ESTIMATION OF EXPOSURE RATE TO NUCLEAR MEDICINE PERSONNEL DURING CARDIAC SPECT IMAGING USING DIRECT AND INDIRECT METHODS: A PHANTOM STUDY

BY

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CERTIFICATE

This is to certify that the dissertation entitled

Estimation of Exposure Rate to Nuclear Medicine Personnel during Cardiac SPECT Imaging Using Direct and Indirect Methods: A Phantom Study

Is the bona fide record of research work done by

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During the period of February 2015

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^{99m}Tc	Technetium-99m
SPECT	Single Photon Emission Computed Tomography
ALARA	As Low As Reasonably Achievable
HUSM	Hospital Universiti Sains Malaysia
PPM	Patient Positioning Monitor
PPSK	Pusat Pengajian Sains Kesihatan
keV	kiloelectronVolt
mSv	milliSievert
mCi	milliCurie
mR	milliRoentgen
h	hour

ABSTRACT

This study was to determine the exposure rate to personnel during the ^{99m}Tc cardiac SPECT imaging procedure using direct and indirect methods. In this study, the single head gamma camera model Symbia-E manufactured by Siemens and the dual head gamma camera model Philips Adac Forte were used to scan the cardiac phantom. The direct method was conducted by measuring the exposure rate from radioactive cardiac phantom using Victoreen 451P-RYR survey meter at various distances (0.5 m, 1.0 m, 1.5 m and 2.0 m). The indirect method was based on mathematical model of exposure rate. The results indicated that exposure rates from direct method were higher than indirect method for both single and dual head gamma camera. The percentage differences between direct and indirect method for 23.71 mCi ^{99m}Tc for single head cardiac SPECT imaging at various distances were between 57.35% and 75%. For 21.80 mCi ^{99m}Tc, the percentage differences were between 29.20% and 58.30% and for 19.89 mCi ^{99m}Tc, the percentage differences were between 19.70% and 50%. On the other hand, The percentage differences between direct and indirect method for 23.71 mCi ^{99m}Tc for dual head cardiac SPECT imaging were between 41.20% and 50%. For 21.80 mCi ^{99m}Tc, the percentage differences were between 16.70% and 48.70% and for 19.89 mCi ^{99m}Tc, the percentage differences were between 20% and 52.10%. As conclusion, the calculated exposure from indirect method for both single and dual head cardiac SPECT imaging were lower than the actual exposure obtained from a direct method. Measurement of the exposure rates received from the cardiac phantom is important to ensure minimal hazard to personnel in nuclear medicine

department and to propose a safe working protocol for personnel performing cardiac SPECT imaging.

ABSTRAK

Tujuan kajian ini dijalankan adalah untuk menentukan kadar dedahan radiasi kepada kakitangan di perubatan nuklear semasa prosedur imbasan ^{99m}Tc SPECT jantung dengan menggunakan kaedah langsung dan tidak langsung. Dalam kajian ini, *single head gamma camera* dan *dual head gamma camera* digunakan untuk membuat imbasan pada fantom jantung. Untuk kaedah langsung, kadar dedahan radiasi diukur menggunakan Victoreen 451P-RYR meter tinjau pada jarak (0.5 m, 1.0 m, 1.5 m and 2.0 m) dari fantom. Untuk penilaian pendedahan menggunakan kaedah tidak langsung, bacaan pendedahan telah dikira dengan menggunakan model matematik bagi pengiraan dedahan. Keputusan kajian ini menunjukkan bahawa kadar pendedahan daripada kaedah langsung lebih tinggi daripada kaedah tidak langsung untuk kedua-dua imbasan menggunakan *single head* dan *dual head gamma camera*. Untuk imbasan SPECT jantung menggunakan *single head gamma camera*, peratus perbezaan antara kaedah langsung dan tidak langsung bagi aktiviti 23.71 mCi ^{99m}Tc di setiap jarak adalah diantara 57.35% dan 75%. Bagi aktiviti kedua iaitu 21.80 mCi ^{99m}Tc, peratus perbezaan adalah diantara 29.20% dan 58.30% dan bagi aktiviti ketiga iaitu 19.89 mCi ^{99m}Tc, peratus perbezaan adalah diantara 19.70% dan 50%. Seterusnya, untuk imbasan SPECT jantung menggunakan *dual head gamma camera*, peratus perbezaan antara kaedah langsung dan tidak langsung bagi aktiviti 23.71 mCi ^{99m}Tc di setiap jarak adalah diantara 41.20% dan 50%. Bagi aktiviti kedua iaitu 21.80 mCi ^{99m}Tc, peratus perbezaan adalah diantara 16.70% dan 48.70% dan bagi aktiviti ketiga iaitu 19.89 mCi ^{99m}Tc, peratus perbezaan adalah diantara 20% dan 52.10%. Sebagai kesimpulan, kajian ini menunjukkan bahawa kaedah

tidak langsung untuk imbasan SPECT jantung dengan menggunakan kedua-dua mesin gamma kamera menunjukkan kadar dedahan radiasi yang rendah daripada kadar dedahan sebenar. Pengukuran kadar dedahan yang diukur daripada fantom jantung juga penting dalam mengurangkan dedahan radiasi kepada kakitangan di perubatan nuklear semasa imbasan SPECT jantung dijalankan.

CHAPTER 1

Introduction

1.1 Background of the study

Nuclear medicine is a morphological study involving radioactive materials in form of radiopharmaceuticals. Nuclear medicine imaging is often applied in several clinical cases involving cardiovascular, gastrointestinal, endocrine, neurological diseases and other abnormalities within the body (RadiologyInfo.org 2014).

