MEASUREMENT OF MASS ATTENUATION COEFFICIENT OF PARAFFIN WAX BY USING LOW ENERGY X-RAY

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MEASUREMENT OF MASS ATTENUATION COEFFICIENT OF PARAFFIN WAX BY USING LOW ENERGY X-RAY

By

NURUL SHAZLIANA BINTI MOHAMAD DAUD

Dissertation submitted in partial fulfilment of the requirement for the
degree of Bachelor of Health Sciences (Honours) (Medical Radiation)

JULY 2024

CERTIFICATE

This is to certify that the dissertation entitled “MEASUREMENT OF MASS ATTENUATION COEFFICIENT OF PARAFFIN WAX BY USING LOW ENERGY X-RAY” is the bona fide record of research work done by NURUL SHAZLIANA BINTI MOHAMAD DAUD during the period from October 2023 to July 2024 under my supervision. I have read this dissertation and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Health Science (Honours) (Medical Radiation).

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated and duly acknowledged. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at University of Science Malaysia or other institutions. I grant University of Science Malaysia the right to use the dissertation for teaching, research, and promotional purposes.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols/ Abbreviations	**Definition**
Al	Aluminium
Z	Atomic number
cm	Centimetre
cGy	centiGray
cm^{-1}	per centimetre
cm2 /g	centimetre squared per gram
ρ	Density
μ/ρ	Mass attenuation coefficient
E_{ef}	Effective energy
Z_{eff}	Effective atomic number
g/cm^3	gram per cubic centimetre
HVL	Half value layer
HUSM	Hospital Universiti Sains Malaysia
I_0	I0 Initial intensity
IC	Ionization chamber
keV	kiloelectron volt
kVp	kilovoltage peak
μ	Linear attenuation coefficient
mm	millimetre
NIST	National Institute of Standard and Technology
PMMA	Polymethyl methacrylate
PVC	Polyvinyl chloride
x	Thickness of material
I	Transmitted photon

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Appendix A	Determination of Effective Energies
Appendix B	Measurement of Mass Attenuation Coefficient

PENGUKURAN TENTANG PEKALI PENGECILAN JISIM LILIN PARAFIN PADA SINAR-X BERKUASA RENDAH

ABSTRAK

Kajian ini merupakan kajian tentang pekali pengecilan jisim lilin parafin pada sinar-x berkuasa rendah dan membandingkannya dengan phantom air pepejal, air, dan Perspex®, yang biasanya digunakan sebagai phantom yang menyerupai sel tisu manusia. Tenaga efektif untuk 60, 81, dan 125 kVp ditentukan,menggunakan kaedah Lapisan Separuh Nilai (HVL) dengan masing-masing adalah 35.22, 37.57, dan 41.20 keV. Keputusan menunjukkan bahawa pekali pengecilan jisim tertinggi pada tenaga efektif yang lebih rendah dan berkurangan dengan tenaga yang lebih tinggi, selari dengan tingkah laku kesan fotoelektrik. Selain itu, didapati bahawa variasi faktor pengaliran sinar-x, ln (I0/I) adalah linear dengan peningkatan ketebalan phantom. Tambahan pula, peratusan perbezaan antara pekali pengecilan jisim antara phantom air pepejal, Perspex, dan lilin parafin daripada air, dengan menekankan peranan air sebagai bahan rujukan utama kerana air mempunyai sifat radiologi yang menyerupai sel tisu manusia

Keputusan yang diperolehi disahkan dengan nilai teori daripada perisian XCOM, mengesahkan ketepatan kaedah yang dilaksanakan. Kajian ini mendapati bahawa sisihan maksimum pekali pengecilan jisim yang diperolehi secara eksperimen berbanding dengan XCOM adalah 25% untuk air, 27% untuk Perspex, 8.4% untuk lilin parafin, dan 44% untuk phantom air pepejal. Kajian ini menyokong penggunaan lilin parafin sebagai bahan tisu setara yang kos efektif untuk aplikasi radiologi dan menyediakan asas yang kukuh untuk penyelidikan masa depan dan penggunaan praktikal dalam radiologi diagnostik dan jaminan kualiti.

