THREE-DIMENSIONAL COMPUTED TOMOGRAPHY DOSE OPTIMISATION AND IMAGE QUALITY IMPROVEMENT OF ABDOMEN-PELVIS USING ADAPTIVE-ITERATIVE DOSE REDUCTION

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To my beloved family, for their endless patience, support, and courage during the hardships in completion of this thesis.

This thesis is dedicated to them.

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ABSTRACT

New development of computed tomography (CT) technology has made CT a versatile and efficient diagnostic modality. This has led to exponentially increased demand in clinical practice with increased risk of radiation exposure to the patients. Most research on CT optimisation concentrates on physical parameters, such as tube potential, tube current and pitch factor. Little research has been done on iterative reconstruction process in dose reduction without compromising image quality in clinical CT examination. Thus, this study investigates dose optimisation and image quality improvement using Adaptive-Iterative Dose Reduction Three-Dimensional (AIDR 3D) reconstruction, compared with conventional filtered back projection (FBP), in abdomen-pelvis CT. In a single-centre cohort study, 100 patients who underwent plain CT abdomen-pelvis using a 80-multidetector CT system were retrospectively analysed. Patients were divided into three groups according to the scanning protocol. Group 1 patients (n = 39) were scanned with 120 kVp standard dose FBP reconstruction. Iterative reconstruction was used for 120 kVp low dose group 2 (AIDR 3D standard, n = 28) and 100 kVp low dose group 3 (AIDR 3D strong, n = 33). Quantitative measures of radiation dose, objective image noise and signal to noise ratio (SNR) were obtained. The results were compared between all groups and correlated to body mass index (BMI). Subjective image quality evaluations were graded by two radiologists. The volume CT dose index ($CTDI_{vol}$), dose length product (DLP), and effective dose (E) in low dose AIDR 3D studies (group 2 and group 3) were significantly lower than standard dose FBP CT ($p < 0.05$). Group 3 (100 kVp low dose AIDR 3D strong) obtained highest dose reduction with $CTDI_{vol}$, DLP and E as low as 3.35 ± 1.04 mGy, 172.05 ± 63.32 mGy.cm and 2.58 ± 0.95 mSv respectively. In objective image quality analysis, group 2 and group 3 achieved significant image noise reduction (41.33% versus 52.62%) and SNR increment (62.25% versus 101.47%) compared to group 1. Subjective image noise, artifacts, sharpness and overall diagnostic confidence were greatly improved by AIDR 3D (group 2 and group 3). Moreover, AIDR 3D strong (group 3) was the most optimal iterative reconstruction to demonstrate fine anatomical structures. AIDR 3D could advance dose optimisation and improved image quality for wide range of BMI in the population. Thus, AIDR 3D is a useful algorithm to optimise scanning protocol and practicable in all routine CT examinations at the lowest radiation exposure.

