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

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UNIVERSITI TEKNOLOGI MALAYSIA
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AND IMAGE QUALITY IMPROVEMENT OF ABDOMEN-PELVIS USING
ADAPTIVE-ITERATIVE DOSE REDUCTION

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

NOVEMBER 2017
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.
ACKNOWLEDGEMENT

First and foremost, I would like to express my special appreciation and thanks to Associate Professor Dr. Suhairul Hashim for his tremendously support and encouragement throughout my post graduate studies at Universiti Teknologi Malaysia. Dr. Suhairul was not only my academic supervisor, he also gave me endless guidance and support on my career and life. His vision and kindness influenced me in many ways and will benefit me throughout my future life.

I am also extremely grateful for the advices and effort devoted to this work from my research team members. I was very fortunate to be able to work closely with them during the research: Mr. Muhammad Khalis Abdul Karim, Ms. Nur Ashiqin Bahruddin, Ms. Nasuha Salehhon and Mr. Yahaya Musa. Without their dedication and wisdom, my research would not have gotten to this point. I enjoyed every refreshing conversation, discussion and knowledge sharing session we had, about both science and physics.

I would also like to take this opportunity to express my most sincere gratitude to Dr. Abhijit Ghosh for his generous and advice on my research project. Dr. Abhijit Ghosh had devoted tremendous amount of efforts to this project, from the initial discussion about the idea to the study design, data collection and data analysis. I would also like to thank Dr Suzieta Binti Zamrah and Dr Nurasikin Binti Jamaluddin, as my image quality evaluators and lead me to finish my final stage of the research. I appreciate their contribution and involvement in this project given their very busy schedule as consultant radiologist.

A special thanks to all my family members who supported me in writing and incented me to strive towards my goal.
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 (CTDIvol), 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 CTDIvol, 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 klinikial 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 klinikial. 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 dianalis 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, hingga imej objektif dan nisbah isyarat kepada hingga (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 (CTDIvol), 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 CTDIvol, 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 hingga imej dengan ketara (41.33% berbanding 52.62%) dan kenaikan SNR (62.25% berbanding 101.47%) berbanding dengan kumpulan 1. Hingga imej subjektif, artifak, ketajaman dan keyakinan diagnostik secara keseluruhnya telah diperingkatkan 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.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td></td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td></td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td></td>
<td>xv</td>
</tr>
</tbody>
</table>

## 1 INTRODUCTION

1.1 Background of Study 1
1.2 Problem Statement 4
1.3 Research Objectives 7
1.4 Scope of Study 7
1.5 Significance of Study 8
1.6 Research Hypothesis 8
1.7 Thesis Outline 8
# LITERATURE REVIEW

2.1 Introduction 10
2.2 CT Technology 11
2.3 Radiation Dose and Radiation Risk in CT of Abdomen-pelvis 13
  2.3.1 CT Dose Quantities 14
2.4 AIDR 3D in CT Image Quality 16
2.5 Practical Approaches in Dose Optimisation of Multi Detector CT of Abdomen-pelvis 20
  2.5.1 AIDR 3D Reconstruction 21

# METHODOLOGY

3.1 Introduction 26
3.2 Study Population 26
3.3 CT Acquisition Protocol and Image Reconstruction 28
  3.3.1 K-PACS DICOM Viewer V 1.6.0 29
3.4 Assessment of Image Quality 31
  3.4.1 Objective Image Analysis 31
  3.4.2 Subjective Image Analysis 33
3.5 Radiation Dose Measurements 35
3.6 Statistical Analysis 35
3.7 Operational Framework 36

# RESULTS AND DISCUSSIONS

4.1 Overview 38
4.2 Patient Characteristics and CT Acquisition Parameter 38
4.3 Radiation Dose 41
4.4 The Correlation between Patient’s BMI and CT Dose 54
4.5 Objective Image Quality 61
4.6 The Correlation between Patient’s BMI and Objective Image Quality 70
4.7 Subjective Image Quality 82
5 CONCLUSIONS

5.1 Introduction 93
5.2 Recommendations and Future Studies 96

REFERENCES 98

Appendices A - B 112 - 115
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Highlighted issues regarding AIDR 3D in previous studies</td>
<td>23</td>
</tr>
<tr>
<td>3.1</td>
<td>Scan parameters and various image reconstruction setting</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>Subjective image quality grading scale for general image quality category</td>
<td>34</td>
</tr>
<tr>
<td>4.1</td>
<td>Patient characteristic of the study population</td>
<td>39</td>
</tr>
<tr>
<td>4.2</td>
<td>Radiation dose parameters for the three groups of patients with different scanning protocol</td>
<td>42</td>
</tr>
<tr>
<td>4.3</td>
<td>Comparison between third quartile values of CT dose index volume and dose length product in current study with Malaysia DRLs 2013 and other international DRLs</td>
<td>49</td>
</tr>
<tr>
<td>4.4</td>
<td>Comparison of patient radiation dose in multiple AIDR 3D studies</td>
<td>52</td>
</tr>
<tr>
<td>4.5</td>
<td>Patient dose data for the three different scanning protocols classified by BMI</td>
<td>55</td>
</tr>
<tr>
<td>4.6</td>
<td>Comparison of CT number, objective image noise and SNR in five anatomical structures between group 1, group 2 and group 3</td>
<td>62</td>
</tr>
<tr>
<td>4.7</td>
<td>Objective image noise measurements for the three different scanning protocols classified by BMI</td>
<td>71</td>
</tr>
<tr>
<td>4.8</td>
<td>Signal to noise ratio measurements for the three different scanning protocols classified by BMI</td>
<td>72</td>
</tr>
<tr>
<td>4.9</td>
<td>Subjective image quality analysis</td>
<td>84</td>
</tr>
<tr>
<td>4.10</td>
<td>Subjective image quality scores agreement percentage and Kappa analysis between the two radiologists</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Radiation dose optimisation using AIDR 3D in CT abdomen-pelvis</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Image quality improvement using AIDR 3D in CT abdomen-pelvis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>CT coronary angiogram of a 45 years old male with history of chest pain taken in year 2016 using Toshiba Aquilion PRIME 80 CT scanner</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>The general overview of the research works</td>
<td>6</td>
</tr>
<tr>
<td>2.1</td>
<td>Schematic view of a 3rd generation CT scanner (Operation Manual for Whole-Body X-Ray CT Scanner Aquilion, 2004)</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>Streak artifacts evident in pelvic region of a 50 years old female using routine scanning protocol by Toshiba Aquilion PRIME 80 CT scanner</td>
<td>18</td>
</tr>
<tr>
<td>2.3</td>
<td>Multiple rings appearance seen in the center of the CT liver image acquired with 80 kVp abdomen-pelvis CT protocol using Toshiba Aquilion PRIME 80 Ct scanner</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Schematic diagram of AIDR 3D advanced operational process</td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>Toshiba Aquilion PRIME 80 CT scanner used in this research study</td>
<td>27</td>
</tr>
<tr>
<td>3.2</td>
<td>CT abdomen-pelvis scanogram image that include from bases of lungs to symphysis pubis</td>
<td>28</td>
</tr>
<tr>
<td>3.3</td>
<td>K-PACS software for DICOM images viewing and measurement</td>
<td>30</td>
</tr>
<tr>
<td>3.4</td>
<td>CT dose report of a 75 years old woman post CT abdomen-pelvis displayed in K-PACS viewer</td>
<td>31</td>
</tr>
</tbody>
</table>
3.5 Detail placement of ROIs in (a) right hepatic lobe, aorta and spleen at the level of main portal vein and placement of ROIs in (b) bladder and both sides of gluteus maximus muscles at tip of greater trochanter level

3.6 Schematic diagram of research process

4.1 Comparison between CT dose index volume for entire study cohort

4.2 Comparison between dose length product for entire study cohort

4.3 Effective dose distribution in group 1 patients with protocol 120 kVp standard dose FBP reconstruction

4.4 Effective dose distribution in group 2 patients with protocol 120 kVp low dose AIDR 3D standard reconstruction

4.5 Effective dose distribution in group 3 patients with protocol 100 kVp low dose AIDR 3D strong reconstruction

4.6 Comparison between effective dose for entire study cohort

4.7 Relationship between BMI and CTDI_{vol} in (a) group 1, (b) group 2 and (c) group 3 patients

4.8 Relationship between BMI and DLP in (a) group 1, (b) group 2 and (c) group 3 patients

4.9 Relationship between BMI and $E$ in (a) group 1, (b) group 2 and (c) group 3 patients

4.10 Objective image analysis of the CT number measured in liver, aorta, spleen, bladder and gluteus maximus muscle for the entire study cohort

4.11 Objective image analysis of the image noise measured in liver, aorta, spleen, bladder and gluteus maximus muscle for the entire study cohort

4.12 Objective image analysis of the signal to noise ratio measured in liver, aorta, spleen, bladder and gluteus maximus muscle for the entire study cohort
4.13 Plain axial CT abdomen-pelvis images at the level of the main portal vein from three sample patients individually scanned with (a) 120 kVp standard dose FBP (b) 120 kVp low dose AIDR 3D standard and (c) 100 kVp low dose AIDR 3D strong

