RADIATION DOSES, CANCER RISKS AND OPTIMIZATION PROCESS OF ROUTINE COMPUTED TOMOGRAPHY (CT) EXAMINATIONS IN JOHOR

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DEDICATION

To my beloved parents & wife...

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ABSTRACT

The concerns towards radiation–induced cancer from Computed Tomography (CT) examinations have led to the encouragement of CT dose monitoring and further optimization of the scanning parameters. Therefore, in this study, radiation dose from CT scan and its related risks to the patients from current CT practice were analysed. In the first stage, this thesis started the discussion on the level of current knowledge among radiology personnel towards CT radiation risk and its optimization. There is no significant difference of the current knowledge of CT optimization between the two professions of interest herein, the medical and the allied health groups. A CT dose survey was conducted in 8 CT facilities for a 6-month period, encompassing data for 1024 patients with various CT examinations that included regions of the abdomen, brain and thorax. CT-EXPO (Version 2.3.1, Germany) software was used to validate the dose information such as CT Dose Index (CTDI) and dose-length product (DLP). The proposed Diagnostic Reference Levels (DRLs) were indicated by rounding off the third quartiles (Q3s) of whole dose distributions for weighted CTDI (CTDIw) (in mGy), volume CTDI (CTDIvol) (in mGy) and DLP (in mGy.cm) and their values were; 16, 17, and 650 respectively for CT abdomen; 70, 70, and 1030 respectively for CT Brain and 15, 16, and 670 respectively for CT thorax. In the second stage, the cancer risks of the CT examinations were estimated and the calculation was based on International Commission on Radiation Protection (ICRP) Publication 103 Report and Biological Effects of Ionizing Radiation (BEIR) VII Report. Based on BEIR VII recommendation, the study discovered that the lifetime attributable risks (LARs) of 100,000 populations who underwent abdominal CT examinations for stomach cancer were 2.3 for male and 1.0 for female; while for colon cancer the LARs were 2.3 for male and 0.7 for female. The effectiveness of optimization of CT parameters and application of shielding in routine CT procedures were evaluated. Of 7 protocols (P1 – P7), the k factors were constant for all protocols and decreased by ~8% compared to the universal k factor. It is of interest that k factors from CT-EXPO were found to vary between 0.010 for protocol P5 and 0.015 for protocol P3 due to inconsistency in tube potential and pitch factor. The application of breast shielding to routine CT thorax protocols reduced by 14% the breast’s equivalent dose. Hence, this study supports the importance of initiating protection and optimization processes of routine CT examinations in order to offer safer imaging practices.