ABSTRAK

Pembangunan baharu teknologi tomografi berkomputer (CT) telah membuat CT menjadi modaliti diagnostik yang serba guna dan cekap. Ini telah membawa kepada peningkatan pesat permintaan dalam amalan klinikal dengan peningkatan risiko dedahan sinaran terhadap pesakit. Kebanyakan penyelidikan mengenai pengoptimuman CT tertumpu kepada parameter teknikal, seperti keupayaan tiub, arus tiub dan faktor *pitch*. Segelintir penyelidikan yang dilakukan ke atas proses pembinaan semula lelaran dalam pengurangan dos tanpa menjejaskan kualiti imej dalam pemeriksaan CT klinikal. Oleh itu, kajian ini mengkaji pengoptimuman dos dan peningkatan kualiti imej menggunakan pembinaan semula *Adaptive-Iterative Dose Reduction* Tiga Dimensi (AIDR 3D), berbanding dengan unjuran tapis semula (FBP) konvensional, dalam CT abdomen-pelvis. Dalam kajian kohort satu pusat ini, 100 pesakit yang menjalani CT abdomen-pelvis menggunakan system CT 80-multidetektor telah dianalisis secara retrospektif. Pesakit telah dibahagikan kepada tiga kumpulan berdasarkan protokol pengimbasan. Pesakit kumpulan 1 (n = 39) telah diimbas dengan 120 kVp berdos standard pembinaan semula FBP. Pembinaan semula lelaran digunakan untuk kumpulan 2 iaitu 120 kVp berdos rendah (standard AIDR 3D, n = 28), dan kumpulan 3 iaitu 100 kVp berdos rendah (AIDR 3D kuat, n = 33). Ukuran kuantitatif dos sinaran, hingar imej objektif dan nisbah isyarat kepada hingar (SNR) telah diperolehi. Keputusan tersebut dibandingkan antara semua kumpulan dan dikaitkan dengan indeks jisim badan (BMI). Penilaian kualiti imej subjektif telah dinilai oleh dua pakar radiologi. Indeks dos CT isipadu ($CTDI_{vol}$), hasil darab dos panjang (DLP), dan dos berkesan (E) dalam kajian AIDR 3D berdos rendah (kumpulan 2 dan kumpulan 3) adalah lebih rendah daripada CT berdos standard FBP ($p < 0.05$). Kumpulan 3 (100 kVp dos rendah AIDR 3D kuat) memperolehi pengurangan dos tertinggi dengan $CTDI_{vol}$, DLP dan E masing-masing serendah 3.35 ± 1.04 mGy, 172.05 ± 63.32 mGy.cm dan 2.58 ± 0.95 mSv. Dalam analisis kualiti imej objektif, kumpulan 2 dan kumpulan 3 mengalami pengurangan hingar imej dengan ketara (41.33% berbanding 52.62%) dan kenaikan SNR (62.25% berbanding 101.47%) berbanding dengan kumpulan 1. Hingar imej subjektif, artifak, ketajaman dan keyakinan diagnostik secara keseluruhan telah dipertingkatkan oleh AIDR 3D (kumpulan 2 dan kumpulan 3). Selain itu, AIDR 3D kuat (kumpulan 3) adalah pembinaan semula lelaran yang paling optimum untuk menunjukkan struktur anatomi halus. AIDR 3D boleh memajukan pengoptimuman dos dan meningkatkan kualiti imej untuk populasi yang terdiri dari pelbagai BMI. Oleh itu, AIDR 3D ialah algoritma yang berguna untuk mengoptimumkan protokol pengimbasan dan boleh dilaksanakan dalam semua pemeriksaan CT yang rutin dengan dedahan sinaran yang paling rendah.

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LIST OF ABBREVIATIONS

AAPM	-	American Association of Physicist in Medicine
AIDR 3D	-	Adaptive-Iterative Dose Reduction 3D algorithm
ALARA	-	As low as reasonably achievable
ASIR	-	Adaptive Statistical Iterative Reconstruction
ATCM	-	Automatic Tube Current Modulation
BMI	-	Body mass index
CAT	-	Computed Axial Tomography
CNR	-	Contrast to noise ratio
CT	-	Computed Tomography
CTDI	-	CT dose index
$CTDI_{100}$	-	CT dose index from 100 mm
$CTDI_{vol}$	-	Volume CTDI
CTDIw	-	Weighted CTDI
DICOM	-	Digital Imaging and Communications in Medicine
DLP	-	Dose length product
DRLs	-	Diagnostic reference levels
E	-	Effective dose
FBP	-	Filtered back projection
FC 18	-	Convolution Kernel 18
FDA	-	Food and Drug Administration
HU	-	Hounsfield Unit
IAEA	-	International Atomic Energy Agency
ICRP	-	International Commission on Radiation Protection
IEC	-	International Electrotechnical Commission
IR	-	Iterative reconstruction
IRIS	-	Iterative Reconstruction in Image Space
IVC	-	Inferior vena cava

kVp	-	Kilovoltage peak
MBIR	-	Model-Based Iterative Reconstruction
MDCT	-	Multi Detector Computed Tomography
MPR	-	Multi-planar reconstruction
NaI	-	Sodium Iodide
NMRR	-	National Medical Research Registration
NRPB	-	National Radiological Protection Board
PACS	-	Picture Archiving and Communication System
PMMA	-	Polymethyl methacrylate
ROIs	-	Region of interests
SAFIRE	-	Sonogram-Affirmed Iterative Reconstruction
SD	-	Noise index
SNR	-	Signal to noise ratio
STD	-	Standard deviation
UK	-	United Kingdom
UNSCEAR	-	United Nation Scientific Committee on Effects of Atomic Radiations