Nuclear medicine imaging procedures are non-invasive and it is a method that helps physicians to diagnose and evaluate medical conditions of patients. These imaging scans uses radioactive materials called radiopharmaceuticals (RadiologyInfo.org 2014). A radiopharmaceutical is a combination of radioactive source commonly ^{99m}Tc and ^{131}I with chemical substances for diagnosis or therapy in a tracer quantity with no pharmacological effect. The radiopharmaceuticals are administered intravenously or orally to the patient before being scanned under the gamma camera. Administration of radiopharmaceutical into patient's body, which consists of gamma or positron emitter, can lead to an exposure to nuclear medicine personnel involve in the imaging procedure.

The nuclear medicine personnel will receive occupational exposure while performing procedures as they help positioning the patient on the scanner bed, monitoring the patient during data acquisition, removing the patient from the bed and escorting the patient to the department.

The principles of the protection to nuclear medicine personnel from ionising radiation in all areas of medicine are directed at prevention of deterministic effects and minimization of risk for stochastic effects. These principles include use of dose limits for workers and general public and 'As Low As Reasonably Achievable' (ALARA) principle to keep doses well below the dose limits. Dose limit for workers is 20 mSv/year and for public is 1 mSv/year (ACT 304).

Most nuclear medicine laboratories do not provide separate control room for technologists, which are quite close to patient during data acquisition and cause additional radiation exposure to them besides the exposure during the imaging prodecure (Bayram et al, 2011). Preparations of radiopharmaceuticals may consequently cause high exposure to a laboratory staff. This requires measurement of risks due to exposure as well as training and a strict compliance with the established radiation safety standards (Elsevier et al, 2011).

There are three basic concepts apply to all types of ionizing radiation that limit how much radiation a person can receive in a particular situation. They are time, distance and shielding (G Marshall, S Keene et al 2006).

Time

The amount of radiation exposure increases and decreases with the time people spend near the source of radiation. By minimize the time during handling of radioactive material, the exposure will be reduced. The total radiation dose is directly proportional to the time of exposure.

Radiation Dose Received = Dose Rate x Time (1.1)

Distance

By maximizing the distance from the radioactive materials, the exposure will be reduced. The inverse square law stated that the dose is inversely proportional to distance, therefore, greater distance means less exposure. In example, if the distance of the radiation source from the body is increase by a factor of 2, the radiation dose will reduce by a factor of 4 given by the proportionality of.

$I \alpha 1/d^2$ (1.2)

Shielding

Shielding provides attenuation of ionizing radiation thus reducing the intensity of the ionizing radiation. The amount of shielding required to protect against different kinds of radiation depends on the type and the quality of the beam. Shielding materials functions differently according to types of ionizing radiation.

1. Alpha particles

Alpha particles can be absorbed by a thin sheet of paper or by a few centimetres of air due to its low penetrating power and loses its energy quickly at depth of medium. Collisions with air molecules causing alpha particles to lose their energy until eventually they give up all of their energy and are absorbed. In a sheet of paper the molecules are much close together so the penetration of alpha particles is less than in air.

2. Beta particles

Beta particles travel faster than alpha particles and carry less charge (one electron compared to the 2 protons of an alpha particle). Therefore beta interacts less readily with the atoms and molecules of the material through which they pass. Beta particles can be stopped by a few millimetres of aluminium.

3. Gamma and x-rays

Gamma and x-rays collectively known as photon are the most penetrating type of ionizing radiations. Photons are highly energetic waves and are poor at ionising other atoms or molecules. It cannot be said that a particular thickness of a material can absorb all gamma radiation. Many centimetres of lead or many meters of concrete are required to absorb high levels of photons.

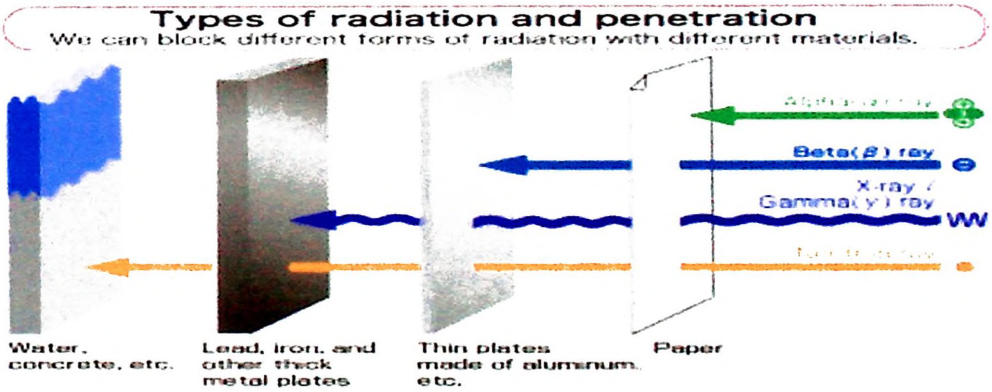

Figure 1.1 Different attenuation and penetrating power of ionizing radiations.

As a conclusion, the exposure to nuclear medicine personnel will be reduced as they minimized the time during handling the radioactive material, keep the maximized distance and apply the shielding around them.

1.2 Problem statement

To receive an absorbed radiation dose, one must first actually be exposed to radiation (Trapp & Kron, 2008). Knowing and limiting the radiation exposures from radioactive patients are necessary for keeping the radiation dose as low as reasonable. Besides that, time, distance and shielding are three parameters that must be taken into account.

Without the support of actual measurement (direct) such as radiation detector probes, calculated (indirect) exposure rates can be used. Two theoretical exposure models that are frequently used to calculate the exposure rates are unshielded point source models (NUREG, 1998) and line source models.

