ESTABLISHING DOSE REFERENCE LEVEL FOR COMPUTED TOMOGRAPHY (CT) EXAMINATIONS IN MALAYSIA

by

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LIST OF ABREVIATIONS

(ALPHABERTICAL ORDER)

AEC	automatic exposure control
AELB	Atomic Energy Licensing Board
ALARA	as low as reasonably achievable
CAD	coronary artery disease
CAP	chest, abdomen and pelvis
CCT	conventional computed tomography
CT	computed tomography
CTA	computed tomography angiography
CTDI	computed tomography dose index
CTU	computed tomography urography
DLP	dose length product
DNA	deoxyribonucleic acid
DQE	detective quantum efficiency
DRL	dose reference level
ECG	electrocardiogram
ESD	entrance surface dose
FDA	Food and Drug Administration
FOV	field of view
FWHM	full width of half maximum
HRCT	high resolution computed tomography
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ImPACT	Imaging Performance and Assessment of Computed Tomography
LINAC	linear accelerator
MRI	magnetic resonance imaging

MSCT	multi-slice computed tomography
NDT	non destructive testing
NRPB	National Radiological Protection Board
PACS	picture archiving and communication system
PMMA	polymethylmethacrylate
PNS	para nasal sinus
RCR	Royal College of Radiologists
SFOV	scan field of view
SNR	signal to noise ratio
SPR	scan projection radiograph
SSCT	single slice computed tomography
TLD	thermoluminescent dosimeter
USM	Universiti Sains Malaysia

PENENTUAN ARAS RUJUKAN DOS BAGI PEMERIKSAAN TOMOGRAFI BERKOMPUTER DI MALAYSIA

ABSTRAK

Kajian ini dijalankan bersama dengan Lembaga Perlesenan Tenaga Atom, Malaysia untuk menubuhkan aras rujukan dos bagi pemeriksaan tomografi berkomputer di Malaysia. 426 pemeriksaan ke atas pesakit dewasa dan 26 pemeriksaan ke atas pesakit kanak-kanak yang terdiri daripada pelbagai jenis pemeriksaan tomografi berkomputer dikumpulkan daripada 33 daripada 109 (30.3%) hospital yang mempunyai tomografi berkomputer di Malaysia. Pengukuran bagi Indeks Dos Tomografi Berkomputer di udara ($IDTB_{udara}$) dilakukan ke atas tiap-tiap tomografi berkomputer di hospital yang terlibat di dalam kajian ini bagi menyelidik nilai ketentuan pengimbas berbanding dengan data yang diterbitkan oleh *ImPACT*. Dos berkesan untuk semua pemeriksaan tomografi berkomputer dihitung dengan menggunakan *ImPACT Dosimetry Calculator* ke atas kedua-dua nilai $IDTB_{udara}$ *ImPACT* dan nilai $IDTB_{udara}$ yang diukur sebagai satu perbandingan. Kajian ini mendapati bahawa 4% hingga 22% nilai sisihan di antara kedua-dua nilai tersebut dan sisihan tersebut menunjukkan faktor yang mempengaruhi dos yang disumbang daripada mesin. Setiap protokol yang digunakan pada pemeriksaan tomografi berkomputer tertentu dianalisa dan didapati bahawa keupayaan tiub (kV_{puncak}) bukanlah penyumbang utama dalam sisihan dos berkesan kepada pesakit. Parameter yang lain seperti hasil darab arus tiub – masa (mAs), jarak pengimbasan dan ketiadaan prosedur yang piawai merupakan penyumbang utama dalam sisihan dos berkesan dalam hampir kesemua pemeriksaan tomografi berkomputer. Dos berkesan yang dihitung menggunakan $IDTB_{udara}$ *ImPACT* dibandingkan dengan kajian bagi memberi gambaran penggunaan tomografi berkomputer di Malaysia. Dos berkesan bagi pemeriksaan rutin kepala, rutin dada dan pelvis berada di dalam julat yang sama berbanding kajian *European guidelines*, United Kingdom dan Taiwan. Bagi pemeriksaan rutin abdomen, dos berkesan berada dalam

julat yang sama dengan kajian di Taiwan dan *European guideline* tetapi berada 55.1% lebih tinggi berbanding dengan kajian di United Kingdom. Akhir sekali kajian ini juga menyediakan nilai suku ketiga bagi dos berkesan setiap pemeriksaan tomografi berkomputer yang dikumpulkan daripada kajian ini untuk dijadikan rujukan dalam menubuhkan aras rujukan dos bagi pemeriksaan tomografi berkomputer di Malaysia.

ESTABLISHING DOSE REFERENCE LEVEL FOR COMPUTED TOMOGRAPHY (CT) EXAMINATIONS IN MALAYSIA

ABSTRACT

This study is conducted with the collaboration of the Malaysian Atomic Energy Licensing Board (AELB) in order to establish dose reference level (DRL) for computed tomography (CT) examinations in Malaysia. 426 examinations for standard adult patients and 26 examinations for paediatric patients comprising different types of CT examinations were collected from 33 out of 109 (30.3%) hospitals that have CT scanner in Malaysia. Measurements of Computed Tomography Dose Index in air ($CTDI_{air}$) were done at every CT scanner in the hospitals that were involved in this study to investigate the scanner-specific values comparable to the data published by the ImPACT. Effective doses for all CT examinations were calculated using ImPACT Dosimetry Calculator for both ImPACT $CTDI_{air}$ and measured $CTDI_{air}$ values as a comparison. This study found that 4% to 22% of deviations between both values and the deviations represent the dose influence factors contributed by the CT machines. Every protocol used at certain CT examinations were analysed and it was found that tube potential (kV_p) was not the main contribution for effective doses deviation. Other scanning parameters such as tube current – time product (mAs), scan length and non-standardisation in some of the procedures were significant contributors to the effective dose deviations in most of the CT examinations. Effective doses calculated using ImPACT $CTDI_{air}$ were used to compare with other studies to provide an overview of CT practice in Malaysia. Effective doses for examinations of routine head, routine chest and pelvis are within the same range with studies conducted for the European guidelines, the UK and Taiwan. For the routine abdomen examination, the effective dose is still within the range compared to the studies for European guidelines and Taiwan, but 55.1% higher than the value from the study conducted in the UK. Lastly, this study also provided the third quartile values of effective doses for every CT

examination collected in this study so that they could be used as reference in establishing the dose reference level of CT examinations in Malaysia.