MEASUREMENT OF MASS ATTENUATION COEFFICIENT OF PARAFFIN WAX BY USING LOW ENERGY X-RAY

ABSTRACT

This study explores the mass attenuation coefficient properties of paraffin wax at kilovoltage x-ray energies and compares these properties with those of solid water phantom, water, and Perspex, which are commonly used to mimic human tissue. Using the Half-Value Layer (HVL) method, we determined the effective energies for 60, 81, and 125 kVp, finding values of 35.22, 37.57, and 41.20 keV, respectively. The results showed that mass attenuation coefficients were highest at lower effective energies and decreased with higher energies, consistent with the behaviour of the photoelectric effect. Besides, it was noted that the variation of x-ray transmission factor, ln (I0/I) was linear with the increased of phantom thickness. Additionally, we assessed the percentage deviations of the mass attenuation coefficients of solid water phantom, Perspex, and paraffin wax from those of water, emphasizing water's role as a reference material due to its radiological similarity to human tissues. The results obtained were validated against theoretical values from XCOM software, confirming the accuracy of our methods. Current study suggested that the maximum deviation of mass attenuation coefficient obtained experimentally in comparison to that of XCOM were 25% for water, 27% for Perspex, 8.4% for paraffin wax, and 44% for solid water phantom. This study supports the use of paraffin wax as a cost-effective tissue equivalent material for radiological applications and provides a solid foundation for future research and practical use in diagnostic radiology and quality assurance.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Photons attenuates when interacts with materials. The attenuation of photons with materials includes the absorption and scattering. The attenuation of photons depends mainly on the energy of photons and the density of the materials influenced by the electron density and effective atomic number, Z_{eff} of the materials. In the interaction of photon, there are two types of attenuation which are linear attenuation coefficient, μ and mass attenuation coefficient, μ/ρ that are frequently employed to characterise the beam attenuation qualities. This attenuation coefficient characterizes on how the ability of material to penetrate by the photon energy. In a previous study by Nair et al., (2017) the attenuation coefficient is the crucial parameter used fabricated tissue equivalent phantom to measure the ability to imitate human body tissue.

XCOM is a software that provides total mass attenuation coefficients of any element, compound, or mixture from 1 keV to 100 GeV by theoretically accounting for all interactions of the material with photons (Belgin, 2022). According to (Frimaio *et al.*, 2019), linear attenuation coefficient depends on the density of material. As a result, mass attenuation coefficient data, which is independent of material density were needed. However, a monoenergetic beam can accomplish these attenuation qualities. The production of the perfect monoenergetic beam itself is still a challenging thus, more researchers have consistently developed a variety of techniques for creating monoenergetic beam. The monoenergetic photon beam commonly produce by spectrometer, synchrotrons and parametric x-ray source (Belgin, 2022). Therefore, this present study utilizes the kilovoltage x-ray beam. The previous study by Chen et al., (2012) proposed the employing of the Half-Value Layer (HVL) method, which offer more economical alternative to generate monoenergetic x-ray beams. It was suggested that the mass attenuation coefficient can be determined by measuring the transmitted photons' x-ray spectrum after they have passed through different thicknesses of material.

The requirements for a good phantom are that the material is equivalent to human tissue, homogeneous, non-toxic, has no bubbles and does not change its nature after several times of irradiation. Since water's radiological characteristics are comparable to those of human tissues, it is frequently employed as a substitute for human tissue. The radiation-absorbing and scattering properties of water are quite similar to those of soft tissue and muscle. This is because both of it are having similar atomic number (Arjunan *et al.*, 2018). The human body is made up of around 70% water molecules, each with an effective atomic number of 7.42. There are two primary reasons for using water as a phantom in radiotherapy dosimetry. First, it was widely available, and its density could be maintained with a reasonable degree of precision in any shape or size, and it was affordable. Second, water phantoms are readily available for beam profile acquisition and dosage measurement (Yadav et al., 2021).

According to Aisyah et al. (2020), the paraffin wax had a similarity to the synthesized bolus including the value of the relative electron density are equivalent to human soft tissue from natural rubber that currently used in radiotherapy treatment. Thus, the paraffin wax is often used as human tissue equivalent phantom mostly in radiotherapy because it uses the high energy of x-ray. According to the research by Pires et al. (2023), the paraffin proved to be an affordable, convenient, successful, and adaptable approach for reducing the air gap between human tissues during irregular superficial cancer irradiations thus, it can be used as human tissue equivalent phantom.

Perspex are now commonly used in diagnostic radiology as human tissue equivalent phantom especially in quality control (QC) and quality assurance (QA). In previous study by Zuber et al. (2021) and Yadav et al. (2021), Perspex also can mimic human tissue and has been used as solid phantom especially in quality control and research on human tissue.

The purpose of this study is to compare the data obtained from XCOM software with the measured mass attenuation coefficients paraffin wax, Perspex slabs, solid water phantom, and water.

