative Reconstruction
LAR	Lifetime Attributable Risk
LDRLs	Local Diagnostic Reference Level
LNT	Linear Non-Threshold model
LSS	Life Span Study
MC	Monte Carlo
MDCT	Multidetector-Row Computed Tomography
MTF	Modulation Transfer Function
MSCT	Multi-Slice Computed Tomography
NCICT	National Cancer Institute Dosimetry System for Computed Tomography
NDRLs	National Dose Reference Levels
NPS	Noise Power Spectrum
PACS	Picture Archiving Communication System
PiDRLs	Paediatric Imaging Diagnostic Reference Level
PMMA	Poly-Methyl Methacrylate
POSDE	Patient – and organ – Specific Dose Estimation
ROI	Region of Interest
SDD	Source to Detector

SNR	Signal to Noise Ratio
SOD	Source to Object Distance
SSDE	Size-Specific-Dose-Estimate
TCM	Tube Current Modulation
TF	Table Feed
TL	Thermo-Luminescence
TLD	Thermo-Luminescence Dosimeter
UMMC	University Malaya Medical Center
UNSCEAR	United Nations Science Committee on the Effects of Atomic Radiations
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Overview

Wilhelm Conrad Roentgen was the first physicist who observed and discovered the evident of X-rays using the Crooks tube (Glasser, 1993). Since its inception in 1895, the field of medicine, which harness of X-rays has been revolutionized in particular for medical diagnostic imaging. Computed tomography (CT) scan is one of the many modalities in the field of medical diagnostic imaging that utilize X-rays to produce high contrast sectional images (Boice, 2015). CT scan was first developed by Godfrey Hounsfield in his laboratory at EMI. During that day CT scan took several hours to collect the raw data for a single scan or "slice" and reconstruct an image. Figure 1.1 shows the first diagnosis of a brain tumor using commercialized EMI CT scan.

Figure 1.1: Godfrey Hounsfield with his first commercial CT scanner in 1971 (Saini, 2004).

With the introduction of helical technology in the late 1980s and multidetector-row computed tomography (MDCT) technology in the late 1990s, CT has shown capability in rapid scanning speed, sub-millimeter resolution, compact anatomical convergence, deep and high-quality image distribution (Zhou et al., 2017). Because of its capacity to provide high resolution of bone and soft tissue, CT scans is considered as a gold-standard for many pathologic diagnosis and currently used for the preparation of radiation therapy treatment (Meyer et al., 2019).

Over the last decade, MDCT has been empowered by their detector configuration from 4-slice scanners to the new 64-slice and 128-slice devices which offer much faster scanning acquisition. This technical advancement has been followed by a major increase in the therapeutic potential of CT (Edmund & Nyholm, 2017). CT is a sophisticated method in generating high contrast sectional images that requires high computing power for image processing and made substantial improvements in acquisition speed, patient comfort, and high spatial resolution (R. Singh, Wu, et al., 2020; Verdun et al., 2015). Furthermore, shorter CT acquisition periods allow for the elimination of patient motion artefacts such as breathing or peristalsis, which improves image quality (Ria et al., 2019; Takam et al., 2020).

Nevertheless, despite its advantages several studies reveal that CT contributes a significant amount of radiation dose in medical imaging (Ferrero et al., 2019; Gao et al., 2018; Rehani et al., 2020). Due to the awareness towards radiation safety, numbers of recent CT innovation have included methods of optimizing radiation exposure and enhancing diagnostic image efficiency, such as anatomical modulation of the X-ray tube current, organ-based modulation of the tube current, sensitivity of the X-ray tube voltage to the patient's anatomy and iterative reconstruction algorithm (Bendriem et al., 2018; Jones & Townsend, 2017).

1.2 Background of study

The utilization of CT scans has inclined significantly due to the capacity of CT to generate high-contrast sectional images. In contrast to a conventional 2D projection imaging system, CT leads to a high-dose radiation in patients. Therefore, there is a need to refine medical imaging procedures such that individuals particularly in children are not subjected to ionizing radiation unnecessarily or at higher exposures than is required to obtain an image of sufficient diagnostic quality. Figure 1.2 shows the frequency of paediatric CT examinations.