CHAPTER 1

INTRODUCTION

1.1 X-rays

X-ray (so called "Röntgen ray") was discovered by a German physicist, Wilhelm Conrad Röntgen in 1895 and he received the first Nobel Prize in Physics for this discovery. X-ray is part of the electromagnetic spectrum which has the highest energy range of all electromagnetic waves (Figure 1.1). It poses the ability of ionising atoms of the absorbing materials and this may cause potential harm to human body. X-ray is able to penetrate into human body and imparts some of its energy to the tissues. Sufficient imparted energy can damage DNA structures and also produce radical ions inside the body where they may be bounded to the DNA chains. If these damages are not repaired, tissues grow abnormally and this abnormality may lead to the growth of tumours in the tissues.

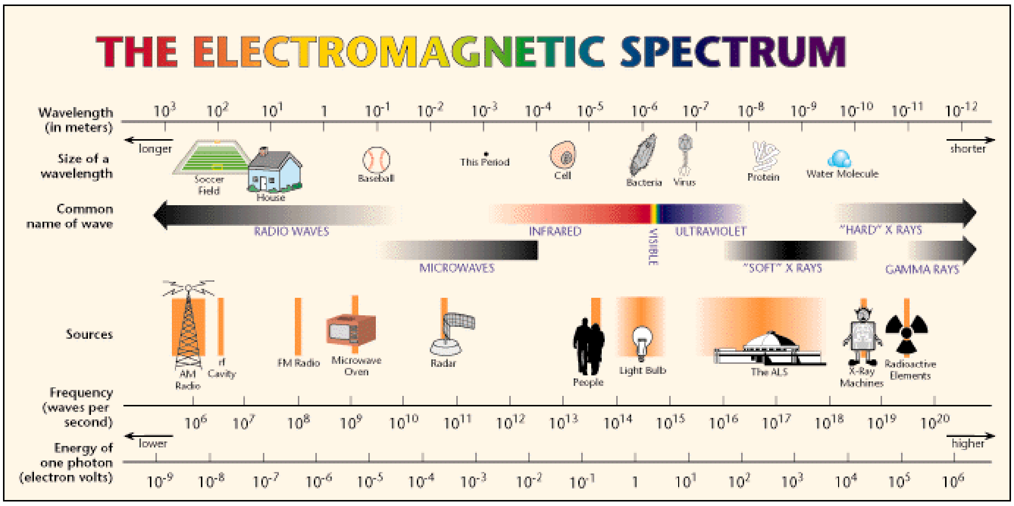

Figure 1.1: Electromagnetic spectrum shows that ionising radiation has the highest energy range. (LBNL 2008)

It is obvious that there are risks in using X-ray. The risk is proportional to the amount of radiation absorbed by the body. Exposure to very high amount of radiation can cause immediate effects such as skin burn, cataract, sterility and even death. It has been reported that 14 British operators died because of over exposure during early introduction of X-ray (1896 - 1903) (MSIT 2008). In addition to that, exposure to low radiation also may cause stochastic effects such as the induction of cancer. These effects probably occur with a latent period, typically from 2 – 20 years (ICRP 2008a).

Besides detriments, there are also benefits in the use of the ionising radiation. Since 19^{th} century, many important uses of ionising radiation have been found and thereafter new technological processes have been developed and deliberately products based on radiation were created (ICRP 1991). X-ray has been successfully applied in many sectors such as non-destructive testing industries, crystallography, microscopic analysis, astronomy, military purposes, medical and others. Undoubtedly, it has given a lot of benefits and advantages to human lives. The use of X-ray has also been diversified and continuously evolved.

In non-destructive testing (NDT) industries, the detection of natural radioactive source (^{17}Oxygen) to detect leakage of water piping is preferred compared to the use of chemical substance. This is because the amount of radioactive source is very small and will decay with time but the chemical substance remains in the piping system which may cause adverse effects to the consumers. The ability to control the production of X-ray (controlling the electrical supply to the X-ray tube) allows easier and safer uses of X-ray compared to that of radioactive materials. In medical radiotherapy for examples, Cobalt-60 systems were replaced by linear accelerators (LINAC) systems and “Gamma Knife” systems were replaced by “X-knife” systems.

1.2 The Use of X-ray in Medicine

It is well-known that in medical practice, X-ray is frequently used for diagnostic purposes. The applications of X-ray in medicine were reported as the largest man-made source of ionising radiation (UNSCEAR 2000). X-ray has been widely applied in medicine since it was first realised by Röentgen in 1897 eventhough during that time the danger of using X-ray has not yet been discovered. Röentgen started the first medical X-ray use where he produced the first X-ray image of his wife's hand (Figure 1.2).

Figure 1.2: First "medical radiography" of the hand of Roentgen's wife. This early radiograph was a 30 minute exposure of the X-ray (MSIT 2008)

At one time, the use of non-ionising radiation like magnetic imaging resonance (MRI) and ultrasound was expected to replace the use of ionising radiation in medicine due to its adverse effects to human health, but it did not happen (Rehani and Berry 2000). Instead, for the last 20 years, the use of X-ray in medical imaging has experienced drastic evolvement in providing better diagnostic examinations around the world (UNSCEAR 2000). Nowadays, the use of ionising radiation in medicine has not been neglected though it is realised that it could give adverse effects to human being.

The introduction of vast range of medical X-ray equipments in modern diagnostic radiology has led to faster and better diagnoses of large proportion of diseases. The number of medical X-ray examinations has shown an increase of 20% globally compared to 10% of global population (UNSCEAR 2000). Benefits to the patients from the uses of X-ray have been established beyond doubt. The practice of contemporary, advanced medicine, without use of ionising radiation appears unthinkable (ICRP 2008a).