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The first Nobel Prize in Physics was awarded to Wilhelm Conrad Roentgen, a German physicist, for his discovery of X-rays in 1895. Since the development of X-ray technology, tremendous progress has been made in the field of medical imaging thus enabling detailed visualization of human anatomy and pathology without surgical intervention.

X-rays while being the most common and cheapest examination, lacks the details and resolution provided by other cross-sectional imaging modalities. Among them, Computed Tomography (CT) scanner is one of the most important imaging modality. With the development of multi detector CT (MDCT) in 1998, CT technology has undergone a revolution with the introduction of high resolution and fast CT scanners including 64, 128, 256 and 320 MDCT. These scanners have far higher capability to obtain excellent radiographic resolution compared to conventional radiography. However, in majority of medical diagnosis, single axial image is not sufficient considering the fact of unique structure in human body. Therefore, multi-planar reconstruction (MPR) from volumetric acquisition of CT play an important role in creating coronal, sagittal, or even 3D volume rendering images originally from axial image as in Figure 1.1. Multi-planar reformatted images provide distinct advantage in image interpretation by viewing the extent of the malignancies of diseases as a whole and improve diagnostic accuracy in medical field (Hodel *et al*., 2009; Honda *et al*., 2011).

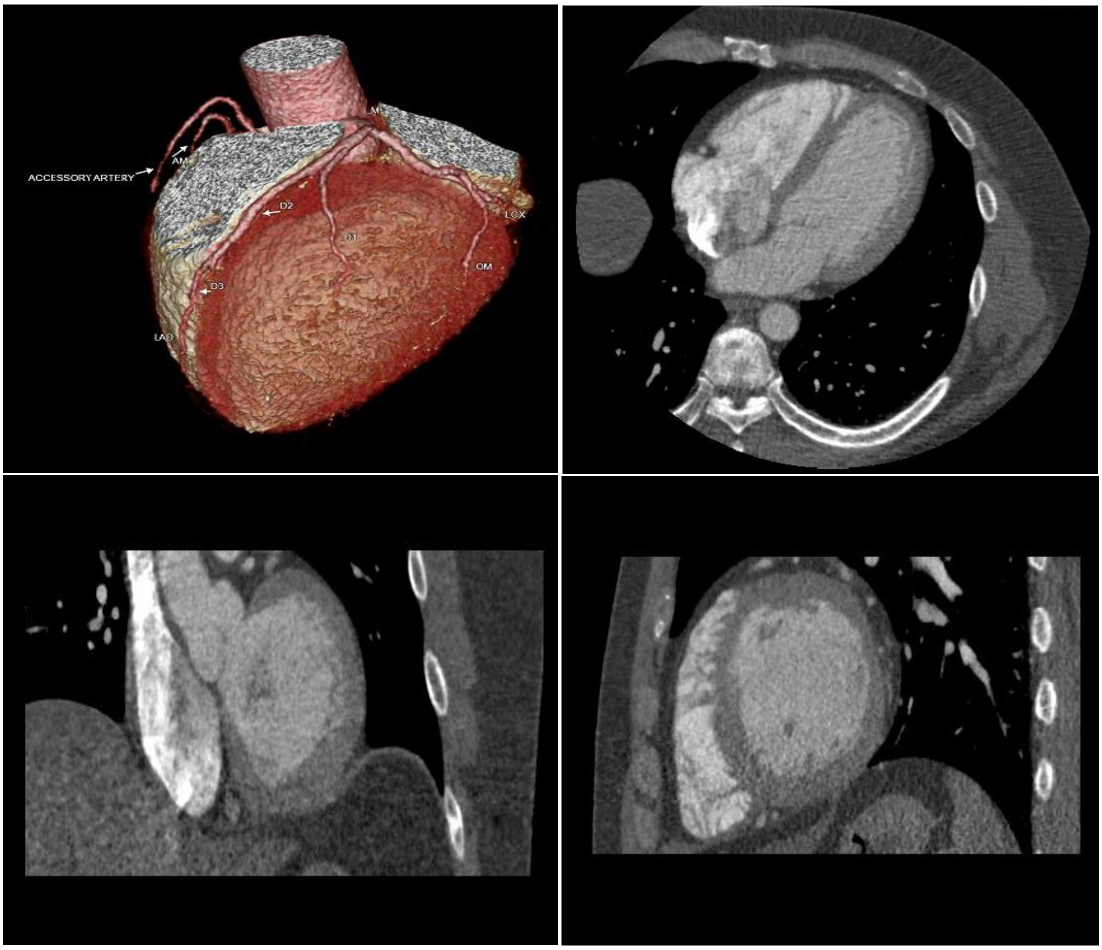

Figure 1.1 CT coronary angiogram image of a 45 years old male with history of chest pain taken in year 2016 using Toshiba Aquilion PRIME CT scanner

CT is a versatile and efficient diagnostic tool that has influenced healthcare industry leading to increased clinical applications throughout the world. It was estimated more than 50,000 clinical CT installations in operation worldwide for the year 2010 (Kalender, 2011). In radiology, CT was not constraint to head imaging alone, but whole body system including chest, abdomen, pelvis, extremities, coronary and functional imaging like perfusion scan. However, this high performance diagnostic tool comes with the price, which is increase in radiation dose to patients. CT uses ionising radiation for its operation that it delivered in far higher doses than conventional X-rays. Thus, the potential of radiation exposure causes health hazards to the patients and has become a concern (Brenner and Hall, 2007; Semelka *et al.*, 2007).