These studies focused on the effectiveness of point source calculation model and compare it to the direct method on ^{99m}Tc cardiac SPECT imaging procedures. Moreover, this study will also strengthen the fact that radiation exposure rates will diminishes with distances.

1.3 Significant of study

In nuclear medicine, there are various radiopharmaceuticals administered for different organ that remain for hours or days. Thus, the radiation protection to nuclear medicine personnel must be taken into account. The significant of this study is to estimate the exposure rate that could result in excessive occupational exposure to the personnel in nuclear medicine.

All diagnostic as well as therapeutic nuclear medicine tests are performed using unsealed source of radiopharmaceuticals. So, the nuclear medicine personnel must be aware of their safe distances while dealing with the unsealed sources. Different time of nuclear imaging procedures will contribute to different level of radiation exposure. Thus, findings of this study can help them minimize their distances and times during a nuclear medicine imaging procedures focused on the cardiac SPECT imaging.

1.4 Aim and Objective

Aim :

The aim of this study is to determine the exposure rate to personnel during the cardiac SPECT imaging procedure.

Objectives :

The specific objectives of this study are:

1. To compare the exposure rate to personnel using direct and indirect method during cardiac SPECT imaging procedure.
2. To determine the exposure rate with respect to distance using the cardiac SPECT imaging using a single head and a double head gamma camera.
3. To propose safe working protocol for personnel performing cardiac SPECT imaging.

CHAPTER 2

LITERATURE REVIEW

Bayram et al. (2010) conducted a study to determine radiation exposure to the technologist during nuclear medicine procedures. Five procedures were selected including ^{99m}Tc-MDP whole body scans. This study used a Geiger-Muller detector to measure exposure rates to technologist at various distances from patients (0.25 m, 0.50 m, 1.0 m and 2.0 m). The average time spent by technologist at these distances also measured. They found that the mean exposure rates measured at various distances (0.25 m, 0.5 m, 1.0 m & 2.0m) from the patient for ^{99m}Tc-MDP whole body scans was 1.31± 0.71 mR/h, 0.56 ± 0.20 mR/h, 0.33 ± 0.12 mR/h and 0.13 ± 0.12 mR/h respectively. They also found that the exposure rates varied significantly for different scanning procedures. As a conclusion, the radiation exposures to technologist may be minimized and lowered when keeping a distance of 2 m or more.

Willegaignon et al. (2006) reported a new proposal for monitoring patients in nuclear medicine. This study compared two methodologies to obtain exposure rates, which is a calculations and measured methods. The study involved patients who received high activities of Na^{131}I. The exposure rates were measured from 0.5 m to 4.5 m (increasing in intervals 0.5 m) from the patients' bodies. The measurement was done using a Geiger-muller and a beta-gamma probe. On the other hand, theoretical exposure rates were calculated using the inverse square law and the point source equation. Based on their results, the mean error between measured and calculated exposure rates at 1.0

m and 2.0 m was 40% and 2% respectively. Therefore, error reduces at longer distance.

Rimpler et al. (2008) carried out the dose rate measurements with a variety of survey-meters. The dose rates of specimen of radiopharmaceuticals (^{99m}Tc, ^{18}F, ^{68}Ga, ^{131}I, ^{90}Y) were determined for distances between 0m and 1m. Based on the dose rate measurements of sources and patients, estimations of radiation doses to the personnel and members of the public could be performed. These estimations were further substantiated with dedicated measurements of whole body exposures and extremity doses. Particular attention was directed to handling and preparation of labelled compounds. Skin dose measurements for the medical staff performing preparations and applications were carried out using ring dosimeters and thermoluminescence dosimeters (TLDs) calibrated to measure the personal dose equivalent at 0.07 mm depth. As a conclusion, dose rate reduced with increasing distance. Nevertheless, this relationship should be kept in mind because of the order of magnitude by which the dose rate can be reduced only by keeping sufficient distance.

Koehler & Natarajan et al. (2007) stated that x-ray radiation is harmful and the effects of ionizing radiation can either be classified as stochastic (random) or deterministic effect (non-random). Through radiation protection, deterministic effects may be prevented and stochastic effects may be reduced. Radiation dose from diagnostic procedures is controlled by government agencies because of the risk associated with stochastic effects. All modern radiation protection guidelines are based upon the linear dose response model without a threshold. Even small dose also can cause biological harm. Heredity effects, cancer, and leukemia are some examples of stochastic effects.

Norsuriani S et al. (2014) conducted a study on measurement of exposure rates to personnel in Nuclear Medicine during ^{99m}Tc-DTPA renal scans and ^{99m}Tc-MDP whole body imaging procedures using direct and indirect methods. 3 patients undergoing ^{99m}Tc-DTPA renal scans and 3 patients undergoing ^{99m}Tc-MDP whole body scan procedures were randomly selected in this study. The direct method was conducted by measuring the exposure rate emitted from patients using Victoreen 451P-RYR survey meter at various distances (0.5 m, 1.0 m and 2.0 m) from the patients. The indirect method was conducted using mathematical model of exposure rate. The results indicated that exposure rates from indirect method were higher than direct method at all nominal distances. For ^{99m}Tc-DTPA renal scans procedure, the percentage difference between direct and indirect method for various distances were 17.16 ± 3.73 (0.50 m), 12.37 ± 9.01 (1.0 m) and 31.07 ± 8.91 (2.0 m) respectively. On the other hand, the percentage differences for ^{99m}Tc-MDP whole body scan for various distances were 166.01 ± 189.98 (0.50 m), 150.92 ± 167.38 (1.0 m) and 62.78 ± 83.74 (2.0 m). This study showed that the exposure rates diminished with the increases in distances. Measurement of the exposure rates received from the radioactive patients is important to ensure minimal hazard to personnel in nuclear medicine department and to propose a suitable programme for radiological protection on the management of radioactive patients.