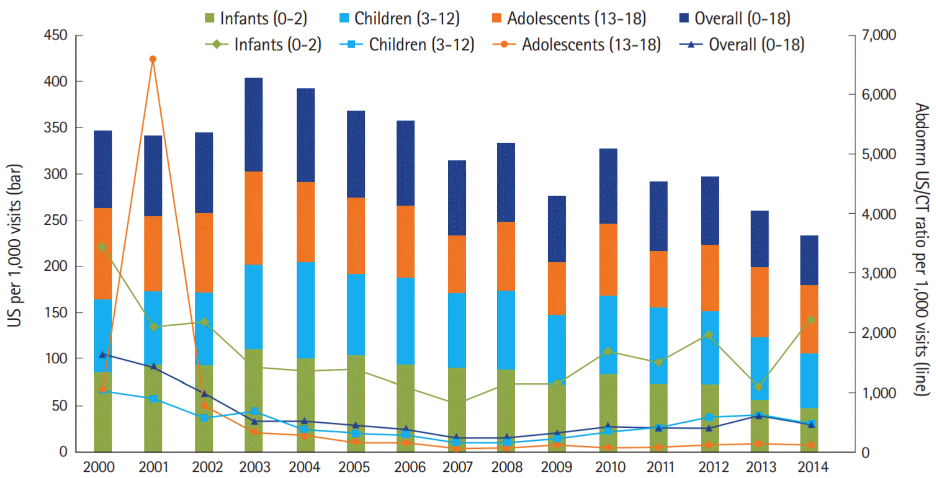

Figure 1.2: Trends by age category in the application of computed tomography (CT) over time (Chang et al., 2018)

As the concern toward radiation dose continuously interest public as well as patients, the "As Low As Reasonably Achievable" (ALARA) principle should then be implemented accordingly. The World Health Organization (WHO) states that safety rationale and optimization are important in children as a consequence of children developing long-term health effects triggered by radiation (WHO, 2004). The unnecessary exposure happen if parameter of the CT acquisition is unoptimized especially when involves patients with much smaller body size (Ferrero et al., 2019; Tonkopi et al., 2017).

The system of automated tube current modulation (ATCM) devices has been developed by most CT vendors to resolve the problem of patient size variation. These systems respond to different patient sizes by decreasing mA in smaller patients and growing mA in larger patients (Fujii et al., 2017; Papadakis & Damilakis, 2019). Furthermore, iterative reconstruction (IR) algorithms have been implemented in the CT to boost the reconstruction of CT (Kubo, 2019; Power et al., 2016). Recently, deep learning reconstruction (DLR) algorithms has been developed in addition to IR algorithms, and they also have a potential to decrease radiation exposure to patients without losing diagnostic image performance (Higaki et al., 2020). Thus, the combination of ATCM, IR algorithm and DLR algorithm in the CT protocol culminated in a decrease of the radiation exposure to patients without losing diagnostic image performance (Gharbi et al., 2018; C. Kim et al., 2018).

The United Nations Science Committee on the Effects of Atomic Radiations (UNSCEAR) states that children are at high risk of experiencing carcinogenic effects owing to the early age of exposure and enhanced radiosensitivity of tissue in certain organs (UNSCEAR, 2010). Figure 1.3 shows radiation dose and projected future cancer related due to paediatric CT examination. Figure 1.4, shows the estimation of the incidence of cancer in particular organs inversely correlated with patient age. The likelihood of occurrence of radiation-induced cancer in children may grow after a long lag time (Brenner & Hall, 2007).