1.2 Problem Statement

Paraffin wax is a white or colourless soft, solid wax that are made from saturated hydrocarbons chain. The used of paraffin wax as human tissue equivalent material has been used around the world in medical field especially in high energy x-ray. However, there still limited research on the radiological properties of paraffin wax to be used as a human tissue equivalent material. In order to investigate the properties of paraffin wax, the mass attenuation coefficients are being used to compared with water as human tissues. The spectral distribution of X-rays in diagnostic radiology must be understood to optimise diagnostic x-ray information and reduce patient doses. However, x-ray photons have polychromatic energy, therefore it is extremely difficult to characterise the beam quality. In addition, the energy spectrum of diagnostic x-ray is difficult and time-consuming procedure to accomplish clinically. Besides, the production of line sources required license and expensive thus, it cannot be done in laboratory. Since the attenuation coefficient is a measure of the photon beams penetrate through materials, direct measurements of the x-ray energy spectrum at various energies are required. A simpler option, the HVL method, can be used to achieve this goal. Many studies have been conducted using various setups and gamma beams with either high or low energy. As a result, limited research has been done on the measurement techniques for mass attenuation coefficients using kilovoltage x-ray effective energies. Every experiment must be carefully and systematically planned to ensure that the method used is consistent with the available data. As a result, validation of the experiment is required by comparing the experimental data to the calculated mass attenuation coefficient.

1.3 Aim of the Study

To determine the mass attenuation coefficient properties of paraffin wax at the kilovoltage x-ray.

1.4 Research Objectives

1. To determine the effective energy of the nominal x-ray in 60, 81, and 125 kVp using HVL method.
2. To compare the mass attenuation coefficient of paraffin wax, solid water phantom, and Perspex at effective energy with water.
3. To compare the experimental mass attenuation coefficient of paraffin wax, solid water phantom, water and Perspex at effective energy with data obtained from NIST XCOM.

1.5 Research Questions

1. What are the effective energies for nominal x-ray of 60, 81 and 125 kVp using HVL method?
2. Which sample has the smallest discrepancies with water?
3. How accurate the mass attenuation coefficient of the samples obtained in the experimental method with XCOM software?

1.6 Significance of Study

This study aims to determine the applicability and reliability of the experimental procedure used to measure the mass attenuation coefficient of the paraffin wax in order to validate the paraffin wax as a tissue equivalent material by using kilovoltage x-ray beam. Several methods have been used in the dosimetry investigations. However, there is a lack of study regarding dosimetry research in radiology using kilovoltage x-ray beams. Therefore, in this study, the determination of the suitability of using kilovoltage x-rays for the measurement of mass attenuation coefficients is being done.

CHAPTER 2

LITERATURE REVIEW

2.1 Attenuation Coefficient

Attenuation is the process where a radiation beam loses intensity as it passes through the material. Photon transmissions are important for the qualification of tissue comparable materials for diagnostic radiological applications (Frimaio *et al.*, 2019). When radiation passes through matter, it is mostly absorbed by pair production, photoelectric, and Compton interactions. Therefore, the energy of the radiation reduces as the thickness of the absorbing material increases. The attenuation coefficient quantifies the penetration and diffusion of photons in a material. Commonly used coefficients to describe beam attenuation properties include the linear attenuation coefficient and the mass attenuation coefficient (Kargar et al., 2019). The common unit to express the linear attenuation coefficient is either in per centimetre or per millimetre. Lambert-Beer Law is the common equation used to describe the attenuation coefficient of the monoenergetic x-ray beam:

$$I = I_0 e^{-\mu x} \qquad (1)$$

where I_0 is the initial intensity of the beam, I is the transmitted beam intensity and x is the penetration depth or thickness of the material (Elsayed, 2023). The total attenuation coefficients also can be expressed as function of x since linear attenuation coefficient depends on the beam energy and absorber thickness

$$\ln\left(\frac{I_0}{I}\right) = \int \mu(x)dx \qquad (2)$$

This function can also be rewrite as:

$$\mu x = \ln\left(\frac{I_0}{I}\right) \tag{3}$$

The equation above commonly used in determining the penetration depth of photon beam.