ABSTRAK

Kebimbangan terhadap kanser teraruh sinaran daripada pemeriksaan tomografi berkomputer (CT) mengarahkan kepada penggalakan pemantauan dos CT dan pengoptimuman parameter imbasan. Oleh itu, dalam kajian ini, dos sinaran daripada imbasan CT dan risiko yang berkaitan kepada pesakit daripada amalan CT semasa telah dianalisis. Pada peringkat pertama, tesis ini memulakan perbincangan mengenai tahap pengetahuan dan kesedaran di kalangan kakitangan radiologi terhadap risiko sinaran CT dan pengoptimumannya. Tidak ada perbezaan yang signifikan mengenai pengetahuan semasa bagi pengoptimuman CT antara dua profesion yang berkaitan, perubatan dan kesihatan bersekutu. Kajian dos CT telah dijalankan di 8 kemudahan CT untuk tempoh 6 bulan, merangkumi data bagi 1024 pesakit dengan pelbagai pemeriksaan CT yang termasuk kawasan abdomen, kepala dan toraks. Perisian CT-EXPO (Versi 2.3.1, Jerman) telah digunakan untuk kesahan maklumat dos seperti indeks dos CT (CTDI) dan hasil darab panjang dos (DLP). Aras Rujukan Diagnostik (DRLs) yang dicadangkan telah ditunjukkan dengan membundarkan kuartil ketiga (Q3) taburan dos keseluruhan bagi pemberat CTDI (CTDIw) (dalam mGy), isipadu CTDI (CTDIvol) (dalam mGy) dan DLP (dalam mGy.cm) dan nilainya; masing-masing ialah 16, 17, dan 650 untuk CT abdomen; masing-masing ialah 70, 70, dan 1030 untuk CT otak dan masing-masing ialah 15, 16, dan 670 untuk CT toraks. Di peringkat kedua kajian, anggaran dan kiraan risiko kanser daripada pemeriksaan CT berdasarkan kepada Laporan Suruhanjaya Antarabangsa Perlindungan Sinaran (ICRP) Penerbitan 103 dan Laporan Kesan Biologi Sinaran Mengion (BEIR) ke-VII. Berdasarkan cadangan oleh BEIR-VII, kajian ini merangkumi risiko agihan jangkahayat (LARs) 100,000 populasi yang menjalani pemeriksaan CT abdomen untuk kanser perut ialah 2.3 bagi lelaki dan 1.0 bagi perempuan; sementara LARs bagi kanser kolon ialah 2.3 bagi lelaki dan 0.7 bagi perempuan. Keberkesanan pengoptimuman parameter CT dan aplikasi alat pelindung dalam prosedur CT rutin dinilai. Daripada 7 protokol (P1 - P7), faktor k adalah malar untuk semua protokol dan berkurang ~ 8% berbanding dengan faktor k semesta. Didapati kesemua faktor k daripada CT-EXPO berubah antara 0.010 bagi protocol P5 dan 0.015 bagi protocol P3 disebabkan oleh ketidakmalaran dalam keupayaan tiub dan faktor jarak. Aplikasi pelindung payudara kepada protokol CT toraks rutin berkurang kepada 14% dos setara payudara. Oleh itu, kajian ini menyokong kepentingan memulakan perlindungan dan proses pengoptimuman dalam pemeriksaan CT rutin untuk menawarkan amalan pengimejan yang lebih selamat.

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LIST OF ABBREVIATIONS

AAPM	-	American Association of Physicist in Medicine
AEC	-	Automatic Exposure Control
ATCM	-	Automatic Tube Current Modulation
BEIR	-	Biological Effects of Ionizing Radiation
BMI	-	Body-Mass Index
BSS	-	Basic Safety Standard
CME	-	Continuous Medical Education
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
CTU	-	CT Urography
CXR	-	Chest X-ray
DLP	-	Dose-Length Product
DDREF	-	Dose and Dose-Rate Effectiveness Factor
EAR	-	Excess Absolute Risk
ERR	-	Excess Relative Risk
FWHM	-	Full-Width at Half-Maximum
GUI	-	Graphical User Interface
HPA	-	Health Protection Agency, United Kingdom
ICRP	-	International Commission on Radiation Protection
IVU	-	Intravenous-Urography
IAEA	-	International Atomic Energy Agency
LAR	-	Lifetime Attributable Risk
LNT	-	Linear Non-Threshold model

LSS	-	Life Span Study
MC	-	Monte Carlo
MIRD	-	Medical Internal Radiation Dose
MSAD	-	Multiple Scan Average Dose
MSCT	-	Multi-Slice CT
NMRR	-	National Medical Research Registration
NURBS	-	Non-Uniform Rational B-Splines
OD	-	Optical Density
PET	-	Positron Emission Tomography
PMMA	-	Poly-Methyl Methacrylate
POSDE	-	Patient- and Organ- Specific Dose Estimation
PPM	-	Planned and Preventive Maintenance
Q3	-	Third quartiles
QA	-	Quality Assurance
SNR	-	Signal-to-Noise Ratio
SSCT	-	Single-Slice CT
SSDL	-	Secondary Standard Dosimetry Laboratory
TF	-	Table-Feed
TL	-	Thermo-Luminescence
TLD	-	TL dosimeter
UFC	-	Ultra-Fast Ceramic
UNSCEAR	-	United Nation Scientific Committee on Effects of Atomic Radiations
WHO	-	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Overview

Since the discovery of X-rays by Wilhelm Conrad Roentgen in the year 1885, the field of medicine has been revolutionized and utilized by a medical field known as radiology. Radiology is one of the branches of medicine that uses various imaging techniques and modalities to produce high-quality images of human anatomy with the aim to provide an accurate diagnosis of diseases. Henceforth, a lot of imaging modalities use X-rays as the main emitting source due to its advantages in providing high contrast radiographic images, including the Computed Tomography (CT) scan.