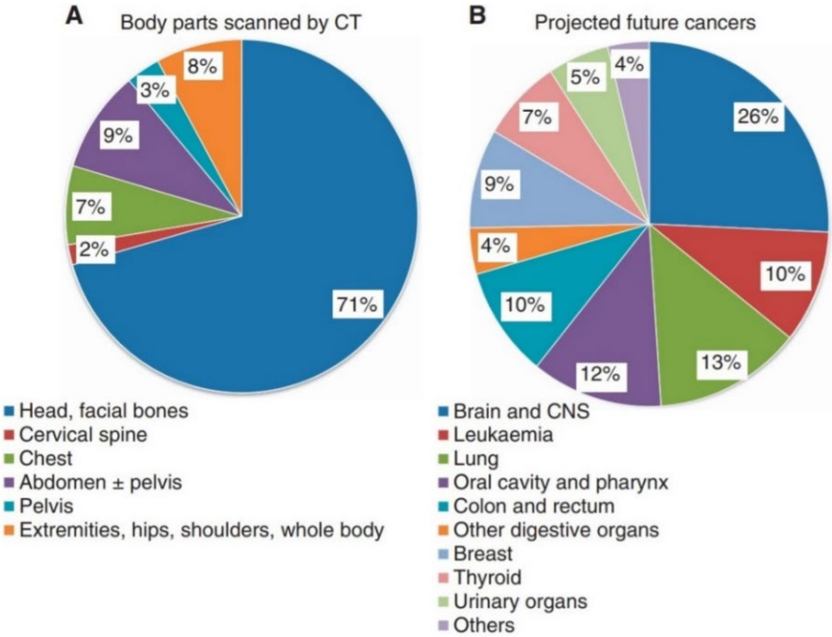

Figure 1.3: Pie chart of the usage of paediatric CT scans by scanned body part. (A) Body parts scanned by CT. (B) Projected future cancers by tumour site (Journy et al., 2017)

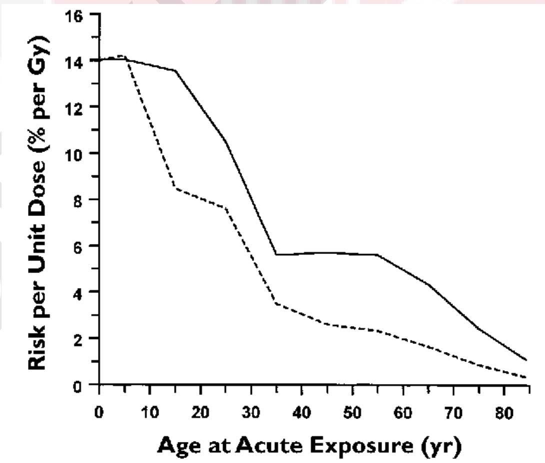

Figure 1.4: The graph indicates lifelong risks of cancer mortality as a feature of age at a single acute exposure per unit dosage, as calculated by the BEIR V (solid line) and in ICRP report 60 (dotted line) (Brenner et al., 2001).

Since children are generally at increased risk of sensitivity to radiation, it is important that any health signs of subtle damage such as cancer are carefully observed in the young age group (Brenner et al., 2001; UNSCEAR, 2018). In addition, the possibility of contracting radiation-induced cancer in children, when it can grow after a long-lasting time, should be emphasized (Brenner & Hall, 2007). Therefore, the researchers could integrate the necessary justification and optimization for a study on the incidence of paediatric CT exposure (Marant-Micallef et al., 2019; Yu et al., 2015).

1.3 Problem Statement

The number of CT examination among paediatric patients has greatly increased and one of the current challenges is the lack of justification during a CT study. The first phase in radiation safety justifies the treatment needed for the patient, or substitute it with other non-ionizing procedures, such as ultrasound and Magnetic Resonance Imaging (MRI) (Al-Rammah, 2016; I. Chang et al., 2018; Menoch et al., 2012). There are two important components of CT clinical application that must be carefully evaluated: radiation dose and image quality. The International Atomic Energy Agency (IAEA) concerned with the optimizing process and considering image quality as an important tool in optimizing process (IAEA, 2012). Several studies found that the Diagnostic Reference Levels (DRLs) was utilized to optimize the CT radiation dose in order to monitor the patient's radiation exposure and ensure that it was consistent with diagnostic requirement (Ekpo et al., 2018; Järvinen et al., 2017; Sulieman et al., 2018). Hence, in 2013, national DRLs was established by the Ministry of Health (MoH) Malaysia via a radiation dose survey conducted between 2007 and 2009. However, the survey is still lacking several informations such as image quality were not apprehended in DRLs survey and there is no comprehensive DRL study on paediatric CT examination. Henceforth, this study can be used as an additional context in the recent situation of CT dosimetry in Malaysia.