Radiation industries in Malaysia are small sized organisations compared to other countries. They are about 20,000 workers using radiation sources being monitored monthly (Noriah, 2010). Efforts to achieve as low as reasonably achievable (ALARA) doses in this country led to less than 1% of the radiation workers exceed 50 mSv annual dose limit for the last 25 years (Noriah, 2010). Atomic Energy Licensing Board (AELB) and Nuclear Malaysia are the regulatory body that actively involved in promoting radiation safety awareness among radiation workers through a good radiation protection programme at the workplace. However, rapid development and widen application of CT in work requirement may cause increased in average doses. Moreover, study of Karim *et al.* (2016) in organ dose evaluation and radiation risk of routine CT examinations in Johor, Malaysia reported that effective cancer risks of 0 to 1449 cancer cases per one million procedures and the radiation risks from CT exist due to its increase in usage every year. Thus, research in optimising CT doses without compromising image quality is needed in Malaysia.

The issue of radiation-induced cancer is highly relevant (Shah *et al.*, 2014) and the risk is increasing when the dose received exceeded dose reference levels (Rehani *et al.*, 2012; Naumann *et al.*, 2014). Although pediatric patients are at greatest risk and are more radiosensitive to radiation (Valentin 2007; Feng *et al*., 2010), the stochastic effects from CT radiation in adults are not negligible. Consequently, CT examinations justification and dose optimisation are necessary to reduce radiation exposure. Much attention on technical solutions to reduce radiation dose in CT (McCollough *et al.*, 2009) has become a hot topic in clinical research. Moreover, CT manufacturers had developed number of new dose reduction technologies that promote low radiation dose without degrading image diagnostic quality. Among these latest innovations, the popular techniques that are being used clinically include tube current modulation, dual-energy CT and adaptive noise reduction filters (Gunn and Kohr, 2010).