Since μ depends on density, a density-independent measure, such as the mass attenuation coefficient, is needed. The mass attenuation coefficient is a measurement of average number of interactions between incident photons with matter in unit mass per unit area thickness of the material irradiated. However, in order to obtain the attenuation properties, the beam used must be homogeneous. The unit is in centimetre squared per gram, cm^2/g. Mass attenuation coefficient, denoted with symbol μ_m or μ/ρ is obtained through the ratio of linear attenuation coefficient to density material where the photon traverse.

$$\mu_m = \frac{\mu}{\rho} \tag{4}$$

The mass attenuation coefficient is a crucial parameter for determining a material's ability to absorb and scatter ionizing radiation, collectively referred to as its attenuation properties. Different materials exhibit varying mass attenuation coefficients, which are influenced by factors such as mass density, effective atomic number, and electron density. Therefore, two materials are considered to have similar attenuation properties for ionizing radiation if their mass attenuation coefficients are comparable.

2.2 Beam Quality

Beam quality of x-ray photon may affect the image contrast, dosimetry instrumentation and patient dose information. X-ray beam used in diagnostic radiology are heterogenous due to its nature of diverse energies. In medical diagnostic energy ranges between 70 kVp and 200 kVp. Due to this wide range, characterizing the beam quality is complicated. The application of Lambert-Beer is monochromatic x-ray beam, collimated and oriented orthogonally to the sample surface, and homogenous without radiation scatter (Oshina & Spigulis, 2021). For polychromatic x-ray beams, more x-rays are absorbed as energy decreases while passing through materials. As a result, the attenuation of a given sample is not directly proportional to its thickness. Moreover, the energy spectrum of polychromatic x-rays covers a wide range, making it difficult to match the x-ray energy to the detector's ideal absorption energy. Therefore, using higher energies is necessary, as they have been shown to provide optimal performance. The production of a monochromatic x-ray beam using synchrotrons is a complex and expensive process. Therefore, the Half Value Layer (HVL) concept is used to characterize beam quality by expressing the attenuation of the primary beam.

2.3 Half-Value Layer (HVL)

The thickness of an absorber that, under narrow beam conditions, attenuates the x-ray tube output by half is known as the HVL. The conventional method of obtaining the HVL involves a sequence of acquisitions with high pure aluminium sheets, which makes it possible to determine the aluminium thickness that results in a 50% reduction in tube output (Bemelmans *et al.*, 2021). The half-value layer (HVL) is a material's fraction of the electromagnetic radiation entrance depth that is directly correlated with the direct linear attenuation coefficient, μ. HVL focuses on a material's thickness that is expected to decrease incident radiation intensity in half of the initial value (Hassanpour *et al.*, 2023). Chen et al. (2012) demonstrated that the conversion of HVL values into linear attenuation coefficient or mass attenuation coefficient can be used to characterise the effective energy of the kilovoltage x-ray beam. The equation for the conversion is as following:

$$\mu = \frac{0.693}{HVL} \tag{5}$$

Referring to Equation 1 (the monoenergetic beam of x-ray), let x = HVL. Then, $\frac{I}{I_0} = 0.5$. Thus,

$$\frac{I}{I_0} = 0.5 = e^{-\mu(HVL)} \tag{6}$$

For every side, the exponential's inverse function is calculated in the same way.

$$In\ (0.5) = In(e^{-\mu(HVL)}) \tag{7}$$

The equation above can be rearranged:

$$-0.693 = \mu \times HVL$$

$$HVL = \frac{0.693}{\mu} \tag{8}$$

The single energy of an x-ray beam that attenuates at the same rate as polychromatic x-ray is equal to the effective energy of the polychromatic energy. Since effective energy is equal to monoenergetic beam radiation, it is practically employed to characterise the x-ray Bremsstrahlung quality (Chen et al., 2012).

2.4 Paraffin Wax as Tisue Equivalent Phantom

A mass of material that resembles human tissue is called a phantom. It is used to mimic many human organs and tissues. Also used for studying the effects of radiation beams on people. Phantom materials can be anything from water to intricate chemical combinations that accurately simulate how radiation might interact with the human body. To evaluate image quality in diagnostic radiology, the ICRU Report 44 (1989) specifies that tissue equivalent materials have linear attenuation coefficients within 5% of the required photon energy interval for each bodily tissue. Furthermore, it is believed that its dispersion properties are like human tissues (Bakri & Ab Razak, 2019).

According to a study by Phani et al. (2024), a wax phantom is used as an affordable and customizable that can be used to evaluate in diagnostic ultrasound scanner. As reported by Yadav et al., (2021), the first wax phantom was made up of paraffin wax with corrective filter magnesium oxide by Siemen's company. A wax phantom not only tissue equivalent but also have an almost like human body in term of absorption and scattering effect. In addition, it is less toxic to manufacture and do not need to control by their temperature (Yadav et al., 2021). In a study by Amin et al., (2020), paraffin wax with a different amount of NaCl can used to imitate human soft tissue and human bone tissue. The study also used mass attenuation coefficients of the mixture in order to prove the tissue equivalent material.