Unoptimized ionizing radiation may cause long-term stochastic effects in youngsters, therefore, it is imperative to focus on the monitoring of effective radiation dose exposure (Kutanzi et al., 2016; Weihrauch-Blüher et al., 2019). According to Ideguchi et al (2018), the effective dose value can be used for cancer risk assessment in children undertaking CT scan. The values in paediatric CT trunk examinations ranging from 3.0 mSv to 25.0 mSv, indicating that the probability of radiation-induced cancer is very high in young people, and currently the average lifetime attributable risk (LAR) of cancer incidence among paediatric was 0.14 percent (Kritsaneepaiboon et al., 2018). To note, there is no comprehensive study on cancer risk assessment has been done locally. Unoptimized CT examination protocols are also generally recognized as a huge contributor to the excessive dose of radiation (Meeson et al., 2012; Smith-Bindman et al., 2019). Consequently, CT parameter optimization is a crucial indicator to measure the minimal dose of radiation with minimal diagnostic value in medical imaging (Paolicchi et al., 2014). However, it is challenging to decide the optimum combination of tube voltage (kVp) and tube current (mAs) for the particular patient size and diagnostic technique due to amperage-related dosage of fixed kilovoltage radiation (Dougeni et al., 2012; Pace & Borg, 2018). Several researchers reported that paediatric CT examination were performed with the using the same settings as adult CT acquisition parameters (Chang et al., 2017; Gonzalez et al., 2013). Primary factors such as CT acquisition parameter and secondary factor such as patient's characteristic were considered as the main factor of dose contribution in CT. Henceforth, the current research aims to introduce optimization technique that able to reduce radiation dose by tradeoff with image quality in CT examination. The findings are included in an assessment of the current state of CT dosimetry, image quality performance and the health concerns associated with cancer. The research framework and the solutions to the problem were illustrated in Figure 1.5.