More recently, renewed interest in iterative reconstruction (IR) are the main focus in CT dose reduction while maintaining high image quality due to limitation of the standard CT reconstruction technique using filtered back projection (FBP) (Renker *et al.*, 2011). Several IR techniques from various vendors were introduced and it was found that Adaptive-Iterative Dose Reduction 3D algorithm (AIDR 3D) capable to work in both raw and image data domain compared to others (Tomizawa *et al.*, 2012). This promising new technology in conjunction with traditional technical optimisation techniques have potential of producing high quality image with even lower doses of radiation.

Moreover, limited research has been conducted in Malaysia focusing on AIDR 3D for CT abdomen-pelvis. The feasibility of AIDR 3D in medical imaging has prospective contribution to Malaysia in terms of national radiation safety regulation and may improve the diagnostic reference levels (DRLs) published by Ministry of Health Malaysia in 2013.

This research aimed to assess the benefits of AIDR 3D reconstruction in CT abdomen-pelvis by using low dose technique. This study allowed us to understand the effects of low dose AIDR 3D in image quality and radiation dose compared with standard dose CT using FBP reconstruction technique. Subsequently, the feasibility of further dose reduction without compromising image quality in reduced 100 kVp low dose AIDR 3D strong setting protocol was evaluated.

1.2 Problem Statement

Widespread use of CT has resulted in increase of medical radiation exposure and risks of long-term stochastic effects from ionising radiation (Smith *et al.*, 2009). It was predicted that 29,000 future cancers in United States were caused by CT scans performed in 2007 alone (Berrington *et al.*, 2009). This had alarmed international agencies, medical professionals and even patients regarding radiation safety in CT. Multiple responsible agencies including International Commission on Radiological Protection (ICRP), International Atomic Energy Agency (IAEA), United Nation Scientific Committee on Effects of Atomic Radiations (UNSCEAR), and American Association of Physicist in Medicine (AAPM) are concerned and contributed in radiation safety measurements with recommendations on radiological protection (AAPM Task Group 23, 2008; UNSCEAR, 2010).

In Malaysia, there was also a notable increase in the use of CT by 161% from 1990 till 1994, based on a national survey (Ng *et al.*, 1999), which is the only latest data available and reported. One of the ways to reduce radiation dose from CT in the population is to reduce the CT-related dose in individual patients. However, dose optimisation while preserving high image quality in MDCT remain challenging in Malaysia. Direct steps such as using low tube potential, high pitch setting and low tube current had been used, but it compromised the image quality by increasing image noise and artifact due to photon starvation (Han *et al.*, 2011). The introduction of automatic tube current modulation (ATCM) facilitated with iterative reconstruction techniques enabled constant image quality and reasonably low dose with respective of the various attenuation body regions. Despite number of studies shown iterative reconstruction have lower image noise compared to FBP (Gervaise *et al.*, 2012; Joemai *et al.*, 2013; Liu, 2014; Naoum *et al.*, 2015), noise reduction potential of AIDR 3D reconstruction with combination of low dose protocol in abdominal pelvic CT is not well established.

As AIDR 3D is the latest available reconstruction technique in Toshiba MDCT 2010, only limited phantom studies being carried out without conclusive clinically assessment (Kim *et al.*, 2014; Klink *et al.*, 2014). Thus, assessment of image quality in low dose AIDR 3D compared to standard dose FBP in real patients study is required. Since radiation dose is one of the major concerns in conjunction with image in diagnostic level, the effectiveness of dose reduction at reduced tube voltage might obtain comparable image quality with iterative reconstruction (Eller *et al.*, 2013; Kataria and Smedby, 2013; Williams *et al.*, 2013). Although Gervaise *et al.* (2014) showed promising dose reduction while having similar image quality in low dose AIDR CT, the feasibility of AIDR in strong setting has not been established. Therefore, combination of low dose protocol at reduced tube potential 100 kVp AIDR 3D strong in CT abdomen-pelvis is ever demanding for further dose optimisation in medical imaging. This study aims to give a clear understanding of how to achieve high diagnostic image quality with the lowest possible dose delivered to the patient with the aid from AIDR 3D reconstruction. Figure 1.2 demonstrates the framework of the research that focus on CT abdomen-pelvis and the main variables involved in order to optimise the highest image quality by utilising the lower dose exposure.