4.14 Plain axial CT abdomen-pelvis images at the level of greater trochanteric tip from three sample patients individually scanned with (a) 120 kVp standard dose FBP (b) 120 kVp low dose AIDR 3D standard and (c) 100 kVp low dose AIDR 3D strong

4.15 Average objective image noise of all ROIs for imaging parameters in each BMI group

4.16 Average signal to noise ratio of all ROIs for imaging parameters in each BMI group

4.17 Comparison of (a) group 1, (b) group 2, and (c) group 3 images in patients with normal BMI (BMI range: 20-25 kg m\(^{-2}\))

4.18 Comparison of (a) group 1, (b) group 2, and (c) group 3 images in overweight patients (BMI range: 25-30 kg m\(^{-2}\))

4.19 Comparison of (a) group 1, (b) group 2, and (c) group 3 images in obese patients (BMI range: 30-35 kg m\(^{-2}\))

4.20 Relationship between image noise and BMI

4.21 Relationship between signal to noise ratio and BMI for (a) group 1, (b) group 2 and (c) group 3 patients

4.22 Axial CT pelvis image with more than average noise and moderate artifacts in (a) 120 kVp standard dose FBP compared to less than average noise and mild artifacts in image performed at (b) 120 kVp low dose AIDR 3D standard and (c) 100 kVp low dose AIDR 3D strong without significant changes in image texture

4.23 Subjective assessment of the fine anatomical structures visibility scores in group 1 (FBP), group 2 (AIDR 3D standard) and group 3 (AIDR 3D strong)
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAPM</td>
<td>American Association of Physicist in Medicine</td>
</tr>
<tr>
<td>AIDR 3D</td>
<td>Adaptive-Iterative Dose Reduction 3D algorithm</td>
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<tr>
<td>ALARA</td>
<td>As low as reasonably achievable</td>
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<tr>
<td>ASIR</td>
<td>Adaptive Statistical Iterative Reconstruction</td>
</tr>
<tr>
<td>ATCM</td>
<td>Automatic Tube Current Modulation</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
</tr>
<tr>
<td>CAT</td>
<td>Computed Axial Tomography</td>
</tr>
<tr>
<td>CNR</td>
<td>Contrast to noise ratio</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>CTDI</td>
<td>CT dose index</td>
</tr>
<tr>
<td>CTDI&lt;sub&gt;100&lt;/sub&gt;</td>
<td>CT dose index from 100 mm</td>
</tr>
<tr>
<td>CTDI&lt;sub&gt;vol&lt;/sub&gt;</td>
<td>Volume CTDI</td>
</tr>
<tr>
<td>CTDI&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Weighted CTDI</td>
</tr>
<tr>
<td>DICOM</td>
<td>Digital Imaging and Communications in Medicine</td>
</tr>
<tr>
<td>DLP</td>
<td>Dose length product</td>
</tr>
<tr>
<td>DRLs</td>
<td>Diagnostic reference levels</td>
</tr>
<tr>
<td>E</td>
<td>Effective dose</td>
</tr>
<tr>
<td>FBP</td>
<td>Filtered back projection</td>
</tr>
<tr>
<td>FC 18</td>
<td>Convolution Kernel 18</td>
</tr>
<tr>
<td>FDA</td>
<td>Food and Drug Administration</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield Unit</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ICRP</td>
<td>International Commission on Radiation Protection</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IR</td>
<td>Iterative reconstruction</td>
</tr>
<tr>
<td>IRIS</td>
<td>Iterative Reconstruction in Image Space</td>
</tr>
<tr>
<td>IVC</td>
<td>Inferior vena cava</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>kVp</td>
<td>Kilovoltage peak</td>
</tr>
<tr>
<td>MBIR</td>
<td>Model-Based Iterative Reconstruction</td>
</tr>
<tr>
<td>MDCT</td>
<td>Multi Detector Computed Tomography</td>
</tr>
<tr>
<td>MPR</td>
<td>Multi-planar reconstruction</td>
</tr>
<tr>
<td>NaI</td>
<td>Sodium Iodide</td>
</tr>
<tr>
<td>NMRR</td>
<td>National Medical Research Registration</td>
</tr>
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<td>NRPB</td>
<td>National Radiological Protection Board</td>
</tr>
<tr>
<td>PACS</td>
<td>Picture Archiving and Communication System</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl methacrylate</td>
</tr>
<tr>
<td>ROIs</td>
<td>Region of interests</td>
</tr>
<tr>
<td>SAFIRE</td>
<td>Sonogram-Affirmed Iterative Reconstruction</td>
</tr>
<tr>
<td>SD</td>
<td>Noise index</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>STD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UNSCEAR</td>
<td>United Nation Scientific Committee on Effects of Atomic Radiations</td>
</tr>
</tbody>
</table>
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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