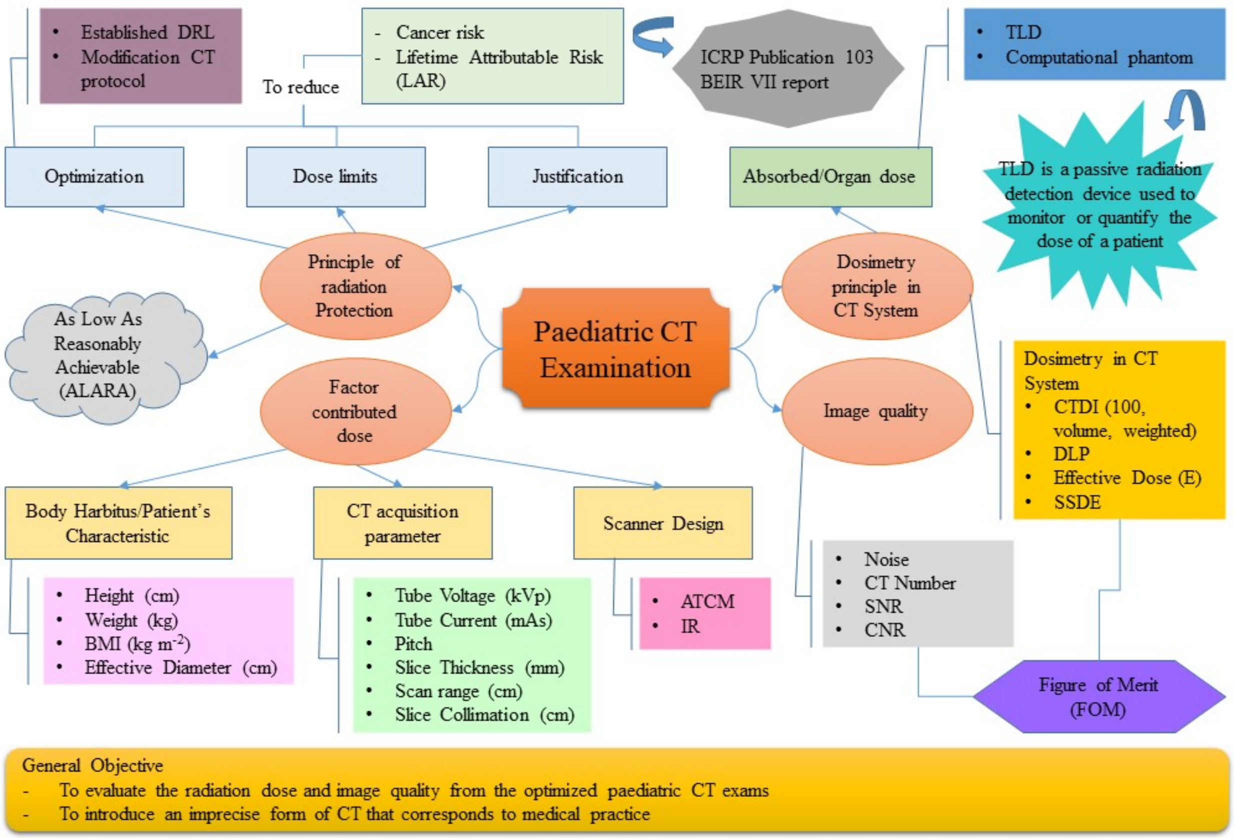

Figure 1.5: Research framework of the thesis focusing on the research problem statement.

1.4 Research Objective

The general objective of this study is to evaluate the radiation dose and image quality from the paediatric CT examinations and to introduce an improvise form of CT optimization that corresponds to medical practice.

Specifically, the objectives embark from the study is:

1. To evaluate the radiation dose and image quality from the routine paediatric CT examinations.
2. To estimate cancer risk and LAR of radiosensitive organs from paediatric CT scan cohort studies.
3. To investigate the impact of CT optimization on paediatric CT acquisition parameter by using anthropomorphic phantom with thermoluminescence dosimeter (TLD) as a passive dosimeter.
4. To determine the Figure of Merit (FOM) that represents the relationship between image quality performance and radiation dose.

1.5 Scope of study

The scope of the study mainly focuses on the paediatric CT dose and its diagnostic value by establishing the local DRLs. The influence of optimized protocols on the dose and image quality is the key of this study and the related radiation risk also needs to be determined. Hence, the work was divided into three parts or three phases;

1) Part I: The data were obtained from the survey method and cross-validated with standard mathematical stylized phantom measurements. The final output of this work, is to establish the local DRLs.

2) Part II: Effective dose and patient-specific organ dose were obtained by using the various techniques including Monte-Carlo calculation and direct measurement. The cancer risk of the examinations is estimated based on ICRP and BEIR VII model. The results were compared to previous data and finally to suggest for the optimization process.

3) Part III: The step for optimization techniques of current CT practice was delivered in term of practicality and theoretically. In this work, the direct measurement technique was used to estimate patient organ dose by inserting dosimeters such as TLDs into a physical anthropomorphic phantom. The objective image quality based on the CT protocols also was accessed.

1.6 Thesis outlines

The general aim of the work is to evaluate radiation dose and to establish indicator for dose optimization in paediatric CT examinations. The personalized perspective such as individual organ dose and the radiation risk associated with population-based CT examinations, also were discuss focussing on the trade-off with image quality in paediatric CT examinations. In Chapter 2, the theoretical basis on ionizing radiation, operational principle of CT scan, CT dosimetry and image quality assessment is briefly explained. Chapter 3 details out the first objective of the study where the radiation dose survey was done in a tertiary hospital with aim to establish the local DRLs from single institutions and compare with other established reference. Chapter 4 answers the second objective where patient's organ-specific dose was determined by using Monte Carlo (MC) calculation technique which requires a primary data such as scanning acquisition parameter, patient's age, weight and height. Furthermore, the related cancer risks from the selected examination also were calculated based on a recommendation model by ICRP Publication 103 and BEIR VII report. In Chapter 5 discusses in details on the optimization of CT CAP parameter study which cover both third and fourth objectives. Furthermore, Chapter 6 includes a summary, general conclusion, and research recommendation for future studies and related field.

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