CHAPTER 3

Materials and Methods

3.1 Materials

3.1.1 Siemens Symbia Single Head Gamma Camera

For SPECT imaging study, single head Gamma Camera, model Symbia-E manufactured by Siemens is used. Symbia-E is a multi-purpose SPECT system ideal for hospitals and outpatient centers. It combines versatility and cost effectiveness in a compact, high performance and reliable system. It was installed in the Nuclear Medicine Department, Hospital USM and belongs to Pusat Pengajian Sains Kesihatan (PPSK) USM. It consists of a gantry ring, rear bed, patient bed pallet, patient, patient positioning monitor (PPM), collimator (s) and detector (s).

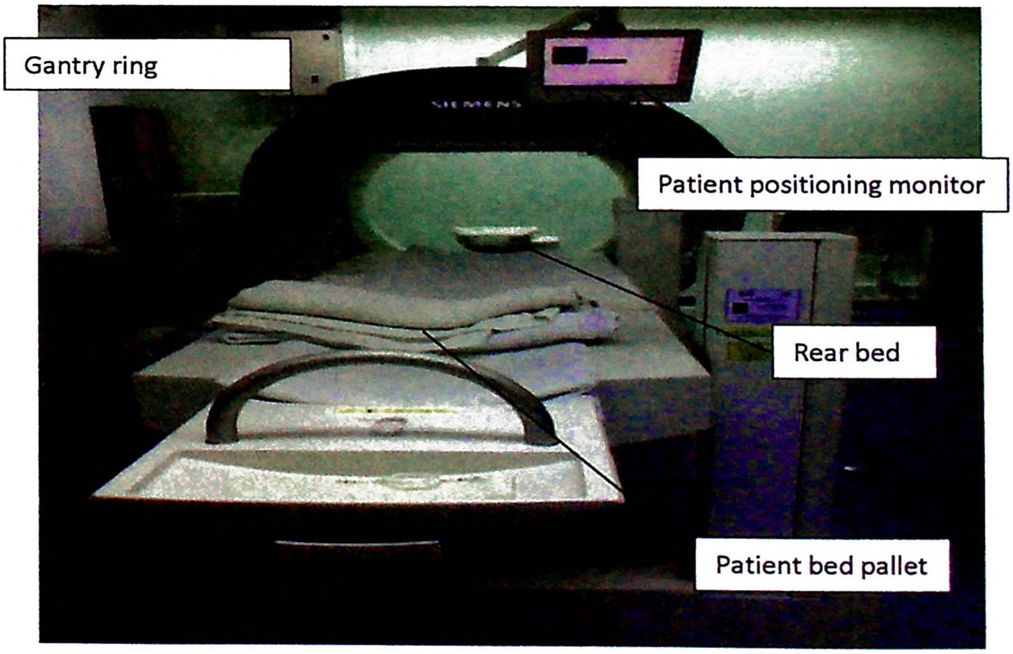

Figure 3.1 Siemens Symbia Single Head Gamma Camera

3.1.2 Philips Adac Forte Double head Gamma Camera

Dual headed gamma camera, Philips Adac Forte also being used in this study. The Philips' Forte nuclear medicine camera is designed for general purpose, SPECT and planar imaging and can produce as many as fifteen different image sets using physician specified protocols. The nuclear camera's unique open design accommodates patients on gurneys, in hospital beds and even in wheel chairs. It was also installed in the Nuclear Medicine Department, Hospital USM.