CT is one of the most vital imaging modalities in radiology, capable of producing high contrast sectional images. The X-rays that transmit through the human body are detected by a detector in a circular motion along the x-y axis. Subsequently, computer processing of the raw data produced from the received detector using Rando transform algorithm, reproducing sectional images in the form of axial, sagittal-coronal and 3D images, as in Figure 1.1 and the details in Chapter 2. The sectional images allows the Radiologist to diagnose diseases accurately in a clinical situation better than 2D radiographic images of conventional X-ray machines (Goo, 2012; Lee *et al*., 2004).

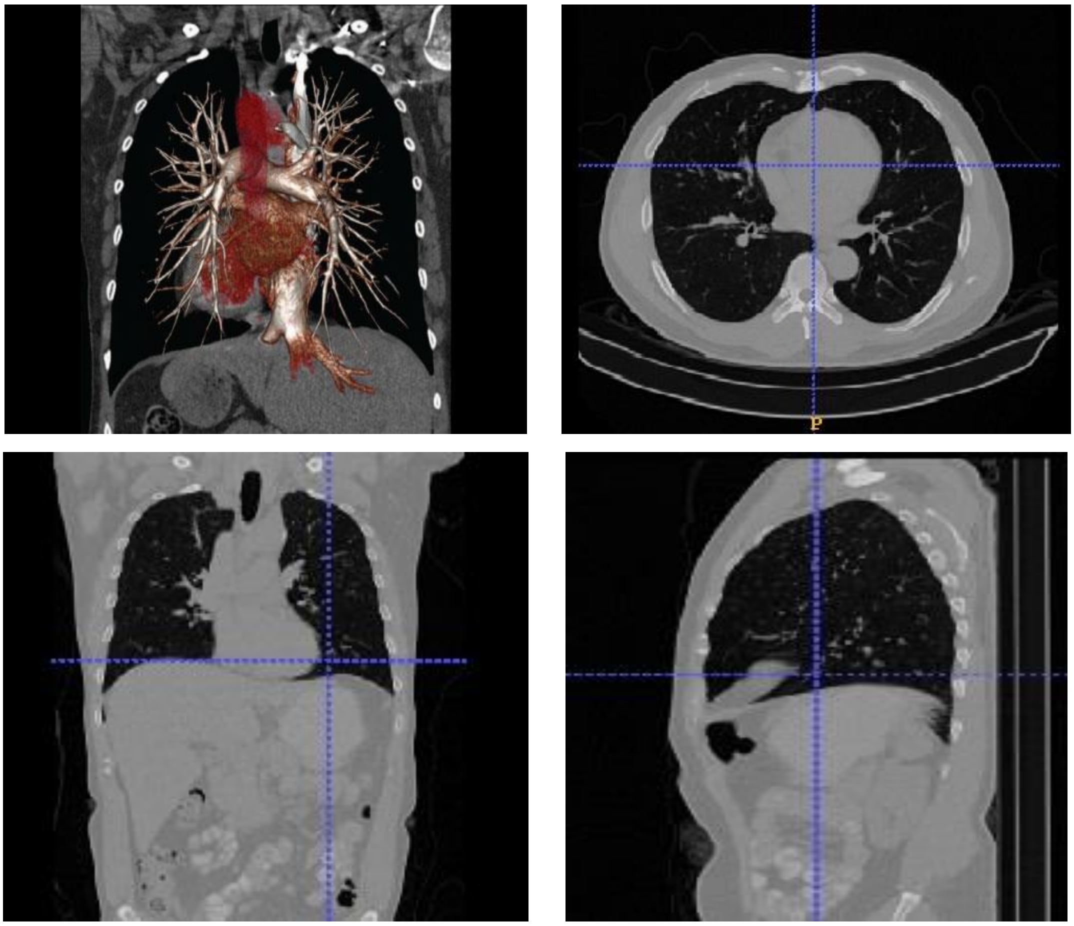

Figure 1.1 CT images of a thorax. The upper right side is axial images of CT thorax and it is followed by sagittal images in lower right side. On the left upper side is a 3D image of CT pulmonary and below on the left side is a coronal image of CT thorax (Workstation images).