1.3 The Introduction of Computed Tomography X-ray System in Medicine

Computed Tomography (CT) was invented by a British engineer, Sir Godfrey Hounsfield who also won the Nobel Prize because of his invention. CT was first introduced in the clinical practice in 1972 which was only limited to the brain scan. Prior to that, X-ray planar radiography and fluoroscopy systems were the main contributors of radiation in imaging (Goldman 2007). CT has fascinated the world with production of high contrast resolution images for visualising soft tissues and the ability of producing tomographic and three dimensional (3D) volumetric images (IAEA 2007). Thus, it has changed the perception on medical diagnostic quality and as a result it has improved the quality of healthcare. Now, CT is becoming a common diagnostic tool in many major hospitals in the whole world.

It is obvious that CT gives a lot of advantages such as faster scanning procedure, good spatial resolution and good contrast, compared to other modalities. Nowadays, many medical centres choose to send cases like accident and emergency cases, urology, cardiac imaging and paediatric imaging for CT scan as their first option for easy diagnosis of the symptoms. In some countries, sinusitis cases were likely referred to CT compared to the plain radiograph because CT were able to show important structures (Zammit-Maepel *et al.* 2003). Having taken notice of that, the manufacturers are also intense in introducing the latest technologies and applications of their CT due to the high demand of the CT scanners. This can be seen in Figure 1.3 where the number of CT scanners installed in Germany has increased linearly (Nagel 2000). Drastic increase happened after 1990 when the helical CT was introduced to the market.

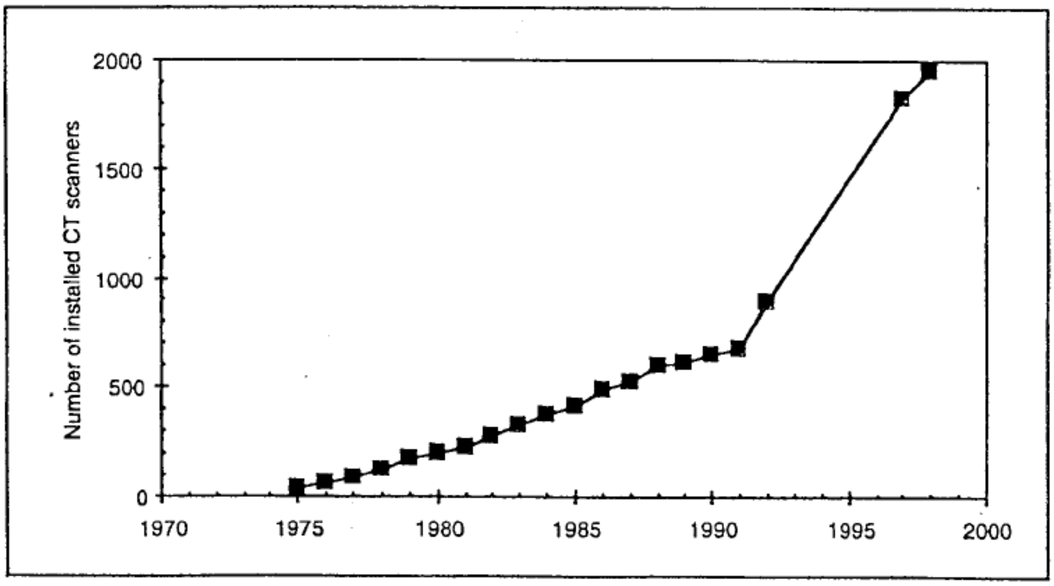

Figure 1.3: The number of CT scanners installed in Germany in year 1970-2000 (Nagel 2000)

In Malaysia, 19 CT scanners were installed in 1990 and this number increased to 38 in 1994 (Ng *et al.* 2008). In 2005, it was reported that 109 CT scanners have been installed (Musa 2005). The increase was about 187% in 10 years and continuously increases with the introduction of 64 channels multi-slice computed tomography (MSCT) where it has advantages in cardiac and whole body imaging. The ability to perform non-invasive cardiac screening has attracted more and more patients to predict the present of coronary artery disease (CAD) in Malaysia. Table 1.1 shows the numbers and percentages of distribution of CT scanners according to the states in Malaysia in 2005.

Table 1.1: Distribution of CT scanners according to the states in Malaysia (Musa 2005)

States in Malaysia	No. of hospitals that have CT scanner			Percentage of distribution (%)
	Government	**Private**	**Total**	
Johor	2	5	7	6.4
Kedah	2	6	8	7.3
Kelantan	1	3	4	2.8
Melaka	1	4	5	5.5
N.Sembilan	1	3	4	3.7
P.Pinang	1	11	12	11.0
Pahang	2	4	6	5.5
Perak	2	5	7	6.4
Perlis	1	0	1	0.9
Sabah	2	2	4	3.7
Sarawak	3	6	9	8.3
Selangor	4	13	17	15.6
Kuala Lumpur	2	22	24	22.0
Terengganu	1	0	1	0.9
Total	25	84	109	100.0

1.4 Radiation Issues in Computed Tomography

The distribution of X-ray in CT is different from planar radiography. In CT, a complete scan consists of thousands of radiation beams projected in circular directions around the object. It is very obvious that CT imparts relatively higher radiation dose than planar radiography. For example, a single routine CT of the chest has been identified to give radiation equivalent dose of 400 planar radiography of the chest (Rehani and Berry 2000).

Council of European Union (1997) has clearly stated in the Council Directive 97/43/EUROTOM (June 1997) that CT produces the radiation as high as that of interventional radiology and radiotherapy:

> *"Member States shall ensure that appropriate radiological equipment, practical techniques and ancillary equipment are used for the medical exposure*
>
> - *of children,*
> - *as part of a health screening programme,*
> - *involving high doses to the patient, such as interventional radiology, computed tomography or radiotherapy."*

The increase number of CT scanners installed world wide has led to drastic increase of CT examinations. The contribution of radiation dose from CT examinations to the patients also increases and this has caused anxiety to the radiological communities. In the UK, it has been reported that CT constituted only about 2-3% of all radiological examination but it has contributed 20-30% to the total radiation dose in medical practices (Shrimpton *et al.* 1991). Until 10 years ago, there was about 35% increase of radiation dose from CT of the abdomen and pelvis in the UK (Wall and Hart 1997) and this increase has made substantial impact on the patient care and, patient and population exposure from medical X-ray (European Commission 2005). In the US, although CT comprised approximately 10% of total diagnostic radiological procedures, but it contributes approximately 65% of the effective radiation dose to the total national medical X-ray examinations (Mettler *et al.* 2000, National Cancer Institute 2002). Based on the United Nations Scientific Committee on the Effects of Atomic Radiation report (UNSCEAR 2000), there was about 20% increase of global collective dose for 5 years period (1985 to 1990 and 1991 to 1996) (Figure 1.4). The number of CT examinations on children is also increasing. It has been reported that 2 – 3 millions of the CT examinations were performed on children every year (National Cancer Institute 2002, Rehani and Berry 2000). Noteworthy, children are more sensitive to the radiation than adults as their growth rates are faster.