2.5 Estimation of Linear Attenuation Coefficients

The attenuation coefficients of material can be obtained by using a web database software called XCOM: Photon Cross Section Database. This software offers total attenuation coefficients for elements, mixtures, and compounds across a broad energy range from 1 keV to 100 GeV. Additionally, it provides data on photon cross sections for scattering, the photoelectric effect, and pair production. The attenuation coefficients presented in the software is equivalent to the total of these interaction coefficients.

Additionally, XCOM software is a simple and basic method to estimate the attenuation properties of a material.

Since it is the simplest and most straightforward method, studies based on the transmission of x-rays are commonly utilised. This method made use of the measured x-ray spectrum of photons that were transmitted through different material thicknesses. As the radiation attenuate, some of the radiation radiation passes through a phantom, some of its energy is transferred to the phantom, while some may pass through and exit the phantom. As the radiation beam passes through the phantoms slab, the beam’s intensity will be reduced due to attenuation. Nair et al. (2017), used this theory and method to determine the mass attenuation coefficient of fabricated phantom used for dosimetry study purposes.

The linear attenuation coefficient of water equivalent phantoms was estimated by measuring the transmitted x-ray beam that traverses through different thickness of various phantoms. The materials' linear attenuation coefficients were then compared to with water, which served as a reference phantom material (Frimaio et al., 2019). The comparisons were done to validate the evaluation of the samples having the smallest discrepancies with reference material. Additionally, it is done to evaluate the experimental method in determining the attenuation coefficients.

Table 2.1 Survey on experimental methods involving polychromatic x-ray beams and phantoms materials in determination of mass attenuation coefficients.

Author (year)	Description/ Finding	Modification
Chen et al., (2012)	• Determination of effective energies for nominal energies used. • Used the commonly used energy in diagnostic radiology ranging from 50 kVp to 125 kVp. • X-ray energy spectrum prediction using the Ipem78 and SpekCal models. compared the calculated models' effective energies with the measured ones.	• The methods of direct measurement of HVL were used in this study. The nominal energies used were 60, 81 and 125 kVp.
Nair et al. (2017)	• This study used a cost-effective material as phantom substitute using polychromatic diagnostic x-ray beam (70 and 85 kVp).	• The methods from their study were used in this study effective materials as phantom substitute using polychromatic diagnostic xray beam (70 and 85 kVp).

	• Samples tested were cardboard and sun mica sheets	• This study used water, solid water phantom, Perspex, and paraffin wax as samples.
Mohd Yusof et al. (2019)	• Lambert-Beer Law was utilized to observe the photon transmission of selected samples. • The measured mass attenuation coefficients of the particleboards were compared to the theoretical values of water by using the XCOM software calculation at similar photon energies	• Instead of comparing the mass attenuation coefficient of phantoms in experiment with water (XCOM), this study compares the mass attenuation coefficient between phantoms with water in experimental and compare the mass attenuation coefficient of phantom between experimental with XCOM

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

3.1.1 X-ray Machine

This study was located at the Satellite X-ray Unit (Radiology Department) in Hospital Universiti Sains Malaysia (HUSM). The x-ray machine utilized was a Bucky Diagnostics model manufactured by Philips Healthcare in Massachusetts, USA, with a three-phase power supply as the source of x-rays. The nominal energies used are 60, 81, and 125 kVp.

Figure 3.1 Philips three-phase x-ray machine to supply x-ray beams.

3.1.2 RTI Piranha Meter

This current study used Piranha Meter by RTI Group, Sweden as a dosimeter with model Piranha Dose Probe with serial number of 1411113. This meter can measure the dose or dose rate by providing an indirect representation of the energy deposited in the chamber. This type of meter measures and displays all parameters instantaneously and concurrently. It calculates kVp, time of exposure (s), total filtration, computed tomography density index (CTDI) parameters, dosage length product, and displays a waveform. This meter is connected with an electronic meter which contains Ocean Next^{TM} software.

Figure 3.2 RTI Piranha Meter to measure the radiation output of the x-ray beams.

3.1.3 Aluminium (Al) sheets

In this study, Al sheets (Nuclear Associates, Fluke Biomedical, USA) with 1mm thickness and density of 2.7 g/cm3 each were used to determine the effective energies of the nominal x-ray energy of 60 kV, 81 kV, and 125 kV by using the HVL concept. Aluminum sheets are frequently used as additional filters in radiography to absorb low energy x-rays and remove needless doses to improve beam quality.