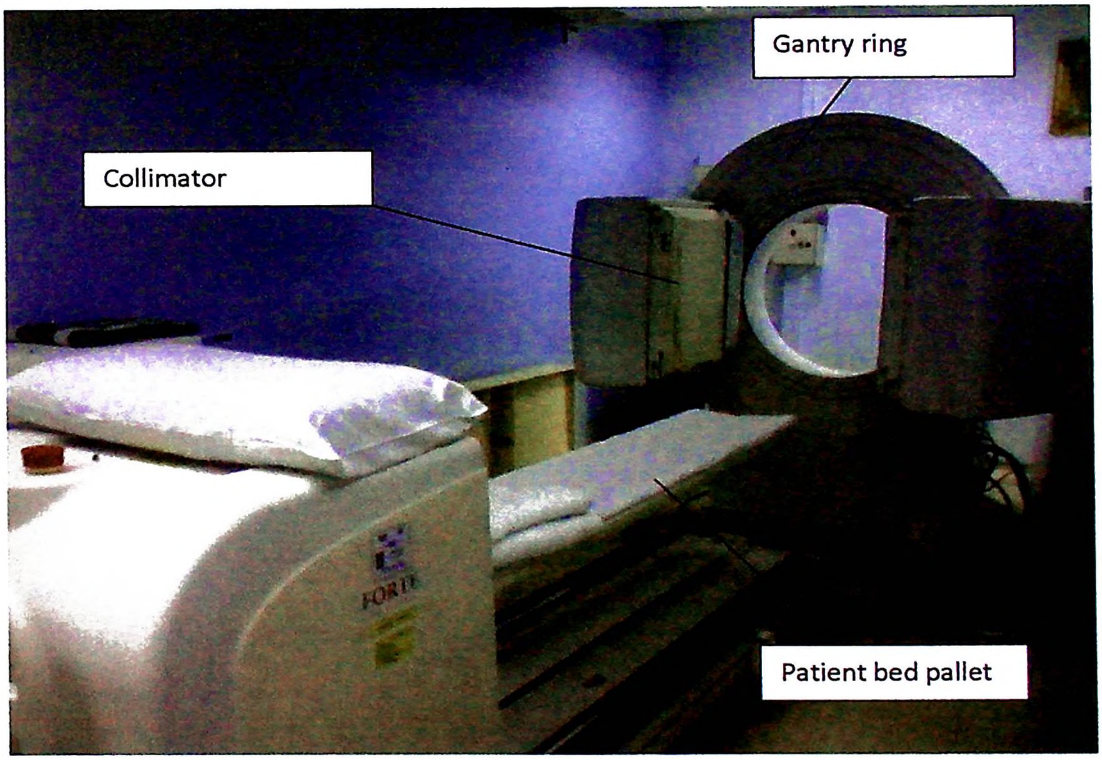

Figure 3.2 Philips Adac Forte Double Head Gamma Camera

3.1.3 Cardiac Phantom

Cardiac phantom was also used in this study as the activity distribution of Technetium-99m inside it will affect the exposure rate to nuclear medicine personnel during SPECT imaging. It consists of myocardium wall and the soft tissue background tank. The myocardium wall was filled with radioactive water (90%) of Technetium-99m while the soft tissue background compartments were filled with radioactive water (10%) of ^{99m}Tc. Cardiac phantom was used in both dual head and single head gamma camera. Cardiac phantom also is a soft tissue equivalent material.

Figure 3.3 Cardiac phantom and Cardiac inserter

3.1.4 Victoreen 451P-RYR Survey Meter

For this study, Victoreen survey meter model 451P-RYR is used. It is a hand-held battery operated unit designed for use in both rugged and normal environments. The model 451P features a pressurized ionization chamber, providing enhanced sensitivity and improving energy response to measure gamma and x-ray radiation. This survey meter is constructed of lightweight, high strength materials and is sealed against moisture.

The model 451P is used in a wide range of medical and health physics applications. It was designed to measure leakage and scatter around diagnostic x-ray and radiation therapy suites. Also, this model is ideal for site surveys and is regularly used by x-ray manufacturers, government agencies, state inspectors, research labs, biomedical technicians and in airports for baggage inspection equipment maintenance.

Figure 3.4 Victoreen Survey Meter

Victoreen 451P-RYR also has the ability to detect beta rays above 1 MeV and Gamma and X-rays above 25 keV. This model also has accuracy within 10% of reading between 10% and 100% if full-scale indications on any range, exclusive of energy response. The internal chamber had 230 cm^3

volume pressurized air ionization chamber up to 8 atmospheres. Table 3.1 summarized the operating range of Victoreen survey meter.

Table 3.1

Operating range of Victoreen Survey Meter

0 – 500 µR/h		**0 – 5 µSv/h**
0 – 5 mR/h		0 – 50 µSv/h
0 – 50 mR/h	**or**	0 – 500 µSv/h
0 – 500 mR/h		0 – 5 mSv/h
0 – 5 R/h		0 – 50 mSv/h

In this study, the calibration factor (CF) and range correction factor (J) were determined. It is because, as the reading of Victoreen 451P-RYR deteriorates in time, the instrument reading obtained from the instrument must be multiplied by CF and J according to this equation :

$$D = B \times J \times CF \quad (3.1)$$

Where,

D – Actual Exposure (mR/h)

B – Instrument Reading (mR/h)

J – Range Correction Factor (Refer table 3.2)

CF – Calibration Factor (Refer table 3.3)

Table 3.2

Range Correction Factor

Range	**Range correction factor**
0 – 5 R/h	1.04
0 – 500 mR/h	1.00
0 – 50 mR/h	1.00
0 – 5 mR/h	0.98
0 – 500 μ/h	0.93

Table 3.3

Calibration factor for x-rays and gamma rays

No.	**Radiation Energy (keV)**	**Tube Capability (Kv)**	**HVL (mm Cu)**	**Calibration Factor (CF)**
1.	47	60	0.24	1.48 ± 2.1 %
2.	84	100	1.08	1.15 ± 1.2 %
3.	121	150	2.46	1.07 ± 1.1 %
4.	171	200	4.07	1.08 ± 1.0 %
5.	218	250	5.32	1.11 ± 1.0 %
6.	^{137}Cs (662)	-	-	1.10 ± 6.6 %
7.	^{60}Co(1250)	-	-	1.14 ± 1.6 %

From the calibration energy, the CF for ^{99m}Tc (141 keV) is **1.178 ± 1.6%.**

(Norsuriani S et al 2014)

3.2 Methods

3.2.1 Direct method

This study focused on the external radiation exposure of nuclear medicine personnel during cardiac SPECT imaging procedure rather than during the preparation and injection of radiopharmaceutical. The external radiation exposures were measured during cardiac SPECT scan for both single and dual head gamma camera. The activity of ^{99m}Tc Pertechnetate inside a cardiac phantom were recorded three times for each single head and dual head gamma camera before the scanning.

External radiation exposures were estimated by using Victoreen 451P-RYR survey meter at various distances (0.50, 1.00, 1.50 and 2.00 m) from the midline of cardiac phantom. In this measurement, the distance of the point of measurement that indicates the distance of personnel from the patient bed was measured using a ruler. The distances were set at 0.50, 1.00, 1.50 and 2.00 m.