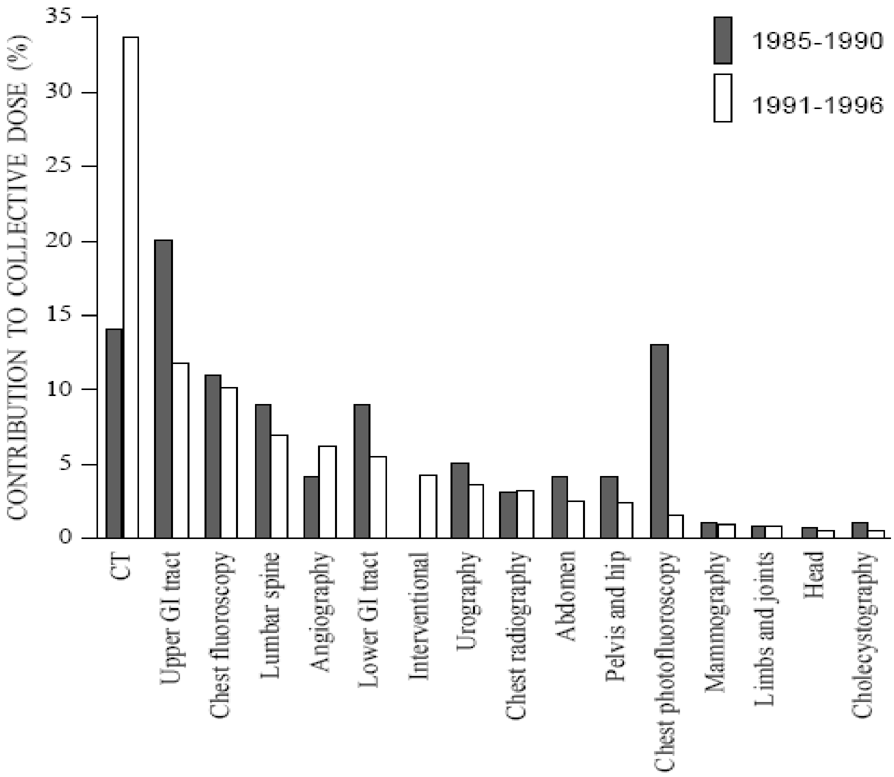

Figure 1.4: The UNSCEAR report shows the percentage contributions by examination type to global collective dose from medical X-ray examinations: comparison of data for 1985-1990 and 1991-1996 (UNSCEAR 2000)

New advancement of the CT has also led to great increase of the radiation dose to the patients. The use of multi-slice computed tomography (MSCT) has aggravated the scenario with the increasing of collective dose of CT examinations because the MSCT produces higher dose to the patients compared to single slice CT (SSCT) (Hunold *et al.* 2003).

1.5 Radiation Protection Concern

Besides producing high radiation dose to the patients, CT still gives “net benefits” in clinical diagnosis. Proper attention must be paid to protect the unnecessary radiation exposures to optimise the benefits and reduce the detriments caused by the radiation. Taken notice of that, the International Commission on Radiological Protection (ICRP) (ICRP 1991) has recommended that the justification process is needed to be carefully considered before performing the CT examination to the patients. They also recommended the “ALARA” (as low as reasonably achievable) principle to be frequently practiced when dealing with radiation. The Royal College of Radiologist (RCR) have also recommended that experienced radiologist should vet all the referral cases of the CT (RCR 1998).

The use of alternative diagnosis like MRI and ultrasound should be taken into account before considering the use of ionising radiation in diagnosing appropriate diseases. Selecting the low dose CT techniques in most of CT examinations also help in reducing the amount of radiation to the patients especially children. Many researches have been done to promote the low dose technique and the protocols are easily obtained from websites and books (European Commission 2005, Nagel 2000).

The Malaysian radiation regulatory bodies have exerted in providing the standards and regulations in the use of radiation apparatus and radioactive sources in Malaysia. The Malaysian Atomic Energy Licensing Act (Act 304) has been legislated in 1984 and its sub-regulations also covered almost every aspect of radiation protection related to the use of ionising radiation in Malaysia.

1.6 Establishing the Dose Reference Level (DRL)

The International Atomic Energy Agency (IAEA) noticed that CT is able to produce good quality images for a wide range of anatomical sites and visualisation of pathologic conditions by adjusting the relatively large number of exposure parameters in the examination protocols factors. In fact, adjusting these protocols will definitely affect the amount of dose to the patients (IAEA 2007). Therefore, the IAEA recommended a specific exposure management should be established in order to optimise the use of CT in clinical usage. The International Commission on Radiological Protection (ICRP) has also recommended the reduction of the dose in CT.

Dose Reference Level (DRL) (also called as "Diagnostic Reference Level") is essentially a guide to the rather indistinct borderline between "good and normal practice" and "bad and abnormal practice" (Sutton *et al.* 2008). It means that there must be data to be compared to each other; a standard data and a data from local practice. This comparison is the first step in optimising patient dose in medical X-ray. The Institute of Physical Sciences in Medicine has recommended that the third quartile value of the dose distribution can be gazetted as the national dose reference level (DRL) (IPSM 1992). The establishment of national DRL comparable to international DRL will be able to give basic reviews of X-ray practices in such countries.