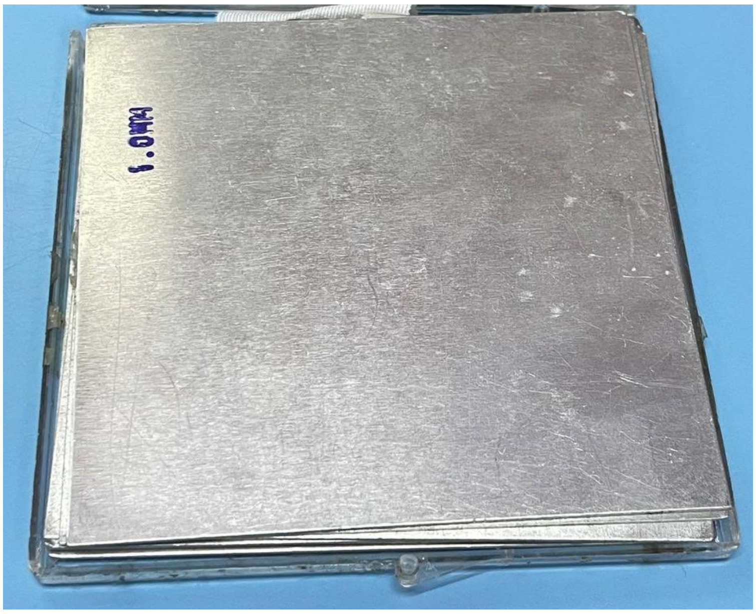

Figure 3.3 Aluminium (Al) sheets used to determine the effective energy

3.1.4 Paraffin Wax

Paraffin wax, commonly known as petroleum wax, is a soft colorless substance made from petroleum, coal, or oil shale. The paraffin wax with density used in this study having mass density of 0.8 g/cm³. In this study, 100% pure paraffin wax with wax code of 464 and stock keeping unit (SKU) of A90083726BW by D Celsius Enterprise was used. Paraffin wax is widely utilized in radiotherapy as bolus material and tissue compensation material for therapeutic purposes, especially in hand treatments.

Figure 3.4 Paraffin wax used to determine mass attenuation coefficient.

3.1.5 Plastic Container Fill with Water

A transparent plastic container of 40 cm x 31 cm x 17 cm was used to fill in the water with a total depth of 8 cm. Water was used as the main reference for phantom material because the human body is mainly composed of water.

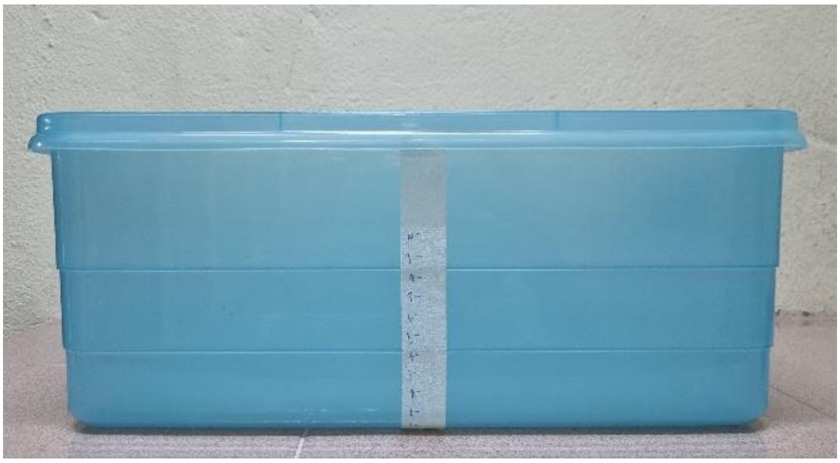

Figure 3.5 Plastic container filled with water used to determine mass attenuation coefficient.

3.1.6 Solid Water Phantom

The solid water phantom with size of 30 cm x 30 cm x 2 cm was used in this study. The radiation properties of this solid water are extremely like those of water in terms of volume. The solid water is produced by PTWFREIBURG with serial number of REF T29672

Figure 3.6 Solid water phantom used to determine mass attenuation coefficient.

3.1.7 Perspex® slabs

In this study, Perspex® slabs of 30 cm × 30 cm × 2 cm were used. Polymethyl methacrylate, or acrylic sheet, is marketed under the Perspex® brand (PMMA). With a density of 1.18 g/cm³, the Perspex® slabs used in this study have applications in the commercial, residential, and medical industries.