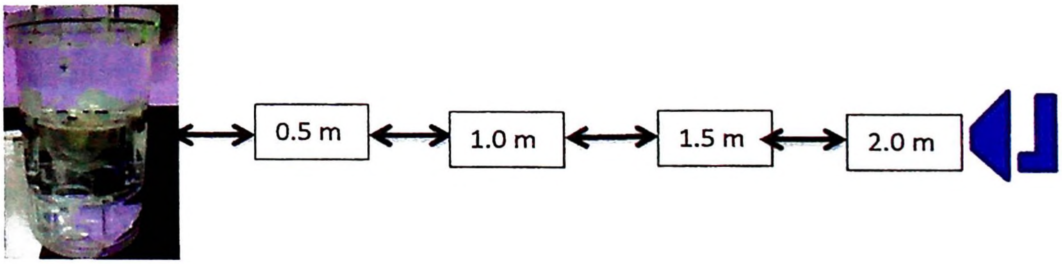

Figure 3.5 The distances of direct measurement using survey meter measured from the cardiac phantom

3.2.2 Indirect method

For measurement of exposure using indirect method, the exposure rate will be calculated by using the equation of

$$X = \frac{n}{d^2}.Ao\ e^{-\mu x}.t \qquad (3.2)$$

Where ,

X : Exposure rate

A_o : Initial activity of the radionuclide (mCi)

d : Distance of the measurement

n : Exposure rate constant of the radionuclide ($R.cm^2/mCi.hr$)

μ : Linear attenuation coefficient of the cardiac phantom

t : Time of measurement

x : The thickness of the phantom

Before cardiac SPECT imaging scan procedure for both single head and dual head gamma camera were done, activity administered to cardiac phantom was calculated by $A = Ao\ e^{-\lambda t}$ formula and were recorded. For exposure rate constant of the radionuclide (n), its value for ^{99m}Tc is 0.60 $R.cm^2/mCi.hr$ (Bayram, 1998). In this study, the distance was 0.50, 1.00, 1.50 and 2.00 m. The exposure rate is then calculated using this formula and the value is compared to the values obtained from the direct method (Victoreen 451P-RYR exposure reading).

CHAPTER 4

RESULTS

4.1 ^{99m}Tc Cardiac SPECT Imaging (Single Head Gamma Camera)

The activities and average activity of ^{99m}Tc administered in the cardiac SPECT phantom is presented in Table 4.1. The graph of exposure rate measured using direct method against the distance of measurement is illustrated in Figure 4.1. The graph of exposure rate measured using indirect method against the distance of measurement is illustrated in Figure 4.2. The graphs of comparison of exposure rate between direct and indirect methods for all ^{99m}Tc activities are illustrated in Figure 4.3 until 4.5. An interpolation line was drawn between the points of measurement in the graphs to ease the reading and to show the exponential function of the graphs.

Cardiac phantom (n=3)	**1**	**2**	**3**	**Average**
Activity (mCi)	23.71	21.80	19.89	21.80

Table 4.1: The activity levels of 99mTc administered in cardiac SPECT phantom for single head SPECT imaging.

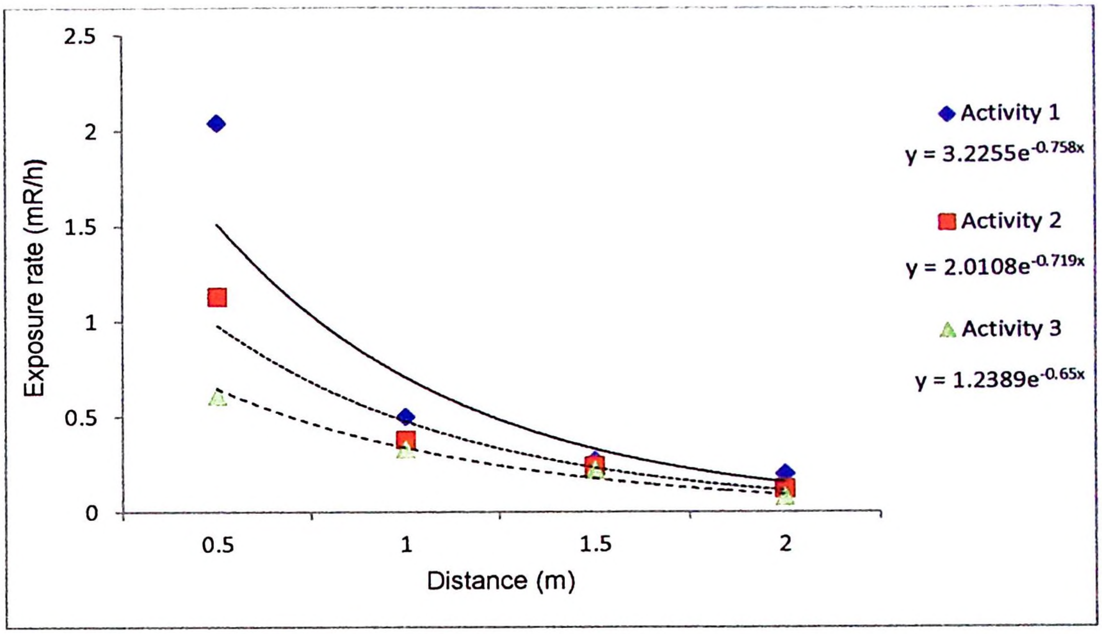

Figure 4.1: The exposure rate against distance of ^{99m}Tc during single head cardiac SPECT imaging using the direct method (n = 3).