The International Atomic Energy Agency (IAEA 1996) and the European Commissioner (2005) have set up the CT guidelines for dose reference levels (DRL) to promote the optimisation of CT practices in medicine. From these guidelines, the CT users should be able to use these data as a standard to be compared with their practices. Hence it will continuously improve the dose reduction without compromising the quality of diagnosis. The guidelines of the radiation protection have been established to provide the safe use of ionising radiation in ensuring the benefits to human lives (ICRP 1991).

Perhaps this has been adopted in some hospitals as a policy and part of their promotions in convincing the public concerning radiation safety.

1.7 Conducting the Study

In order to establish a guideline of optimised CT protocols to be used in clinical usage, many studies need to be conducted to provide the required data as a reference. The World Health Organisation (WHO 2008) has stated that the global burden of radiation related disease must be based on the scientific assessment of all health risks related to radiation exposure. The guidelines were basically based on the compilation of publications from massive researches and observations associated with the radiation hazards.

A lot of studies related to patient dose in medical X-ray examinations, including CT, have been conducted world wide. Some countries have already established their national DRL. In the UK, the NRPB is continuously reviewing the National Patient Dose Database in every five years and those data were major sources for UK DRL (Sutton *et al.* 2008). Those studies conducted to provide the patients doses to quantify exposures to the patients and, national and international reference level (ICRP 1991, NCRP 1989, Ng *et al.* 1998). In addition, the data can also give general overviews of the overall medical X-ray examinations practices in these countries.

CT studies in some countries have included most of common CT examinations such as routine head, routine chest, routine abdomen and so forth (Shrimpton *et al.* 1991, Tsai *et al.* 2007), but some studies were done to investigate the doses for special procedures such as CT fluoroscopy for the biopsy, CT multi-slice of the heart for calcium scoring, CT for paediatrics and so on (Huda *et al.* 2000, Ravenell *et al.* 2001, Ware *et al.* 1999). The combination of all results from wide scale and dedicated surveys give a comprehensive CT dose guidance levels. It should also be used as a reference for the ongoing collation of further data so as to facilitate the analysis of trends and periodic review of national reference doses (Shrimpton *et al.* 2005). Thus, these data could be an effective way to optimise the use of ionising radiation in medical imaging procedures (European Commission 2005).

1.8 Studies Conducted in Malaysia

Studies related to the ionising radiation doses have been conducted in Malaysia. A national study to provide patient dose data of general radiography has been conducted from 1991 – 1995 (Ng *et al.* 1998) and a study of patient dose undergoing interventional radiological procedures was done from 1993 – 1995 (Sapiin *et al.* 2004). Mean glandular doses from mammography examinations were also determined in a study conducted in 1999 (Jamal *et al.* 2003).

There were very few studies of CT doses that have been conducted in Malaysia. Those known studies were meant for dedicated organs such as eyes and thyroids (Sobari 2000) and abdominal examinations (Ali 2005). Indeed, there is still no study to provide comprehensive data of CT dose values in Malaysia has been published.

1.9 Rationale of the Study

Establishment of DRL has been proven to be an excellent method in optimising the medical X-ray practices in several countries. The establishment of DRL requires data from the medical X-ray practises to be compared to the standard values. Since there are not many studies on patient doses undergoing CT examinations in Malaysia, it is essential to begin with a national study in order to provide comprehensive data of CT doses in Malaysia. With the support from the AELB as one of the regulatory bodies in Malaysia, this study will be likely to become the important reference to establish the DRL in Malaysia. This study also provides the overall overview of the CT safety practices in Malaysia and the results are compared with studies in other countries to identify the level of CT practice in Malaysia compared to those countries. It is very important in order to optimise the use of ionising radiation in medical as it is recommended by the International Commission on Radiological Protection (ICRP 1991).

As other countries have already started with more complicated CT procedures such as doses for paediatrics, coronary angiography and CT fluoroscopy therefore this study is essentially a pioneer in providing basic figures of doses of CT examinations in Malaysia. Perhaps, with this study, more opportunities in developing new complicated studies or enhancing the data from similar studies that can be done in future works.

1.10 Scope of this Study

This study will investigate the effective doses of CT examinations that are commonly practiced in both government and private hospitals throughout Malaysia. This study will be focusing on CT examinations like routine head, routine chest, routine abdomen and routine pelvis. These data will be compared to other studies from different countries such as the UK (Shrimpton *et al.* 2005) and Taiwan (Tsai *et al.* 2007) and also to the European guidelines (Council of European Union 1997). Then, this study will also look into the quality of the CT scanners in Malaysia where the measurement of $CTDI_{air}$ will be compared to that of from accredited source such as ImPACT data set (ImPACT 2006a, ImPACT 2006b).

1.11 Objectives of the Study

The objectives of this study are as follows:

a. To provide the statistical data of total effective dose to the patients undergoing common CT examinations in Malaysia for the establishment of Dose Reference Level (DRL).

b. To compare the total effective doses to the patients undergoing CT examinations with other countries in identifying the trends of CT practices in Malaysia.

c. To estimate the total effective dose to the patients based on the scanner-specific air kerma values. Then these values will be compared to total effective doses in (a) to study the accuracy level for a CT scanner.

1.12 Organisation of the Dissertation

This dissertation consists of six chapters. Chapter 1 gives the introduction to X-ray, computed tomography, radiation protection and the establishment of Dose Reference Level (DRL). It also consists of the introduction to the problems that were faced during the establishment of DRL. Lastly in this chapter, the objectives and scope of the study as well as the organisation of the thesis are included. Chapter 2 deals on the theoretical review of the basic principle of CT, latest technologies in CT, dosimetry in CT and factors that influence the dose, and also the theory of ionisation chamber and phantoms used to measure the dose. In Chapter 3, the materials and the methodology of conducting the study are explained in details. Then, Chapter 4 presents the results and discussion of the study as well as the analyses of errors of the calculations. It also consists of comparisons to other related studies and also the steps taken to overcome the problems encountered in this study. Finally, Chapter 5 concludes this thesis and provides suggestions for future works.

1.13 Outline Plan of the Project

This study was a collaborative national survey between the Universiti Sains Malaysia (USM), Penang and the Atomic Energy Licensing Board (AELB), Malaysia. The financial support of this study was also provided by the AELB under a research grant (LPTA:KOD/024/16). This study only investigates patient doses undergoing common CT examinations in Malaysia.