Figure 3.7 Perspex® slabs phantom used to determine mass attenuation coefficient.

3.1.8 Fabricated stand

The stand was used to place samples that needed to be irradiated. This fabricated stand was made of polyvinyl chloride (PVC) pipes. The PVC was chosen as it is a multipurpose thermoplastic polymer that is renowned for being strong, resilient to abrasion, and lightweight.

Figure 3.8 Fabricated stand used to place the phantoms during irradiation.

3.1.9 XCOM software

The attenuation coefficients and cross sections for chemicals and mixtures at energies ranging from 1 keV to 100 GeV can be produced using XCOM software. This software was developed by National Institute of Standards and Technology. For the processes of incoherent scattering, coherent scattering, photoelectric absorption, and pair production in the field of the atomic nucleus and in the field of the atomic electrons, the software offers total cross sections, attenuation coefficients, and partial cross sections.

3.2 Methodology

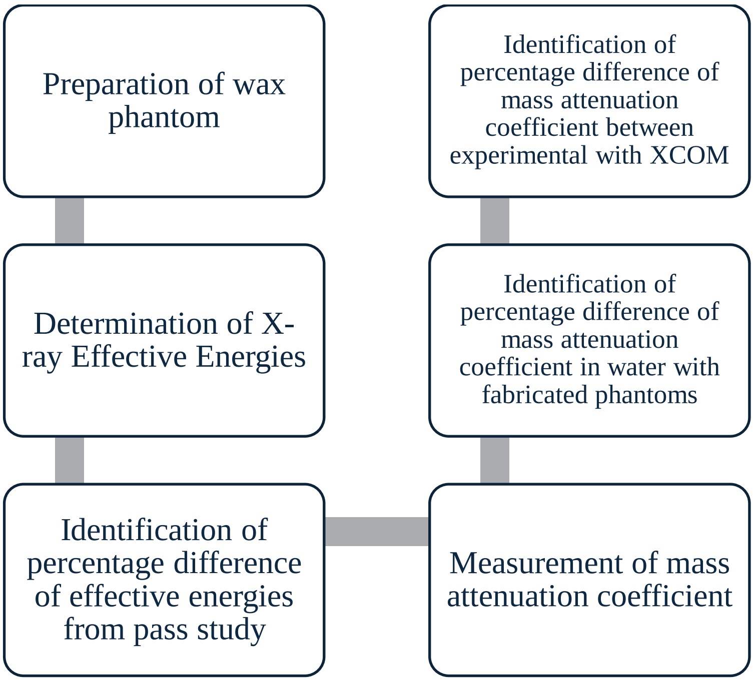

Figure 3.9 Flow chart for this experiment

3.2.1 Preparation of wax phantom

Paraffin wax, often called crystalline wax, is typically a white, tasteless wax-like material. It is solid at room temperature, with a melting point of around 37 °C (99 °F) and a boiling point around 370 °C (698 °F). Paraffin is a hydrocarbon combination; hence its melting point is less rigorous than that of a pure compound. The wax was melted by double boiling method as its melting point is below the boiling point of water which is 100ºC.

Figure 3.10 The Paraffin wax was melted in double boiling method

After the melting of the paraffin wax, the wax was poured on a silicon mould to shape the wax into a slab with size 18 cm x 18 cm x 1 cm. The silicon is used as a mould as the silicon has a high melting point. This high melting point is caused by the strong covalent bonds that hold all the silicon atoms together, which require a substantial amount of energy to break them. The melted wax then left at room temperature until solidified.