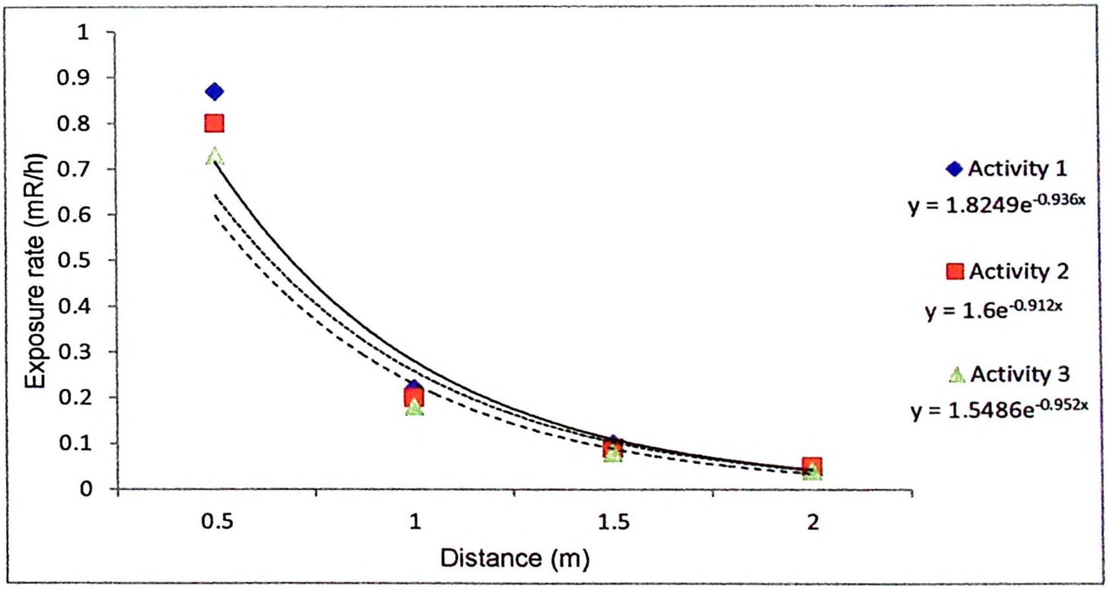

Figure 4.2: The exposure rate against distance of ^{99m}Tc during single head cardiac SPECT imaging using the indirect method (n = 3).

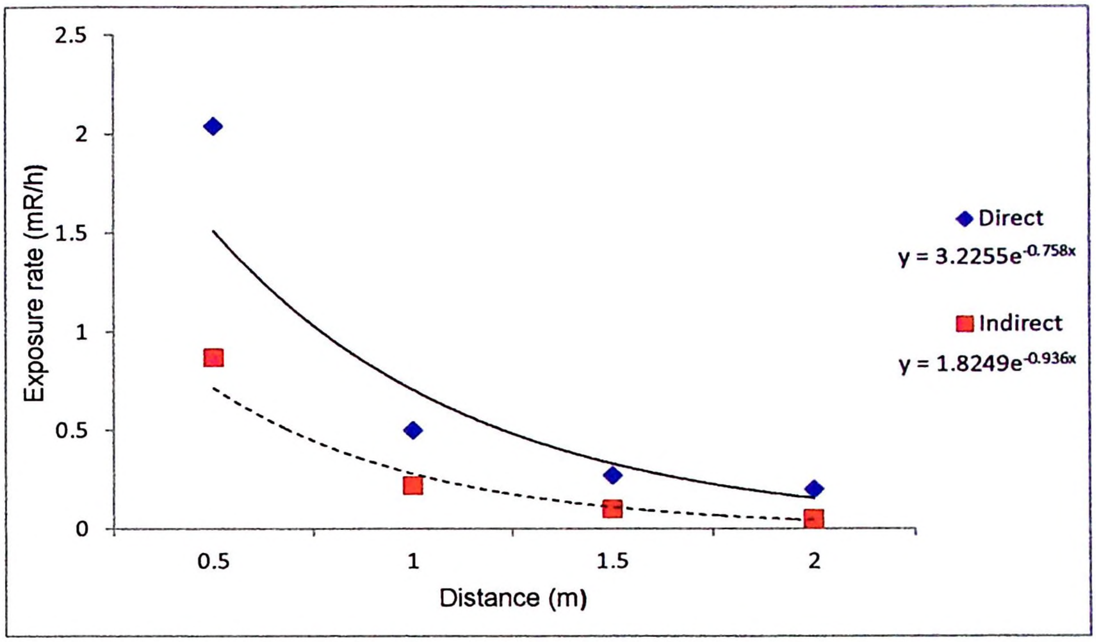

Figure 4.3: The exposure rate against distance for direct and indirect methods during single head cardiac SPECT imaging using at 23.71 mCi ^{99m}Tc.