This study has been conducted for more than two and the half years beginning August 2005. It covered 30.3% of total number of hospitals in Malaysia (both government and private hospitals) that have at least one CT scanner.

The results of this study are compared to the studies from the European guidelines (European Commission 2005), the UK (Shrimpton *et al.* 2005) and Taiwan (Tsai *et al.* 2007) as well as the previous study conducted in Malaysia (Ali 2005).

CHAPTER 2

DOSIMETRY IN COMPUTED TOMOGRAPHY

2.1 The Development of Computed Tomography (CT)

Computed Tomography (CT) scanners had gone through great improvement since the first CT was introduced in the market (Figure 2.1). From 1972 until now, there were five generations of CT which are well-known and have been successfully used in clinical works (see Table 2.1).

Table 2.1: General descriptions of CT generations

First generation	Introduced in 1972. Had single X-ray tube that produced “pencil” beam ray and two detectors to produce two slices of brain images.
Second generation	Introduced in 1974. Using X-ray “fan” beam and had 20 detectors to produce an image. Scanning time as fast as 20 seconds.
Third generation	Introduced in 1975. Using larger “fan” beam. X-ray tube and the detectors rotate as a single unit around the patient through 360^0.
Fourth generation	Designed in 1974. Had a single X-ray tube producing “fan” beam and rotating. Detectors were installed static in a circumference shape outside the X-ray tube orbit.
Fifth generation	Electron beam CT is a new concept. Introduced in 1984. No moving part. Electron deflected around the patient and hit the target to produce X-ray. Has the shortest temporal resolution.

The installations of the CT systems were not limited to the diagnostic imaging departments but was also extended to the radiotherapy simulation, non-invasive cardiac imaging and recently dual imaging modalities i.e. Positron Emission Tomography – Computed Tomography (PET-CT) and Single Photon Emission Computed Tomography – Computed Tomography (SPECT-CT) where they have become among the popular systems in the new era of diagnostic imaging. Furthermore, CT systems are producing true digital images where those images will give better result when performing the post-processing such as volume rendering, CT subtraction angiography, vessel analysis of cardiovascular etc. Post-processing is now becoming so important and gives a lot of advantages to the users. Therefore, most of the CT manufacturers have included these features in the CT post-processing workstation as well as secondary independent workstation so that post-processing of the images can be performed simultaneously during the scanning. Latest advancement of the CT is the development of real time CT (so called "4D CT") where the 3 dimensional images are displayed during the scanning.

Figure 2.1: First clinical CT, EMI Mk I brain scanner (The Science Museum 2004)

From the CT component to the CT application software, there were lots of improvements as well as the introduction of new features in the latest model of CT. Faster gantry rotation, more powerful X-ray tubes, smaller detector size, higher capacity of image storage etc. are some of the improvements of the CT component. Multi-slice CT (MSCT) is the biggest improvement in CT technology where a new type of the detector was introduced to produce multiple images in one X-ray tube rotation. It gives a lot of advantages compared to the single slice CT (SSCT) in many aspects such as higher resolution, larger coverage of the scanning region, faster temporal resolution, higher detective quantum efficiency (DQE) and so on. That is why the MSCT is gradually replacing the SSCT in most of the hospitals around the world.

2.1.1 Helical CT

In 1989, helical CT has been applied in third generation CT. The use of the slip ring technology has enabled the X-ray tube to rotate 360^0 continuously (Figure 2.2). Prior to that, the conventional CT scanners were using electrical cables to transmit data from the detector to the processing unit outside of the gantry but the length of the electrical cables limit the rotation of the tube. Slip ring technology has totally eliminated the limitation of transmitting data from the moving parts inside the gantry (especially X-ray tube and detector) to the processing unit. Helical CT technique has changed most of the body scanning procedures. For example, it can carry out a chest CT within a single breath-hold. With higher tube heat capacity, a modern CT is able to carry out entire trunk from chest to pelvic region in few seconds.

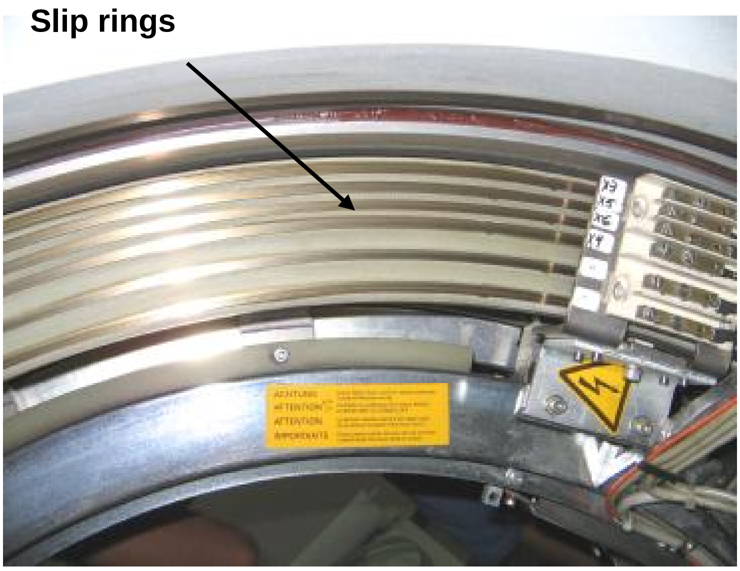

Figure 2.2: The use of the slip ring technology to transmit out the data from the moving part

Picture taken of CT Siemens Somatom Plus 4

Generally, helical CT has been used in various ways; to scan with standard protocol in shorter time or to scan with the same practical time but larger scanning coverage or to scan higher axial resolution to closely approach the isotropic voxel of high-quality data sets for 3-dimensional post-processing and diagnosis.

2.1.2 The Aids from Computer Technology

The development of computer technology has really assisted the development of CT technology. In the beginning, CT was known as CAT (computer assisted tomography); proving that computer is the basic component of the CT. Nowadays, stating the state-of-the-art computer technology is a mandatory requirement in preparing a specification of new CT scanner.