Nowadays, CT has become a one of the recognized diagnostic imaging tools for radiological investigation since the inception of the CT scan EMI Mark I by Godfrey Hounsfield in 1972 (Jessen *et al*. 1999; Tsapaki *et al*. 2010; Rehani 2012; Kalender 2014; Hounsfield 1976a). Unlike film-cassettes techniques, which use a larger but passive detector, CT has minimized the unnecessary amount of scattered radiation by allowing sequential irradiation slabs of tissue and collimation of the detector. Furthermore, in the year 1988, a slip-ring technology was introduced that made a continuous rotation of the gantry and detectors possible (Kalender *et al*., 2008). Thus, during helical mode acquisition, the table is able to move continuously while the detectors are rotating and produce images by utilizing interpolation techniques. This allows spiral CT capable in obtaining a larger volume of information in sub-second time, resulting in shorter breath hold and subsequently, minimizes motion artifacts. However, despite its benefits, the CT scan is considered as one of the most hazardous imaging modality as it contributes greater dose exposure.

Figure 1.2 G.F Hounsfield with his first commercial CT scanner, EMI Mark I (Buzug *et al*., 2009).

1.2 Background of study

The advancement of CT technology and requisite for better image quality lead to the geometry of the CT systems becoming much more complex and with the employment of more detectors (Fuchs *et al*., 2000). Therefore, the dosimetry in CT has become a challenging task for many researchers with the addition of the increasing demand for individual dose tracking in medical imaging (Fearon *et al*., 2011).

In the year 2001, the International Commission on Radiological Protection (ICRP) raised concern that with increased use of CT there was a possibility that the radiation dose from CT examinations was high. A 2006 United States (US) radiation dose survey categorized CT exams as the largest source of medical exposure in the USA (National Academy of Sciences, 2006). This trend is due to the advantages of CT modality in providing the high diagnostic value of images with faster and accurate diagnosis which steered to a number of unjustified request for CT examinations by physicians. With increase in public concern, many agencies introduced monitoring processes also establishing Diagnostic Reference Levels (DRLs). As expected, the multinational surveys show that with radiation doses from CT exceeding reference levels this could increase the risk of cancer (radiation-induced cancer) (Brenner, 2012; Hall and Brenner, 2008; Feng *et al.*, 2010; Swanson, 2012).).

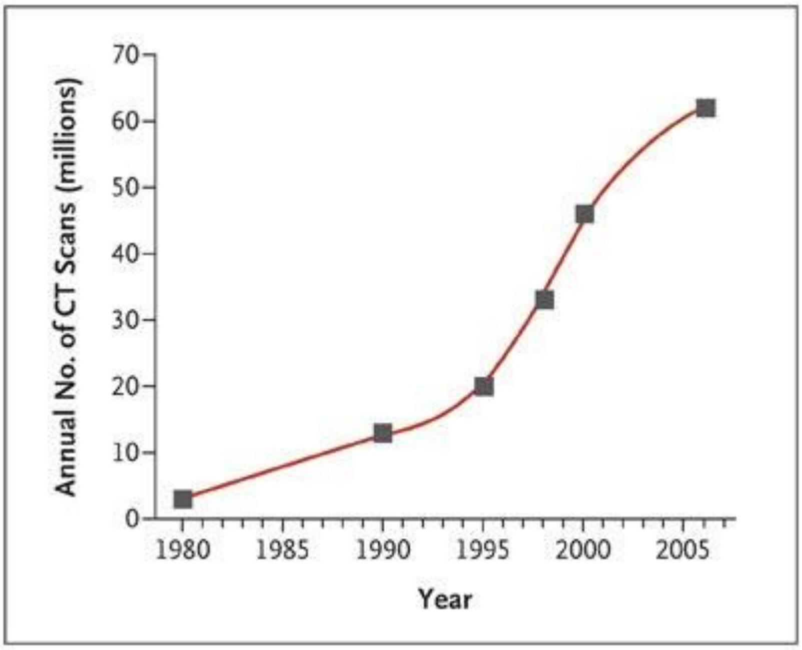

Figure 1.3 The number of CT scans examinations performed in the US (Smith-Bindman *et al.*, 2009)

In 2003, a survey conducted in the UK by Health Protection Agency (HPA) indicated that the total effective population radiation dose to be 47% even thougt it only represented 9% of all x-ray examinations done in the country (Jones and Shrimpton, 1991; Shrimpton *et al.*, 2006). According to Naumann *et al.* (2014), the risk of radiation is greater for pediatric patients as they receive higher absorbed dose compared to an adult even using the same scan parameters (Naumann *et al.*, 2014; Rehani *et al.*, 2012). As illustrated in Figure 1.4, the radiation dose to patients was varies based on the type or region of examinations, the abdominal CT investigations have the highest effective dose values (Sokolovskaya and Shinde, 2016; Pantos *et al.*, 2011; Sabarudin *et al.*, 2015)

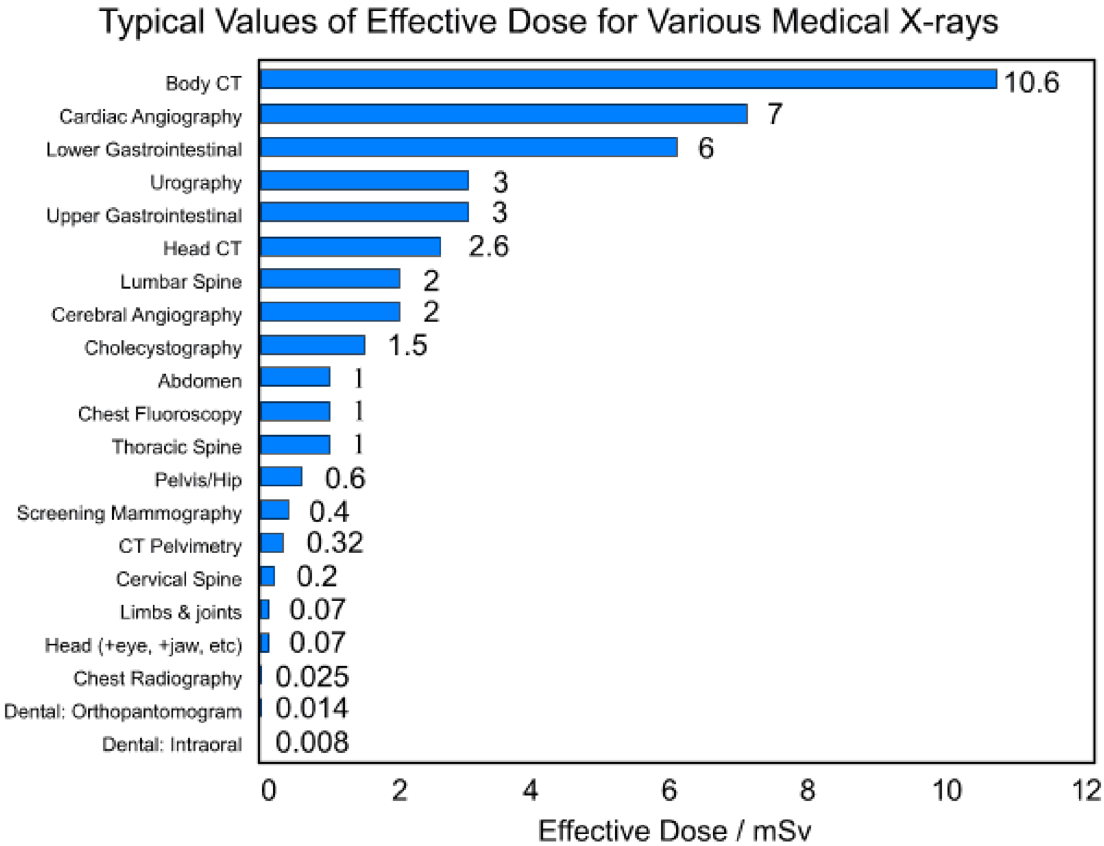

Figure 1.4 Effective dose values from radiological examinations were based on the type of examinations, modality used and region of scanning (Australian Radiation Protection, 2013).

As a result of the increased utilization of CT and increasing radiation dose to the population, CT optimization techniques have become a major focus of the medical research community. Furthermore, much research has focused on finding the most accurate means of dosimetry, patient-specific, although current existing dosimetry for CT system are still usable worldwide (Edyvean, 2013; Fearon *et al.*, 2011; Jessen *et al.*, 1999; Tsalafoutas *et al.*, 2012). This includes the use of the Monte Carlo (MC) simulation method such as anthropomorphic mathematical simulation as well as the use of direct methods using small dosimeters, for instance thermoluminescence dosimeters (TLD).

Generally, the biological risk associated with the exposures of individual or populations to ionizing radiation can be categorized into two effects; deterministic and stochastic effects (Alpen, 1998). Deterministic effects are the acute outcomes of the absorbed dose when exceeding a certain threshold (> 1 Gy). The doses received from CT examinations typically are much lower compared to dose threshold, ranging from 10 – 50 mGy. The dose delivered from CT to a specific anatomical region is sometimes repeated up to three phases depending on the clinical needs (Kalender, 2014). As consequences, effects such as hair loss, skin injuries and erythema have been reported, especially from CT brain perfusion studies as shown in Figure 1.5.

Figure 1.5 Patients suffering from epilation due to CT brain perfusion examinations (New York Times Magazine, 2009)

Stochastic effects of radiation describe the potential chronic risks of radiation exposure. Generally, the typical doses from radiological examinations do not cause immediate cell death, but the ionization process could result in DNA strand breaks. The DNA strand breaks are commonly caused by the interaction of DNA hydroxyl with the ionized atoms and become hydroxyl radicals. These DNA breaks are usually repaired by cellular repair mechanism or the cell is into apoptosis. In the case of incorrect repair of DNA, cell proliferation continues despite genetic mutation and led to carcinogenesis effects.

Normally, the risk from radiation has been defined by using the linear non-threshold model (LNT), based on epidemiological studies including data from 1945 atomic bomb survivors (Figure 1.6) (National Academy of Sciences, 2006). Although the LNT models at low dose have been questioned for accuracy, many researchers show great interest in estimating cancer risk from CT examinations as radiation dose from CT is quite high and potentially more hazardous compared to other modalities. The various techniques of calculation and new applications have been introduced in order to demonstrate an overview of cancer risk from CT. Concerning the above matter, it is necessary to properly assess and monitor radiation dose from CT examinations, in particular, estimating the patient- and organ- specific dose (POSDE) and risk.

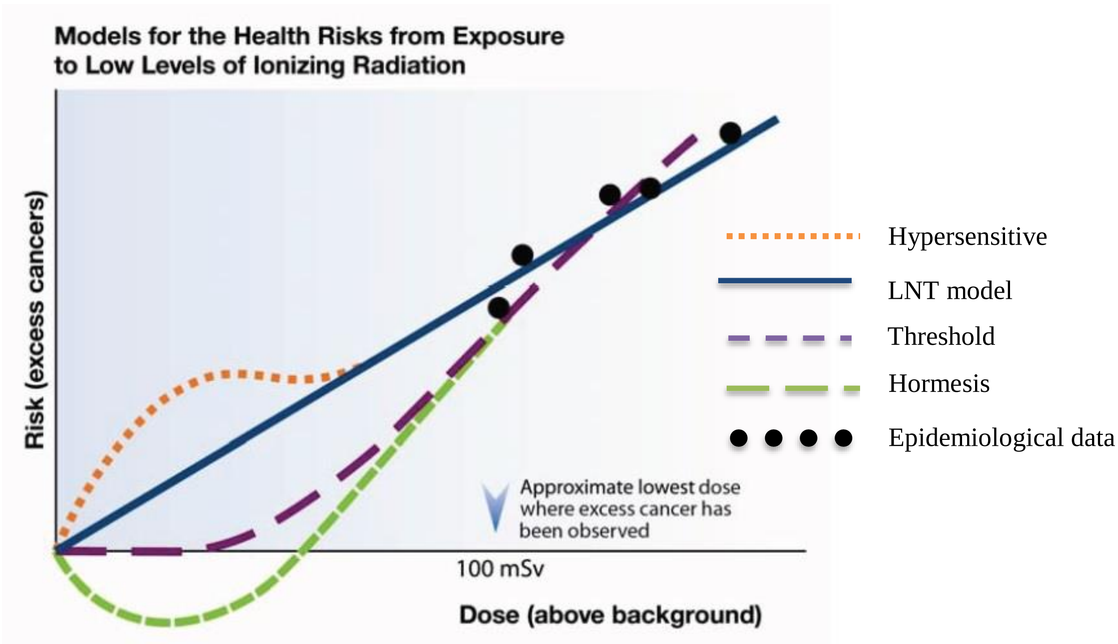

Figure 1.6 The LNT model uses for estimate risk from low dose exposure (Canadian Nuclear Safety Commission, 2013)

1.3 Problem statement and motivation

A number of studies have related that exposure from CT scans is responsible for increasing the risk of cancer (Brenner and Hall, 2007; Berrington de Gonzalez *et al.*, 2009). Brenner predicted radiation-related risks in a population by using the data from survivors of the atomic bombs dropped on Japan in 1945, where the average effective dose is around 20 mSv (Brenner and Hall, 2007; Naumann *et al*., 2014).

As conclusion, they have established finding that the dangers of malignant neoplastic disease are greater for paediatrics than adults as paediatric patients are more radio-sensitive to radiation and have a longer lifespan to get cancer. Furthermore, Berrington *et al.* reported that 29,000 of future cancers could be linked to CT scans performed in the USA in 2007 (Berrington *et al.*, 2009). Consequently, this has alarmed responsible agencies such as the ICRP, United Nation Scientific Committee on Effects of Atomic Radiations (UNSCEAR), American Association of Physicist in Medicine (AAPM), the International Atomic Energy Agency (IAEA) and have alerted the public that the radiation risk from CT may possibly be harmful and dangerous (Rehani, 2012; AAPM Task Group 23, 2008; UNSCEAR, 2010; Balonov and Shrimpton, 2012).

The primary goal of this study is to measure radiation dose from routine CT examinations and to introduce accurate CT dosimetry that matches to Malaysian clinical practice. It is also essential to estimate the risk to Malaysian populations that have undergone CT examinations since there are several issues related to the inaccuracy of standard CT dosimetry that need to be addressed. Figure 1.7 shows schematically the problem statement of the current study. In general, the present study is intended to provide information on the issues of current dosimetry in CT technology. The data obtained from the study forms part of the review of the present situation of CT dosimetry and its related health risks. In future, this thesis could also be used as a supplementary document in support of baseline information on the recent situation of CT dosimetry in Malaysia.

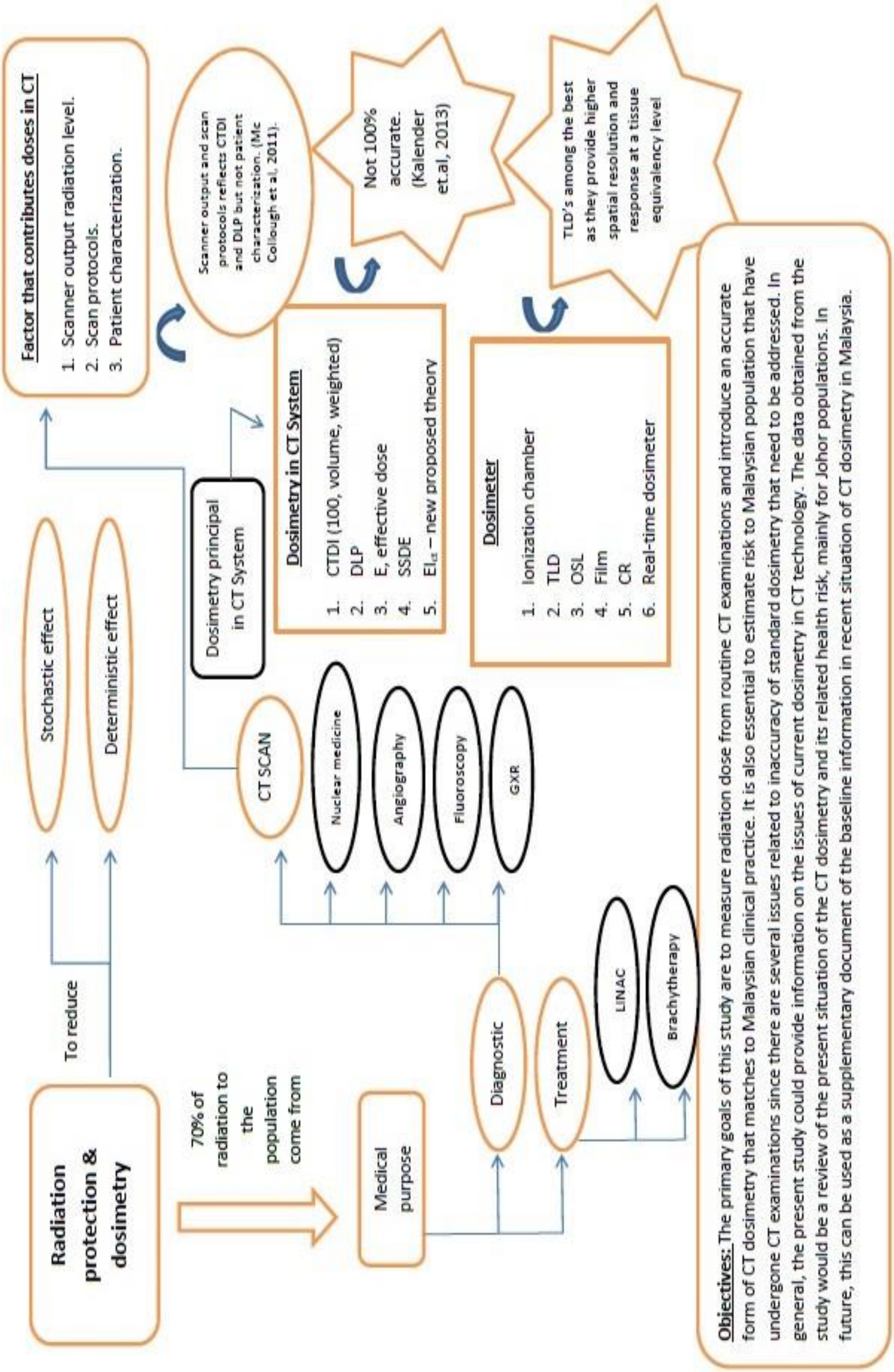

Figure 1.7 The schematic diagram of thesis problem statement

1.4 Research Objectives

The objectives of this study are:

1) To assess knowledge and awareness of radiology personnel towards optimization techniques and radiation risk of CT examinations.

2) To evaluate the standard acquisition protocols and radiation dose exposure received by the patient from current CT practice, finally establishing local DRLs.

3) To measure the radiation risk from CT scan cohort studies using a variety of calculation methods.

4) To investigate organ absorbed dose and CT optimization techniques on an adult anthropomorphic phantom.

5) To introduce a method for the determination of patient- and organ- specific dose (POSDE) by using Monte Carlo simulation method.

1.5 Scope of study

The scope of the study involves determination of the accuracy of organ radiation dose measurement from CT examinations and the evaluation of related radiation risk. To achieve this, the study was divided into three parts;

1) Part I: The data was obtained from the survey method and cross-validated with standard mathematical stylized phantom measurements. Local DRLs were established and radiology personnel awareness relationship was evaluated.

2) Part II: Various methods of calculation based on ICRP and BEIR VII were used to estimate patient organ dose and radiation risk. The risk calculation was made on the whole perspective and then narrowed down to specific clinical CT examinations.

3) Part III: Direct measurements were used to estimate patient organ dose by inserting dosimeters such as TLDs into a physical anthropomorphic phantom. Further, steps for optimization techniques of current CT practice were introduced.

1.6 Thesis outlines

This thesis gives a comprehensive overview of CT practice in Johor state including dose exposure evaluation, organ absorbed dose assessment, radiation risk among the population, steps for optimization and the introduction of novel applicable method for evaluating individual specific dose. The basics of the dosimetry and estimation of risk is undoubtedly mathematics. However, the beauty of computed tomography cannot be understood without a basic knowledge of X-ray physics and signal processing. With respect to the title of this thesis, it is structured to provide understanding in current CT practice.

In Chapter 2, the fundamentals of CT dosimetry, the milestones and current research in CT dosimetry and its related risks are briefly explained. In Chapter 3, the materials and method used are discussed briefly. In Chapter 4, Chapter 5 and Chapter 6 the results and discussion will be presented on; the establishment of DRLs, radiation risk measurement, and optimization process, respectively. Furthermore, the conclusion of the thesis will be provided in Chapter 7.

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