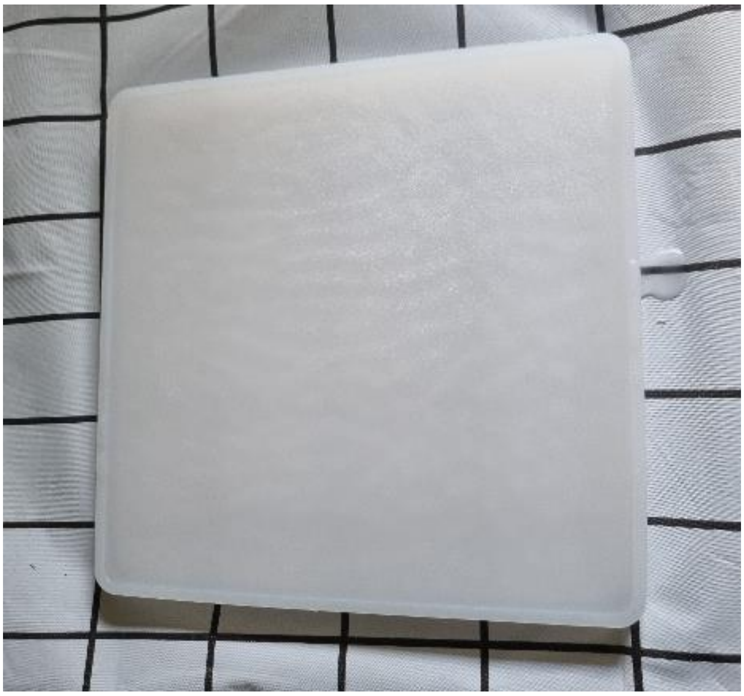

Figure 3.11 The melted paraffin wax was poured into a silicon mould.

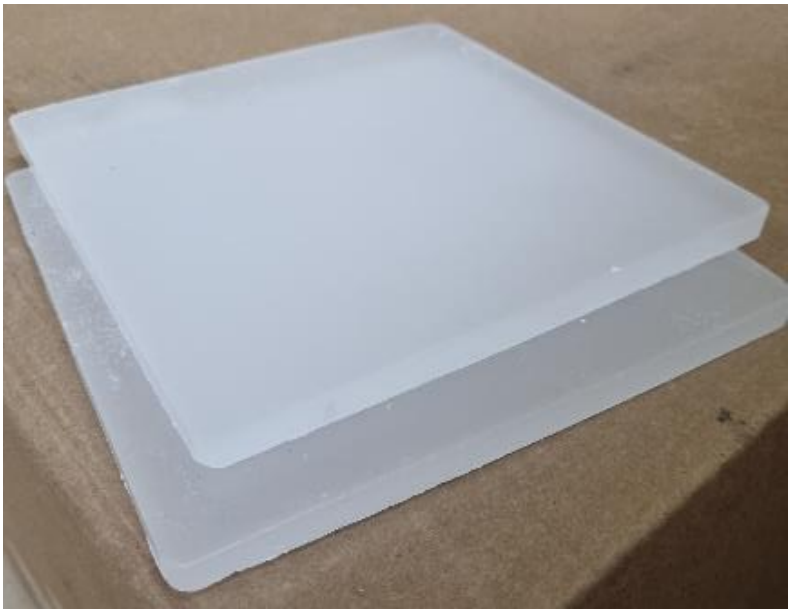

Figure 3.12 The solidified paraffin wax that used to determine mass attenuation coefficient

3.2.2 Determination of X-ray Effective Energies

The term "Half Value Layer (HVL)" refers to a beam quality expressing parameter that is based on a material's attenuation of the primary X-ray. This is where the concept of effective energy originates (Kato *et al.*, 2011). In this study, the effective energy is determined by using 60, 81, and 125 kVp as the nominal energy. The distance of measurement between the x-ray tube and the detector was 100 cm with 12 cm x 14 cm field size on the detector. The detector was placed on the table couch and connected to the electronic reader. The detector is irradiated directly without any additional filter. Every measurement was repeated three times to get the average reading. The additional filter of Aluminum (Al) sheet with thickness of 1 mm was inserted on the collimator. Then, with the increment of 1 mm thickness of Al sheet, the detector was irradiated until the average reading reached half of the initial reading.

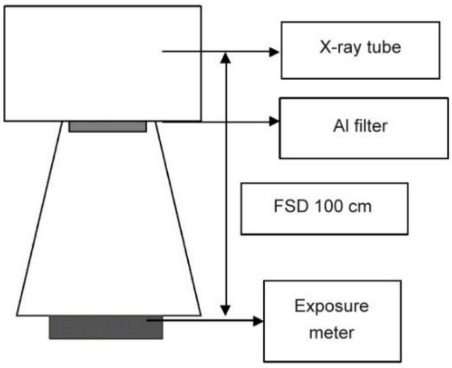

Figure 3.13 The schematic diagram of the experimental setup for half-value layer measurement (image courtesy by Chen et al., 2012).

Then, a semi-log graph of log photons transmission vs Al thickness (mm) was plotted. The 50% intensity of the initial reading was calculated using the equation of the straight line from the graph obtained. This was used to estimate the HVL for each nominal energy used in this study. Next, the value of the linear attenuation coefficient was obtained from the graph while the mass attenuation coefficient of Al was calculated by using equation 4. After obtaining the mass attenuation coefficient of the Al, the