Faster processing capability of the microprocessors in computer leads to the faster reconstruction of CT images. The first CT scanner which was developed by Hounsfield in his laboratory took several hours to acquire the raw data for a single scan or "slice" and then it took days to reconstruct a single image from this raw data (Imaginis 2007). Now, latest models of CT scanners are able to display up to 16 images in a second, and with some simplications made, they are also able to display real time images during scanning (ImPACT 2001a).

The faster processing capability has also enabled the introduction of advance applications such as CT Fluoroscopy, CT Angiography, CT Perfusion, Multi Planar Reconstruction (MPR), Maximum Intensity Projection (MIP) and Volume Rendering. These interactive features have attracted more users to purchase the post-processing workstation in their CT packages. However, the ability of multi-slice CT scanners to produce larger number of images in a whole body scanning causing a major issue for workstation performance, film display and Picture Archiving and Communications System (PACS) (Kopp *et al.* 2000) because it basically requires huge capacity of the computer storage.

2.1.3 Multi-slice CT (MSCT)

Multi-slice CT scanner (MSCT) or so called “multi detector CT (MDCT)”, was introduced in 1998. It has capabilities of producing more than one image in one X-ray tube rotation. The main difference between MSCT and SSCT is the design of the detectors. The first multi-row detector was producing two images in a rotation. Most recent multi-row detector has the ability to produce up to 256 images in a rotation. Multi-row detector typically is wider in Z-axis; consist of multiple rows of small pieces of detector elements (Figure 2.3). The smallest size of a detector element is 0.5 mm x 0.5

mm (ImPACT 2008). Therefore, in Z-axis, a piece of 64 detector rows consists of 64 elements x 0.5 mm which is equal to 32 mm wide compared to SSCT which has a detector of typically 10 mm width (Figure 2.3). The wider detector can give larger coverage of scanning.

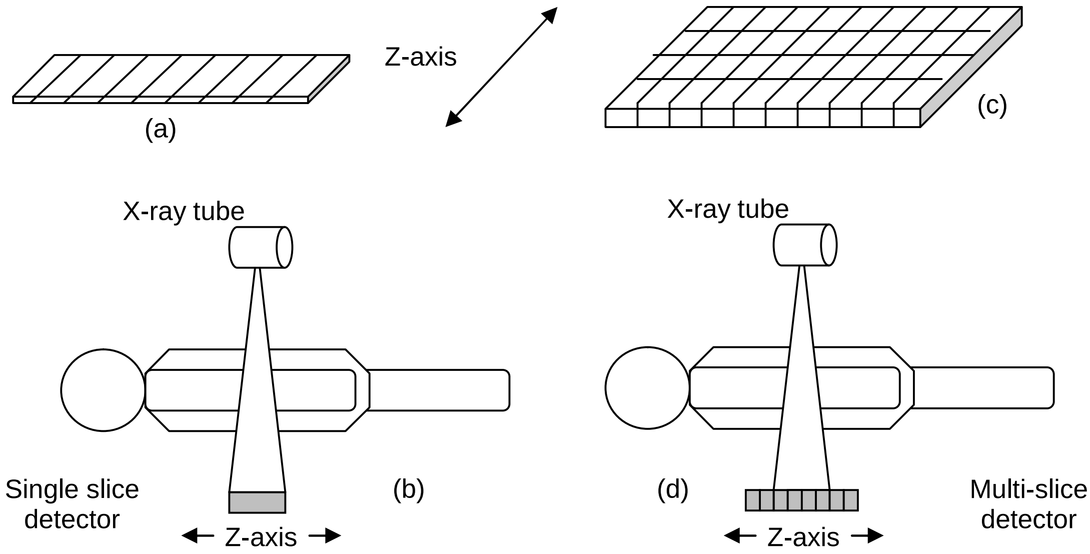

Figure 2.3: Schematic diagram of isometric solid state CT detector (not to scale); (a and b) single slice CT detector, (c and d) multislice CT detector

Another advantage of using the multi-row detectors is the ability of selecting different detector configurations or combinations. In SSCT, the slice thickness of an image is always referred to the beam width of irradiated slice thickness, but in MSCT, this term is seldom misunderstood by the CT users. For example, the reconstruction of 5 mm slice thickness of an image in MSCT can be formed from 1.25 mm x 4 image or 2.5 mm x 2 image or 5 mm x 1 image. Complete configurations need to be referred to the manufacturers' specifications and in fact, different model of MSCT has different selections of detector configuration. Changing the reconstructed image thickness will not affect the amount of radiation but selecting different configuration will result in the different amount of radiation produced by the X-ray tube. Further explanation is provided in Section 2.5.1.1.

2.2 Dose Distribution in CT

Dose distribution in computed tomography is completely different from that for the planar radiography. In planar radiograph, a single X-ray beam projection is required in order to produce a 2-dimensional image. The total linear attenuation coefficient, μ_{total} decreases the amount of dose exponentially in planar radiography. Therefore, measuring the entrance surface dose (ESD) in planar radiography is an acceptable method in determining the absorbed dose of the body. In CT, the radiation is distributed equally in the scanning plane and the dose distribution in the body depends to the mass attenuation coefficient. The radiation is not uniformly distributed throughout the body and therefore, measuring the ESD to calculate absorbed dose is irrelevant (Figure 2.4).

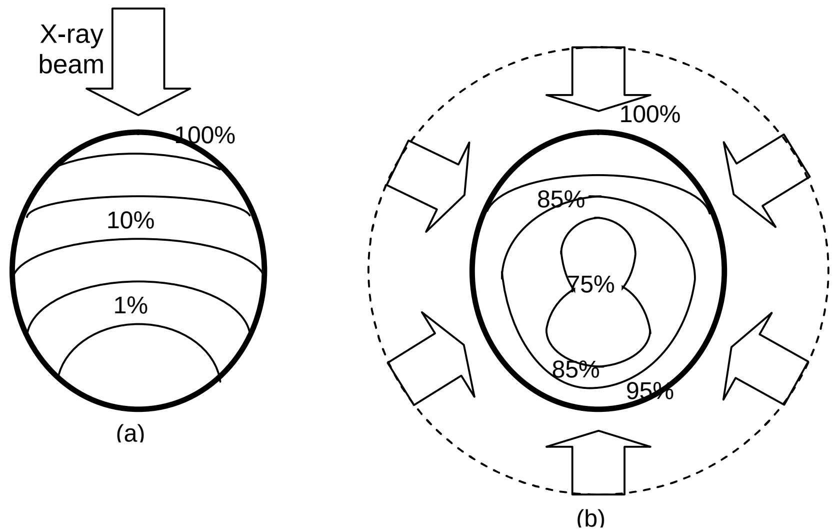

Figure 2.4: Cross sectional view of typical dose distribution in (a) planar radiography and (b) computed tomography

The transverse projection of CT is also different from planar radiography. Planar radiography is basically using cone beam shape where the beam is collimated to cover the scanning region. CT scanner is using fan beam shape where the irradiated slice thickness typically varies from 0.5 mm to 40 mm (in Z-axis) depending on the model of the CT scanner. Single axial scan produces single peak dose profile (Figure 2.5).