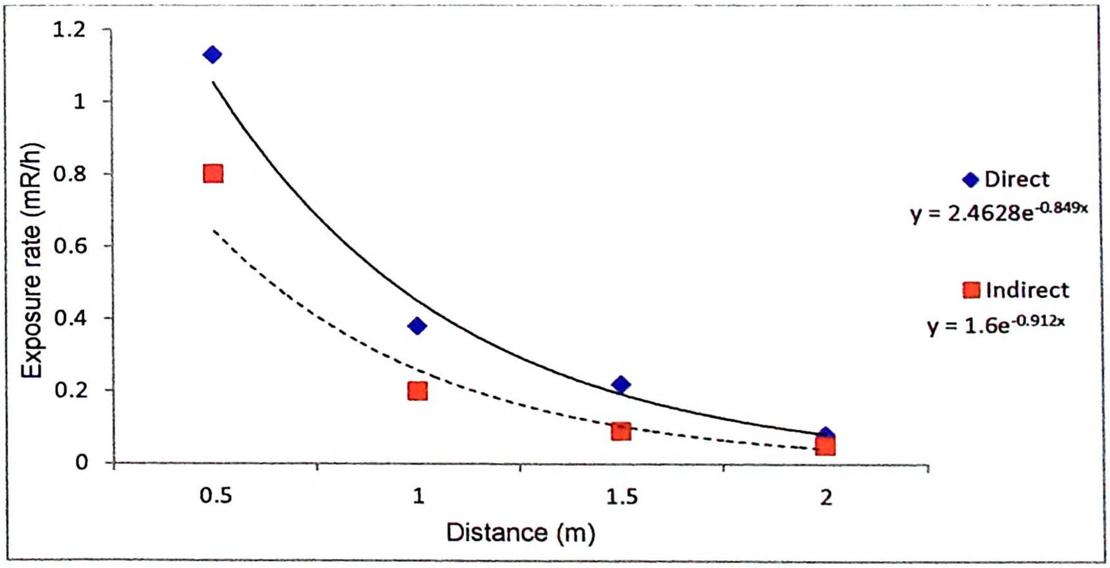

Figure 4.4: The exposure rate against distance for direct and indirect methods during single head cardiac SPECT imaging using at 21.80 mCi ^{99m}Tc.

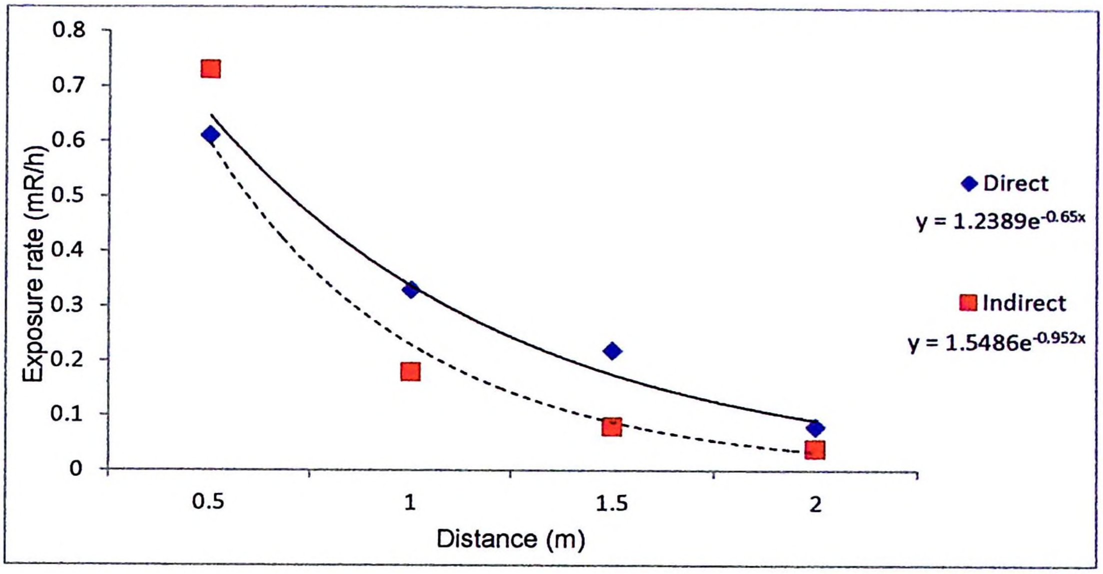

Figure 4.5: The exposure rate against distance for direct and indirect methods during single head cardiac SPECT imaging using at 19.89 mCi ^{99m}Tc.

Based the exposure rate measured against the distance in Figure 4.1 and Figure 4.2, it is illustrated that the exposure rate decrease exponently at the function of distance for both direct and indirect method of exposure rate measurements. It is also illustrated that there is a significant deviation of exposure rate at distance nearer to the phantom for direct methods. The deviation is found to be less significant for indirect method. The deviation however decreased as the distance of measurement from the phantom increased for both direct and indirect methods of exposure rate measurement. The comparison of exposure rate, as presented in Figure 4.3 until 4.5 showed an agreement between direct and indirect methods. However, there were significant deviations of exposure rate at distance nearer to the phantom between the direct and indirect methods for all three activity levels of ^{99m}Tc. The deviation between the direct and indirect methods was found to be reduced as the distance of measurement from the phantom was increased.

The mean and standard deviation of exposure rates between direct and indirect method at a distance between 0.5 m and 2.0 m is summarized in Table 4.2. It is shown in Table 4.2 that the mean exposure rates from direct method were higher than the indirect method at all distance of measurements between 0.5 m and 2.0. The SD was also found to be decreased as the distance of measurement was increased.

	Mean exposure rate ± SD							
Distance	0.5 m		1.0 m		1.5 m		2.0 m	
Method	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
	1.26 ± 0.59	0.80 ± 0.06	0.40 ± 0.07	0.20 ± 0.02	0.24 ± 0.02	0.09 ± 0.01	0.13 ± 0.05	0.05 ± 0.00

Table 4.2: Mean and SD of exposure rate between direct and indirect method

^{99m}Tc in single head cardiac SPECT phantom (n=3)

4.2 ^{99m}Tc Cardiac SPECT Imaging (Dual Head Gamma Camera)

The activities and average activity of ^{99m}Tc administered in the cardiac SPECT phantom is presented in Table 4.3. The graph of exposure rate measured using direct method against the distance of measurement is illustrated in Figure 4.6. The graph of exposure rate measured using indirect method against the distance of measurement is illustrated in Figure 4.7. The graphs of comparison of exposure rate between direct and indirect methods for all ^{99m}Tc activities are illustrated in Figure 4.8 until 4.10. An interpolation line was drawn between the points of measurement in the graphs to ease the reading and to show the exponential function of the graphs.

Cardiac phantom (n=3)	**1**	**2**	**3**	**Average**
Activity (mCi)	23.71	21.80	19.89	21.80

Table 4.3: The activity levels of 99mTc administered in cardiac SPECT phantom for dual head SPECT imaging.