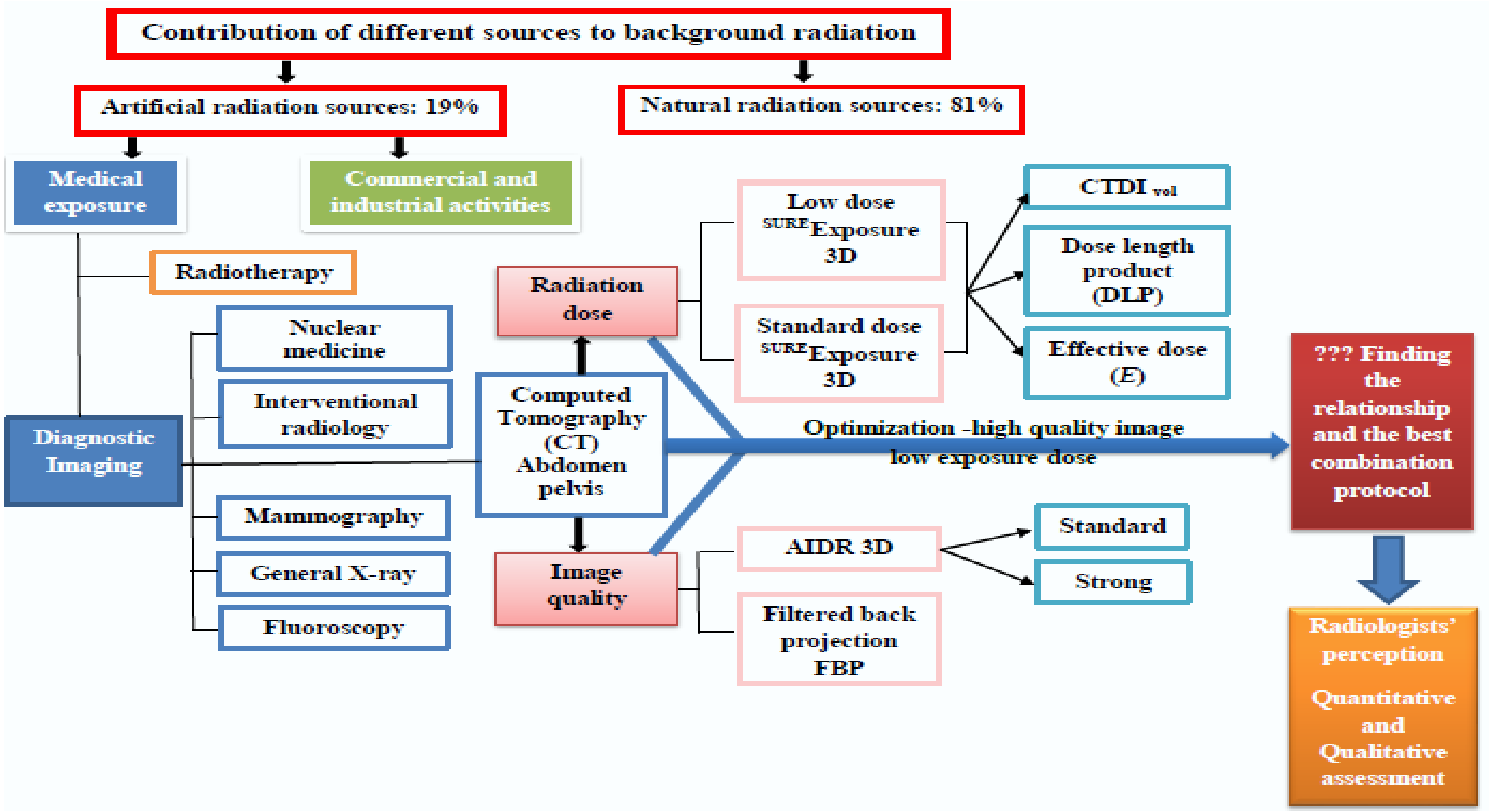

Figure 1.2 The general overview of the research works

1.3 Research Objectives

This study aims to evaluate the benefits of AIDR 3D in clinical work. Specifically, the objectives of the study are;

i. To verify the image quality improvement using AIDR 3D technique in CT abdomen-pelvis patients study.
ii. To determine the effectiveness of dose reduction between low dose, reduced 100 kVp low dose and standard dose abdominal pelvic CT scanning protocols with different reconstruction algorithms.
iii. To optimise the scanning protocol for delivering good diagnostic image quality with the lowest possible radiation dose.

1.4 Scope of Study

This is a retrospective study of 100 patients who underwent CT abdomen-pelvis in one hospital in Johor Bahru. Patients were categorized into 3 groups according to the specific scanning tube potential and reconstruction algorithms being used and further subcategorised into 4 different Body Mass Index (BMI) groups for correlation analysis with radiation dose and objective image quality. Based on all data obtained, image quality was assessed for both objective and subjective criteria while dose reports obtained from the CT console were documented and calculated for estimation of dose reduction. Image quality in this study was limited to physical measurements of image noise and signal to noise ratio (SNR) and subjective image quality was graded by radiologist according to their experience and perception of a good image quality. Model observers for detection and measurement of abnormality in specific disease was not available in this work. Results from low dose AIDR 3D standard, reduced 100 kVp low dose AIDR 3D strong and standard dose FBP groups were compared and statistically analysed. Finally, the effects of AIDR 3D reconstruction in radiation dose and image quality were determined.

1.5 Significance of Study

The results of this study provide information on radiation dose and image quality obtained in the plain CT abdomen-pelvis with different dose settings, tube potential and reconstruction techniques. The image quality, which depend on both dose setting, tube voltage and reconstruction algorithm are important for clinical imaging. The optimal protocol obtained can be used as a benchmark in future imaging that involve CT abdomen and pelvis and applicable in various CT examinations. This study enhanced our understanding of the effects of AIDR 3D in dose reduction and image quality improvement, thus introducing a new practicable protocol to conquer the deficiency in current CT abdomen-pelvis practice. The implementation of AIDR 3D in low dose CT improved patient radiation safety and Malaysia healthcare quality.

1.6 Research Hypothesis

It was hypothesized that AIDR 3D reconstruction would obtain good image quality in CT abdomen-pelvis while low dose setting was used. Secondly, reduced tube voltage 100 kVp with combination of iterative reconstruction can further reduce radiation dose with similar image quality compared to 120 kVp standard dose CT.

1.7 Thesis Outline

Five chapters are included in this thesis with each chapter has a different focus of content. Started with chapter 1 about the brief introduction of the study, follow by study background, problem statement involved, research objectives and scope of study follow by research significance and hypothesis.

In chapter 2, the literature reviews the CT technology from past to modern MDCT, radiation dose, radiation risk in CT abdomen-pelvis and dose quantities. Image quality in CT is briefly explained. While the last part of literature discussed briefly about practical approaches in optimising dose and recent iterative reconstruction techniques, particularly on AIDR 3D for CT abdomen-pelvis.

Chapter 3, research methodology provides methods and materials used in this study. The details how the image quality evaluated in both objective and subjective methods and its criteria for scoring are explained. Radiation dose measurement, calculation and validation further explained, including software for image viewing and measurement. Lastly, data comparison and statistical analysis involved are described.

Results and discussions are presented in Chapter 4 with supporting figures and tables. Subtopic results of patient characteristics, CT acquisition parameter, radiation dose measurements and image quality assessment are discussed and compared to previous literatures.

Chapter 5 includes conclusion of the present research. It summarise the main findings to address each objectives. Suggestions of future works are included for research improvement.

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