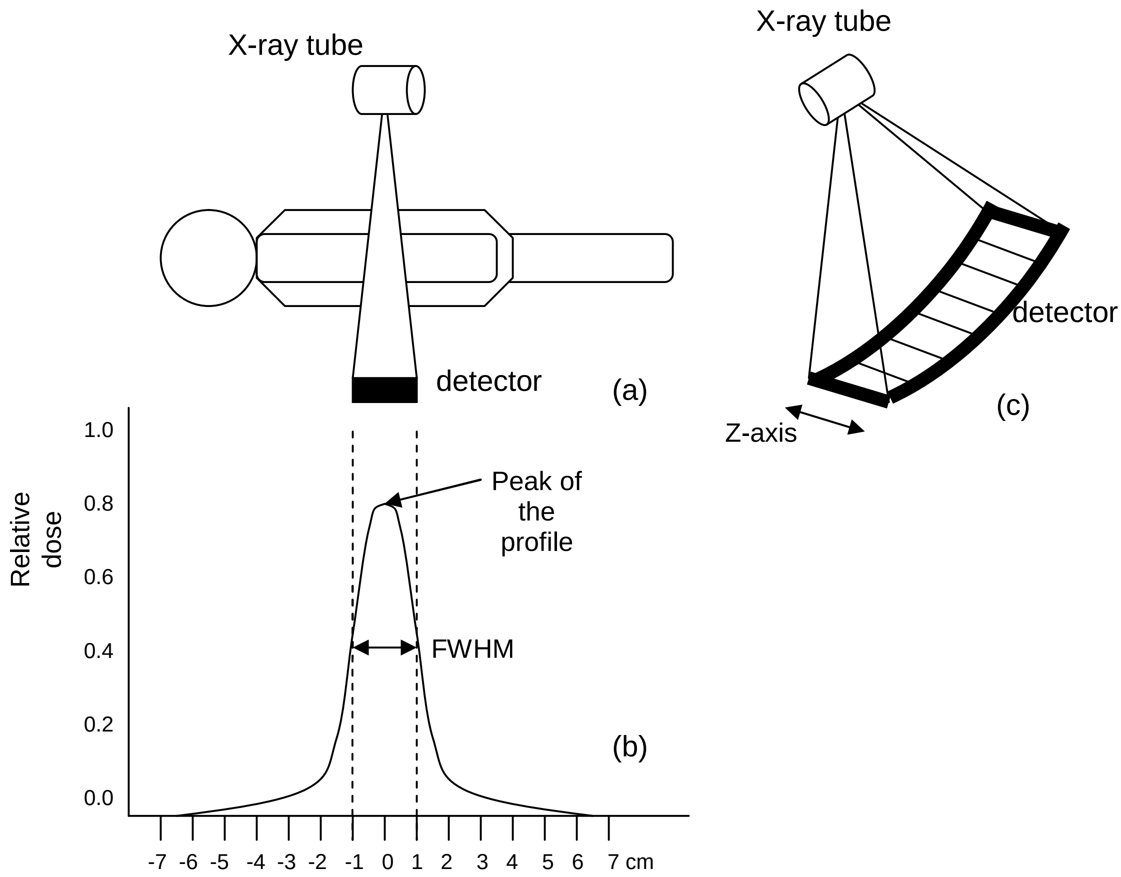

Figure 2.5: (a) Transverse projection of single scan in Z-axis; (b) Dose profile of single scan, slice width = 20 mm; (c) X-ray "fan" beam shape of CT scanner

2.3 CT Dose Descriptors

There were several dose descriptors of the CT have been introduced. Computed Tomography (CT) doses to the patients were typically expressed in organ dose and effective dose. The International Commission on Radiological Protection (ICRP) recommended that the effective doses be directly related to the stochastic radiation risks and also able to be used for relative comparison to other diagnostic examinations (ICRP 1991). Those dose descriptors were very useful to radiological communities and the patients to better comprehend of the effects of the radiation (NCRP 1989). Effective dose to each individual represents the total amount of radiation absorbed in whole body and gives good indicator of radiation detriment (McCollough and Schueler 2000). Thus, the European Community has come out with a directive to require the assessment of the patient dose so that the dose quantities are easily obtained for the assessment of the risk associated with CT examinations (Council of European Union 1997).

As the principle of CT is different from planar radiography, the terminology of doses for CT is also slightly different. Dose measurement in planar radiography is typically referred to the entrance surface dose (ESD) whilst in CT, it is usually referred to Computed Tomography dose index (CTDI). The use of the term “dose index” rather than “dose” was introduced to differentiate between planar radiography dosimetry and CT dosimetry. The method of measuring CT dose was also slightly different from plain radiography and the calculation of entrance surface dose of the CT was more complicated (Goldman 2007). Dosimetry measurements are important in optimising the CT dose and also became part of quality control test for the CT scanners (AAPM 1993, IEC 1994, IPEM 1997). The measurement methods were diversified to describe or characterise the radiation dose delivered by a scanner (Jessen *et al.* 1998).

2.3.1 Computed Tomography Dose Index (CTDI)

Computed Tomography Dose Index (CTDI) was defined as the summation of dose contributed along a line which is parallel to the axis of rotation of CT X-ray tube (in Z-axis) (Nagel 2000). The CTDI can be calculated using the formula: